

Social cues at encoding affect memory in 4-month-old infants

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Available evidence suggests that infants use adults' social cues for learning by the second half of the first year of life. However, little is known about the short-term or long-term effects of joint attention interactions on learning and memory in younger infants. In the present study, 4-month-old infants were familiarized with visually presented objects in either of two conditions that differed in the degree of joint attention (high vs. low). Brain activity in response to familiar and novel objects was assessed immediately after the familiarization phase (immediate recognition), and following a 1-week delay (delayed recognition). The latency of the Nc component differentiated between recognition of old versus new objects. Pb amplitude and latency were affected by joint attention in delayed recognition. Moreover, the frequency of infant gaze to the experimenter during familiarization differed between the two experimental groups and modulated the Pb response. Results show that joint attention affects the mechanisms of long-term retention in 4-month-old infants. We conclude that joint attention helps children at this young age to recognize the relevance of learned items.

Keywords: Event-related potentials; Long-term memory; Joint attention; Infancy; Visual recognition.

MEMORY IN YOUNG INFANTS

Memory increases in precision and durability during infancy (Bauer, 2006). However, the empirical evidence on memory development in the first half year of life is somewhat ambiguous. Research shows that visual recognition of memory items depends on a complex interplay of several variables.

For example, the familiarization time required to elicit a behavioral response that is indicative of memory processes changes with age in the first year of life. According to Rose, Gottfried, Melloy-Carminar, and Bridger (1982), the time required to encode a stimulus sufficiently to produce a novelty preference in visual paired comparison tasks decreases between 3.5 and 6.5 months. With 15 s or 20 s of familiarization time, 3.5-month-olds switched from a familiarity response (elicited with 10 s) to a chance response, and with

30 s they showed a novelty preference. Similarly, 6.5-month-olds showed familiarity preferences with 5 s, chance responses with 10 s, and novelty preferences with 15 s of familiarization time.

Furthermore, memory interval affects recognition as assessed by familiarity versus novelty preferences. Fagan (1973) reported that 6-month-olds recognized a familiar stimulus after an interval of 2 weeks but younger infants did not. In contrast, 4-month-old infants showed novelty preferences immediately after familiarization but not after 5 min (Pancratz & Cohen, 1970). Similarly, the type of visual preference at the time of recall is also affected by memory interval. As Bahrnick and Pickens (1995) demonstrated in 3-month-old infants by using object motion stimuli, novelty preferences were observed after 1 min, no preferences after 1 day or 2 weeks, and familiarity preferences at 1 and 3 months after familiarization.

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Thus, null preferences might obscure a memory shift from novelty to familiarity preferences and do not necessarily represent a lack of memory. Finally, the interpretation of age differences in memory and forgetting is often hampered by difficulties in controlling for age differences at initial learning (Howe & Courage, 1997). To reduce this source of ambiguity, younger infants need to receive more extended learning opportunities to reach similar levels of initial learning as older infants and toddlers.

Neural indicators such as event-related brain potentials (ERPs) may provide more sensitive markers of memory for previously presented objects than behavioral assessments (de Haan & Nelson, 1997; Roder, Bushnell, & Sasseville, 2000; Thiessen & Saffran, 2009). The Nc component in the infant ERP is a negative deflection peaking between 400 and 700 ms after stimulus onset. Nc amplitude has been observed as varying with stimulus probability and stimulus familiarity, thus serving a novelty-detection function (Ackles, 2008; Courchesne, Ganz, & Norcia, 1981). Others have described the Nc as relating to more general attentional arousal (Richards, 2003) and attentional orienting to salient stimuli (de Haan & Nelson, 1997, 1999). Nc latency has been shown to be longer in recognition of novel than of familiar stimuli (Ackles, 2008; Kopp & Lindenberger, 2011), suggesting faster processing of the familiar ones. In contrast, longer Nc latencies to familiar events have been associated with more elaborated recognition processes, such as extensive memory search (Karrer & Monti, 1995) and reintegration of memory traces (Bauer et al., 2006; Bauer, Wiebe, Carver, Waters, & Nelson, 2003). The positive deflection Pb peaking between 200 and 400 ms has been described as being related to contextual processing and stimulus expectancy (Hill Karrer, Karrer, Bloom, Chaney, & Davis, 1998; Karrer & Monti, 1995). Both amplitude and latency of Nc and Pb undergo changes within the first year of life (Webb, Long, & Nelson, 2005). Positive slow wave activity (PSW) is usually analyzed as mean activity or area score of activity in a time window between 700 and 1500 ms after stimulus onset. PSW has been found to be related to frequency information (Nelson & Collins, 1992) and updating of memory representations (de Haan, 2007).

As with behavioral observations, the presence of memory-related ERP effects in infants around four months seems to be affected by the amount of familiarization. Reynolds and Richards (2005) demonstrated that in 4.5-month-old infants, ERP differences between novel and familiar stimuli were only observed after a prior familiarization exposure. Similar conclusions were drawn by Pascalis, de Haan, Nelson,

and de Schonen (1998), who habituated 3-month-olds to facial stimuli and observed familiarity-related ERP differences in subsequent recognition. Moreover, Nelson and Collins (1991) proposed that ERP activity would distinguish between novel and familiar events only when the familiar event is presented more frequently than the novel one.

Experimental evidence about memory-related ERP modulations in 4-month-old infants is mixed. Nelson and Collins (1992) investigated PSW activity and did not observe differences between familiar and novel items. In contrast, using the same recognition paradigm, PSW was sensitive to such manipulations in 6- and 8-month-olds (Nelson & Collins, 1991, 1992). Richards (2003) reported Nc and PSW amplitudes as being similar for familiar and novel stimuli in 4.5-month-olds. In a longitudinal study in the first year of life, results of the 4-month-olds revealed no memory effect in Nc amplitude or latency but an interaction of familiarity-related processes with stimulus type (faces vs. objects) in PSW amplitude (Webb et al., 2005). Although the Pb component changes with age in the first 6 months of life, it has not been reported to vary with memory in very young infants (Karrer & Monti, 1995; Webb et al., 2005). From this evidence taken together, the mechanisms underlying memory-related ERP modulations in 4-month-old infants are unclear. In addition, little is known about long-term memory effects at this age.

SOCIAL LEARNING

Cognitive development in infancy is closely related to social development. Infants are sensitive to social cues from early on and use these cues for learning (Farroni, Csibra, Simion, & Johnson, 2002; Reid, Striano, Kaufman, & Johnson, 2004; Striano & Stahl, 2005; Wu & Kirkham, 2010). Joint visual attention, defined as the ability to consider information about one's own visual attention in parallel with information about other people's visual attention (Mundy, Sullivan, & Mastergeorge, 2009), may be a critical indicator for social learning. Joint attentional engagement is characterized by the infant's gaze alternations between an object (e.g., a toy) and an adult person. This interaction may be accompanied by other social cues such as vocalizations, head turns, eye contact, or gestures. Some authors emphasize responding and initiating dimensions that seem to reflect different processes in early ontogeny (Mundy et al., 2007). Specific criteria for the development of joint attention abilities are subject to debate. In a more conservative view, Tomasello, Carpenter, Call, Behne, and Moll (2005) proposed that

joint attention is related to the child's ability to understand others as intentional agents. Accordingly, infants under the age of 9 months would not be able to share goals and perceptions with others, and only infants older than 14 months would be able to show collaborative engagement. However, other research suggests that joint attention abilities develop gradually in the first year of life. Gaze following has been observed in infants as young as 2 to 3 months (D'Entremont, Hains, & Muir, 1997; Scaife & Bruner, 1975), and sensitivity to triadic attention has been demonstrated at 3 months of age (Striano & Stahl, 2005).

Importantly, there has been evidence that joint attention promotes cognitive development. For example, early joint attention was associated with later communication skills (Carpenter, Nagell, & Tomasello, 1998; Mundy et al., 2007) and object processing in infants aged 9 months or younger (Cleveland, Schug, & Striano, 2007; Parise, Reid, Stets, & Striano, 2008; Striano, Reid, & Hoehl, 2006). Again, neural indicators can help delineate early social and cognitive mechanisms, as they can be assessed independently of overt behavioral responses:

THIS STUDY

Recently, using ERP, we investigated effects of joint attention at initial memory encoding of objects on long-term retention processes in 9-month-old infants (Kopp & Lindenberger, 2011). Both immediate visual recognition and recognition after a 1-week delay were affected by joint attention interactions with an adult during the item-familiarization phase. More specifically, PSW activity was modulated by joint attention immediately, with larger mean amplitudes in familiar than in novel items in the experimental group that had been familiarized with the objects in a high-joint-attention context. In addition, Pb amplitude proved to be modulated after the delay by joint attention at initial encoding. Pb responses to familiar objects were more positive in amplitude in delayed as compared to immediate recognition when infants had been familiarized with the items in a low-joint-attention context. In contrast, the large negative deflection Nc varied with stimulus novelty versus familiarity (Reynolds & Richards, 2005), but not with joint attention, thus suggesting that stimulus novelty was dissociable from the relevance of memory items as cued by an adult at previous encoding. Nc amplitudes were larger in response to new than to old objects, with even larger amplitude differences in delayed than in immediate recognition. At the same time, Nc latencies were longer for new than for old items, suggesting

faster processing of familiarized objects. Moreover, brain activity during recognition of familiar objects proved to be modulated by infant-initiated gazes at the adult during familiarization (Kopp & Lindenberger, 2011).

The present experiment aimed to investigate effects of joint attention on memory processes in infants at the age of 4 months. From a developmental perspective, this age group differs substantially from 9-month-olds in terms of both memory (Bauer, 2006; Nelson & Collins, 1992) and joint attention capacities (Cleveland & Striano, 2007). As mentioned earlier, some authors have argued that very young infants might not be able to fully engage in joint attention interactions with an adult (e.g., Carpenter et al., 1998; Tomasello et al., 2005), whereas others have demonstrated that the use of social cues develops gradually and at earlier ages (Cleveland et al., 2007; Striano & Stahl, 2005). Furthermore, as we have described above, it is unclear whether or not 4-month-old infants are able to differentiate familiar from novel items reliably, both immediately and after a retention interval of 1 week. To examine these questions, we adapted a memory test procedure by varying the degree of joint attention at initial encoding.

Our investigation was guided by sets of alternative hypotheses. The first was based on the premise that results obtained in the 9-month-old sample (Kopp & Lindenberger, 2011) would be replicated in the present sample of 4-month-olds. Under this premise, Nc was expected to vary with stimulus familiarity; that is, new stimuli were expected to elicit larger (more negative) Nc amplitudes and have longer Nc latencies than old stimuli. Furthermore, we predicted that PSW mean amplitude would vary with joint attention in immediate recognition. Still in line with our previous data from 9-month-olds, Pb amplitude was expected to vary between joint-attention groups in delayed recognition.

The alternative view posits that 4-month-old infants may lack the capacity to fully engage in joint attention interactions, resulting in short- or long-term ERP modulations that differ from those observed in 9-month-olds. This may become apparent in PSW activity in immediate recognition and in Pb activity in delayed recognition. Lower long-term memory capacities in 4-month-olds than in 9-month-olds may affect Nc modulations. Moreover, in line with previous research in older infants (Parise et al., 2008; Striano et al., 2006), Nc amplitude as an indicator for attentional processes might become more negative during recognition after infants were familiarized with memory items in a high-joint-attention context. Finally, general brain maturation processes as well as variations in the interaction of joint attentional and memory skills

in these young infants may result in a more complex modulation of ERP activity.

METHOD

Participants

A total of 73 infants was tested. All infants were born full term (≥ 38 th week), with birth weights of 2500 g or more. The final sample included thirty 4-month-old infants (14 girls, 16 boys). The mean age at Session 1 was 120.6 days (range 111–130 days), and the mean age at Session 2 was 128.0 days (range 117–137 days). Fifteen infants were randomly assigned to the high-joint-attention (HI-JA) group, and 15 infants to the low-joint-attention (LO-JA) group.

The remaining 43 infants were excluded because of (1) experimental errors or problems with video or EEG equipment ($n = 9$; HI-JA: $n = 5$; LO-JA: $n = 4$); (2) insufficient data for ERP analyses ($n = 18$; HI-JA: $n = 7$, LO-JA: $n = 11$); (3) fussiness in Session 1 ($n = 12$; HI-JA: $n = 8$; LO-JA: $n = 4$) or Session 2 ($n = 2$; HI-JA: $n = 1$; LO-JA: $n = 1$); or (4) inability to participate in Session 2 within the intended 1-week interval ($n = 2$; HI-JA: $n = 0$; LO-JA: $n = 2$).

The ethics committee of the Max Planck Institute for Human Development, Berlin, approved the study. Informed, written consent was obtained from the infants' caregivers.

Procedure: Familiarization

The paradigm combined a standard memory test including a familiarization phase and recognition (Reynolds & Richards, 2005) with an interactive live paradigm adapted from Striano et al. (2006). Infants were tested in a quiet, acoustically shielded room, in an area surrounded by white curtains to prevent visual distraction. Familiarization included the sequential presentation of two colored pictures of toys on a computer screen (distance 70 cm, visual angle 7.13°) in an alternating way. An experimenter monitored the infant's gaze at the screen. When the child had looked at the first object for an accumulated time of 5 s, she switched to the second object. After the next 5 s of accumulated looking time, the experimenter switched again to the first object and so on. A total of four repetitions per stimulus resulted in 20 s of accumulated looking time to each object. The two stimuli were not varied between experimental groups. During the whole familiarization procedure, an experimenter sat beside the computer screen, with her face 60 cm

away from the center of the screen, and 80 cm away from the child. In the HI-JA group, she alternated her gaze between the infant's face and the objects (approximately one turn every 5 s), pointed at the objects (approximately every 8 s), and spoke continuously in a positive tone of voice about them ("Oh, look at this," "What a beautiful toy," etc.) during stimulus presentation. The experimenter was instructed to gaze, speak, and point in a standardized manner, independently of the infant's gaze or affective response. The present experimental manipulation was chosen to contrast a high with a low degree of joint attention. In the LO-JA group, the same experimenter looked at the object on the screen, but not at the infant. She neither pointed nor spoke. Instead, the child was presented via loudspeakers with infant-directed speech that had been recorded in previous sessions in the HI-JA group. Two loudspeakers were placed to the left and to the right side of the screen at a distance of approximately 120 cm from the infant's head. Loudness of the speech presentation was adapted to the average loudness of the experimenter's speech in the HI-JA condition—about 60 dB(A). This procedure resulted in similar amounts of sensory stimulation in the two groups.

Procedure: Immediate and delayed recognition

Immediate recognition (Session 1)

The experimenter left the room after the familiarization procedure. During recognition, infants saw old and new objects in random order. Each item was presented for 1500 ms with a variable blank-screen intertrial interval of 700 to 1200 ms. Novel objects were selected from a pool of 12 stimuli. No more than three old or three new stimuli were presented consecutively. Whenever the infant became fussy or did not look at the screen any longer, an age-appropriate animated movie was presented to entertain the child. Within a session, a maximum of 160 trials were presented, with 80 trials of old and 80 trials of new objects in random order.

Delayed recognition (Session 2)

The recognition test phase was repeated in a second session that took place 6–10 days after the first session. The time interval between Session 1 and Session 2 (memory interval) was on average 7.4 days and did not differ between experimental groups, $t(28) = -1.64$, $p = .113$. In the second session, 80 trials of old

and 80 trials of new objects were again presented. This time, new objects were selected from another pool of 12 objects; that is, new objects in Session 2 differed from new objects in Session 1. The same experimental procedure was applied as in Session 1. On average, 156 stimuli were presented in Session 1 and 153 stimuli in Session 2.

EEG acquisition and data analysis

EEG was continuously recorded at 32 active electrodes with a sampling rate of 1000 Hz and amplified by a Brain Vision amplifier. The reference electrode was placed at the right mastoid, and the ground electrode at AFz. Signals at FP1 and FP2 were monitored to check for vertical eye movements and signals at F9 and F10 for horizontal ones. Impedances were kept below 20 k Ω .

EEG recordings were re-referenced off-line to linked mastoids. A bandpass filter was set off-line between 0.5 and 20 Hz. The continuous recordings were segmented into epochs that comprised a 200-ms baseline before stimulus onset followed by 1500 ms of object presentation. EEG events were matched with video recordings. All trials in which the infant did not look at the screen for the whole 1500 ms were excluded from further analysis. The number of stimuli infants watched did not differ significantly between groups and stimuli (HI-JA: Session 1 old items: 49.0, Session 1 new: 47.8, Session 2 old: 47.8, Session 2 new: 48.7; LO-JA: Session 1 old: 57.7, Session 1 new: 57.2, Session 2 old: 46.9, Session 2 new: 48.7).

Artifacts due to eye or body movements or external sources were automatically discarded when voltage exceeded $\pm 120 \mu\text{V}$. In addition, EEG signals were inspected visually to scan for, and reject, artifacts. A local detrend transform was applied to each EEG epoch. A linear function was subtracted from the data of each segment, slope and limit values of this function being calculated from a 100-ms interval at the beginning and at the end of the segment (Hennighausen, Heil, & Rösler, 1993). Furthermore, a baseline correction to the 200-ms pre-stimulus baseline was performed. Finally, individual averages (ERP) and grand averages across subjects were calculated. Peak amplitudes and latencies of the relevant ERP components were detected for each channel within a predefined latency interval (see below) and submitted to further statistical analyses. Values beyond the range of $M \pm 3 SD$ were excluded from the analyses.

The minimum number of accepted trials per condition and session was 15. For ERP analysis, infants contributed on average 35.3 trials with new stimuli in

Session 1, 36.4 trials with old stimuli in Session 1, 34.3 trials with new stimuli in Session 2, and 31.6 trials with old stimuli in Session 2 to grand averages.

Video recordings

In addition, the behavior of the child and the experimenter was video-recorded in the familiarization phase with 25 frames per second and coded frame by frame, using the software Interact (Mangold International GmbH, www.mangold-international.com). Behavioral categories were infant gazing at object and gazing at experimenter (frequency; proportional duration relative to total familiarization time; mean duration of gazing episodes). Moreover, the frequency of gaze following episodes was coded. Gaze following was defined as a sequence in which the infant first looked at the experimenter and then followed the experimenter's gaze to the object on the screen. Two coders who were blind to the experimental design coded 100% of the behavior and 33% of the behavior, respectively. The inter-rater agreement for infant gaze ($\kappa = .84$) was satisfactory.

RESULTS

Behavioral data

Cumulative looking time at objects was assessed off-line again to verify that infants had looked at each object for a total of 20 s: one-sample *t*-test for first object, $t(29) = 1.34$, $p = .192$, and second object, $t(29) = -0.72$, $p = .474$. Both the frequency of gazes at objects, $t(28) = 1.18$, $p = .247$, and the mean duration of gazing episodes at the objects, $t(28) = 0.08$, $p = .938$, were comparable between the HI-JA and the LO-JA group. Total duration of familiarization—that is, the time until infants had reached the cumulative looking criterion for the two objects—did not differ between the HI-JA group ($M = 87.3$ s, $SD = 38.2$ s) and the LO-JA group ($M = 87.8$ s, $SD = 32.8$ s), $t(28) = -0.04$, $p = .971$. However, the frequency of infant gaze at the experimenter was reliably larger in the HI-JA group ($M = 10.3$, $SD = 8.0$) than in the LO-JA group ($M = 4.9$, $SD = 4.5$), $t(28) = 2.28$, $p = .031$ (Figure 1). Proportional gaze duration at the experimenter was higher in HI-JA than LO-JA children but did not differ significantly between the two groups, $t(28) = 1.57$, $p = .127$. Gazing episodes at the experimenter lasted longer in LO-JA than in HI-JA infants on average, but this difference did not reach statistical significance either, $t(28) = 0.82$, $p = .419$.

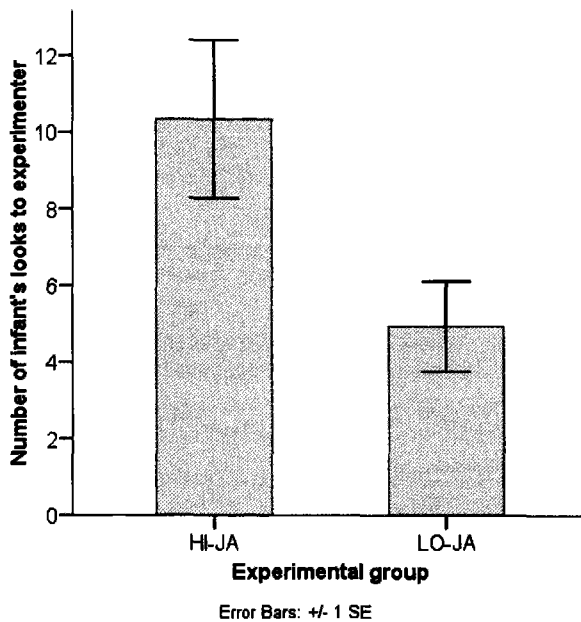


Figure 1. Frequency of infant gaze at experimenter in the HI-JA and LO-JA group during familiarization.

Gaze following episodes during the entire familiarization period, with the experimenter continuously looking at the screen and the infant following her gaze, were observed not only in the HI-JA group (mean frequency = 2.6, $SD = 2.0$), but also in the LO-JA group (mean frequency = 3.1, $SD = 3.3$), $t(28) = -0.47$, $p = .645$. This result indicates that the complete absence of any degree of joint attention cannot be assumed in the LO-JA context, although the experimenter never initiated gaze to the child in this group. In addition, in the HI-JA group, gaze-following episodes were observed in which the experimenter turned her head to the monitor after she had looked at the child and the infant then followed her gaze (mean frequency = 4.2, $SD = 5.6$).

EEG data

Overview of data analysis

Dependent variables for statistical analyses were peak amplitude and peak latency for the Pb (interval: 300–450 ms) and Nc (interval: 450–750 ms), and PSW mean amplitude between 800 and 1500 ms.

The analysis of variance included the between-subjects factor Group (HI-JA vs. LO-JA), and the within-subjects factors Session (1 vs. 2) and Stimulus (new vs. old). Topographical variations were estimated by including the within-subjects factor Region, defined by electrode lines from anterior to posterior. Analyses

showed that parietal (P7, P3, Pz, P4, P8) and parieto-occipital electrodes (PO9, O1, O2, PO10) differed significantly from frontal (F7, F3, Fz, F4, F8), fronto-central (FC5, FC1, FC2, FC6), and central/temporal (T7, C3, Cz, C4, T8) electrodes in Pb amplitude and latency, Nc amplitude and latency, and PSW mean amplitude. At posterior electrodes, the task-relevant ERP components Nc and PSW were not systematically elicited (Figure 2). Small Pb peaks were identified. However, further analyses and the maps in Figure 4 showed that the topographic focus of task-related Pb activity was not located at posterior electrodes.

Based on prior results (Ackles & Cook, 2007; Kopp & Lindenberger, 2011; Richards, 2003; Striano et al., 2006) and given that all of the relevant components were clearly identifiable in anterior regions, subsequent analyses were performed at anterior electrodes (Figure 3). For further assessment of lateralization effects, the within-subject factor Location was included in the ANOVA with the following regions of interest: left-hemisphere (F7, F3, FC5, T7, C3), midline (Fz, FC1, FC2, Cz), and right-hemisphere electrodes (F4, F8, FC6, C4, T8). The final ANOVA included the between-subjects factor Group (HI-JA vs. LO-JA), and the within-subjects factors Session (1 vs. 2), Stimulus (new vs. old), and Location (left hemisphere vs. midline vs. right hemisphere). The significance level was Bonferroni-adjusted to control for multiple comparisons.

Pb. In Session 2, the Pb peak amplitude was significantly more positive in the LO-JA ($M = 0.93 \mu V$) than in the HI-JA group ($M = -3.66 \mu V$; see Figure 4; Session \times Group interaction: $F(1, 28) = 4.97$, $p = .034$, $\eta^2 = .15$). In particular, midline electrodes showed greater Pb amplitude differences between LO-JA ($M = 0.96 \mu V$) and HI-JA children ($M = -2.47 \mu V$; Location \times Group interaction, $F(2, 56) = 4.97$, $p = .010$, $\eta^2 = .15$).

Similarly, Pb latency was reliably affected by Session \times Group, $F(1, 28) = 8.64$, $p = .007$, $\eta^2 = .24$. In Session 2, infants of the LO-JA group had shorter latencies ($M = 363.7$ ms) than infants of the HI-JA group ($M = 387.7$ ms), $F(1, 28) = 6.48$, $p = .017$, $\eta^2 = .19$. In addition, children of the LO-JA group had shorter Pb latencies in Session 2 ($M = 363.7$ ms) than in Session 1 ($M = 383.6$ ms), $F(1, 14) = 8.06$, $p = .013$, $\eta^2 = .36^1$.

The three-way interaction of Session \times Stimulus \times Group on Pb latency was not significant, $F(1, 28) =$

¹ Note that Session \times Group also proved to be reliable on Pb latency in control analyses in posterior electrodes, $F(1, 28) = 5.12$, $p = .032$, $\eta^2 = .16$ (see Figure 2).

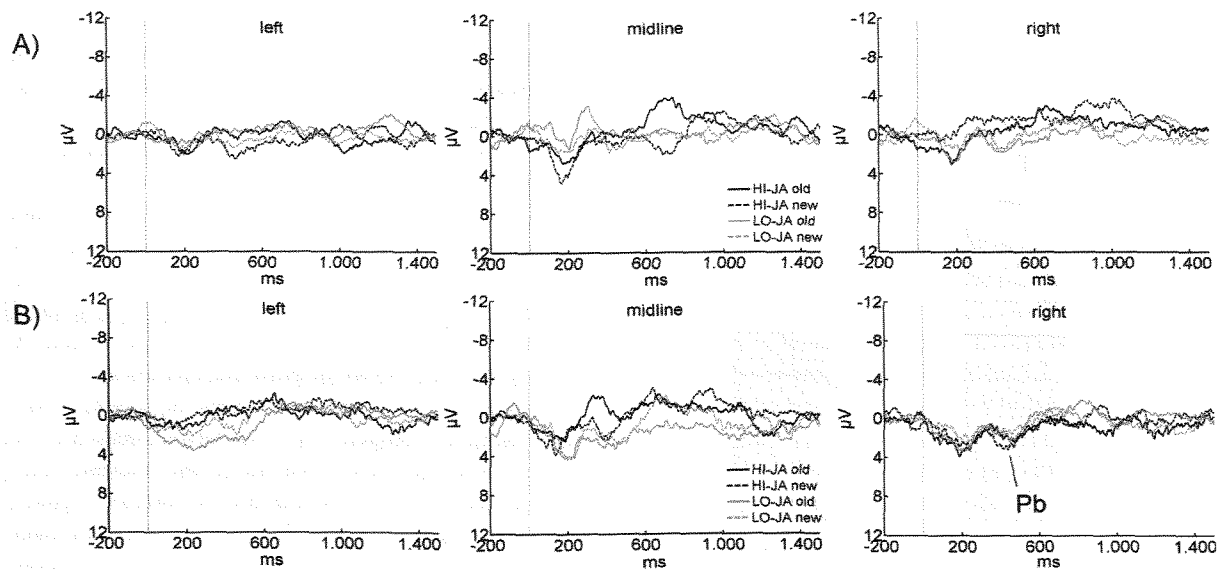


Figure 2. Event-related potentials (ERPs) for Session 1 (A) and Session 2 (B) at *posterior* locations. ERPs were averaged across left-hemisphere (P7, P3, PO9), midline (Pz, O1, O2), and right-hemisphere (P4, P8, PO10) electrodes to improve signal-to-noise ratio for the purpose of illustration. For each session, experimental conditions of old and new items in the HI-JA and LO-JA groups are depicted. At posterior electrodes, Nc and PSW were not systematically elicited.

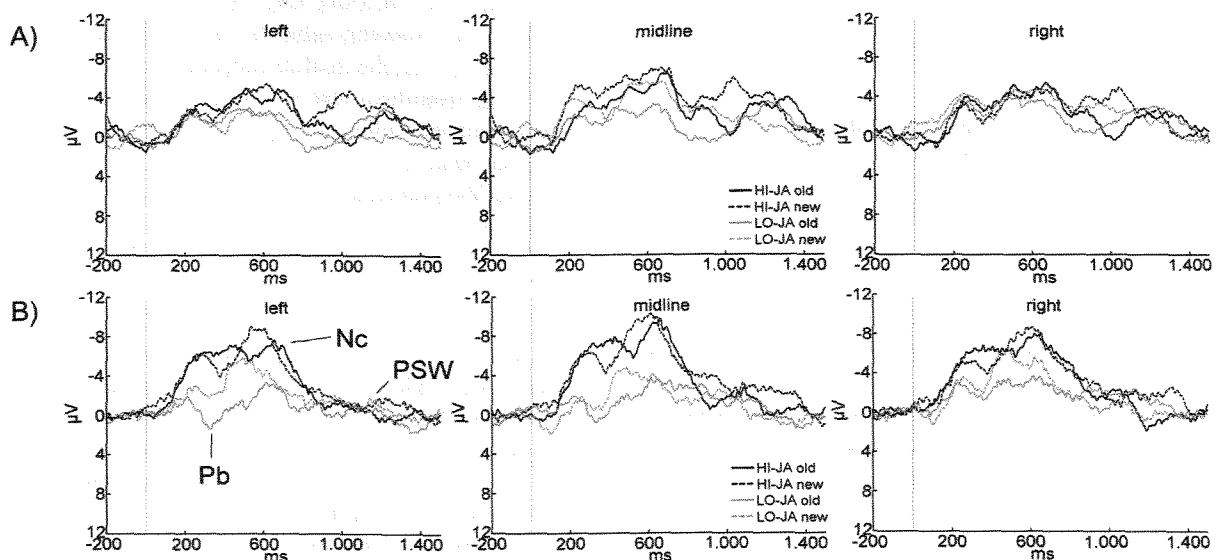


Figure 3. Event-related potentials (ERPs) for Session 1 (A) and Session 2 (B) at *anterior* locations. ERPs were averaged across left-hemisphere (F7, F3, FC5, T7, C3), midline (Fz, FC1, FC2, Cz), and right-hemisphere (F4, F8, FC6, C4, T8) electrodes to improve signal-to-noise ratio for the purpose of illustration. For each session, experimental conditions of old and new items in the HI-JA and LO-JA groups are depicted. In Session 2, Pb peak amplitudes were more positive and Pb latencies were shorter in the LO-JA than HI-JA group. The trend for more negative Nc amplitudes in HI-JA than LO-JA children was not significant. Longer Nc latencies were observed to old as compared to new stimuli, with particularly large differences in Session 2.

3.41, $p = .075$, $\eta^2 = .11$, but only a trend. Planned follow-up analyses for the two sessions indicated that Stimulus \times Group differed between immediate and delayed recognition. In Session 1, LO-JA infants had significantly shorter Pb latencies in old ($M = 373.9$ ms) than in new items ($M = 393.2$ ms) (Stimulus

\times Group: $F(1, 28) = 5.52$, $p = .026$, $\eta^2 = .16$; cf. Session 1 HI-JA group old items: $M = 382.9$ ms; new items: $M = 377.9$ ms), whereas no such interaction was observed in Session 2: Stimulus \times Group: $F(1, 28) = 0.01$, $p = .982$. Moreover, across sessions, a trend for a Stimulus \times Group interaction failed

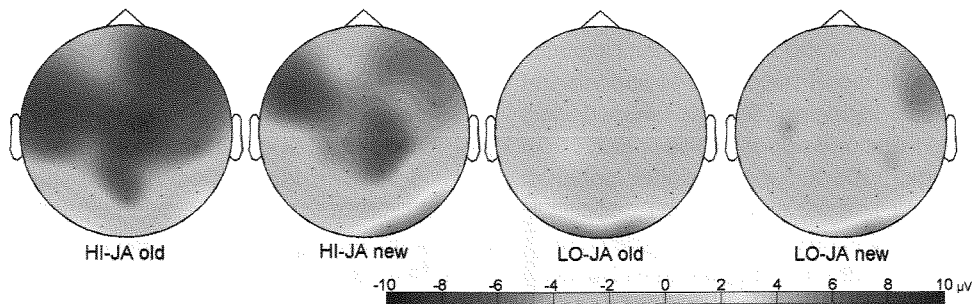


Figure 4. Topographical maps for the time interval of 300–450 ms corresponding to Pb activity for each experimental condition in Session 2. LO-JA infants had more positive amplitudes than HI-JA infants.

to reach statistical significance, $F(1, 28) = 3.07$, $p = .091$, $\eta^2 = .10$. Splitting experimental groups, however, showed that Pb latencies were reliably longer with old ($M = 387.3$ ms) than with new stimuli ($M = 370.8$ ms) in the HI-JA group, $F(1, 14) = 5.82$, $p = .030$, $\eta^2 = .29$ (cf. LO-JA group old items: $M = 370.7$ ms; new items: $M = 376.5$ ms).

Nc. Infants in the HI-JA group tended to have more negative Nc peak amplitudes ($M = -10.4 \mu\text{V}$) than infants in the LO-JA group: $M = -7.1 \mu\text{V}$; Group: $F(1, 28) = 3.65$, $p = .066$. Visual inspection of the ERP waveforms suggested a lateralization towards left-hemisphere electrodes. Therefore, and based on previous neural findings in joint attention research (Grossmann & Johnson, 2010; Parise et al., 2008), a possible contribution of Location was examined further. The interaction Location \times Group was not significant on Nc amplitude, $F(2, 56) = 0.59$, $p = .557$. Separate location analyses revealed a stronger contribution of left-hemisphere electrodes, Group: $F(1, 28) = 4.07$, $p = .053$, $\eta^2 = .13$, than midline, Group: $F(1, 28) = 3.43$, $p = .075$, $\eta^2 = .11$, or right-hemisphere electrodes, Group: $F(1, 28) = 2.85$, $p = .102$, $\eta^2 = .09$, but in neither location was significance reached at $\alpha = .05$.

In contrast, Stimulus had a reliable main effect on Nc latency, $F(1, 28) = 4.63$, $p = .040$, $\eta^2 = .14$. This result indicated that Nc peaks were elicited by old stimuli ($M = 629.7$ ms) after longer latencies on average than by new stimuli ($M = 602.2$ ms). This main effect was qualified by a reliable Session \times Stimulus interaction, $F(1, 28) = 4.84$, $p = .036$, $\eta^2 = .15$, with longer Nc latencies with old than with new items, particularly in Session 2. Furthermore, these Nc latency differences occurred reliably in all electrodes, but the largest differences were observed in left electrodes: old items: 635.4 ms, new items: 601.0 ms; Location

\times Stimulus interaction: $F(2, 56) = 4.42$, $p = .016$, $\eta^2 = .14$.

PSW. No significant effects of Group, Session, Stimulus, or Location were found on PSW mean activity.

Age and memory interval

Infant age (days) and memory interval between Session 1 and 2 (6–10 days) could possibly affect memory-related brain activity. Therefore, we included both factors as covariates in separate control analyses. Infant age was not related to any of the analyzed ERP components. Memory interval did not have significant main effects or interaction effects on any of the ERP components in Session 2.

Behavioral covariates and ERP components

Frequency and proportional duration of infant gaze at the experimenter and frequency of gaze following episodes in the familiarization phase were included as covariates in the analyses of ERP components in later visual recognition, again with the factors Group, Session, Stimulus, and Location.

In the LO-JA group, Pb amplitudes to familiar stimuli increased with increasing frequencies of infants' looks at the experimenter in old items, $F(1, 13) = 6.06$, $p = .029$, $\eta^2 = .32$, but not in new items, $F(1, 13) = 0.62$, $p = .446$ (Figure 5); Stimulus \times Frequency of Gaze at Experimenter: $F(1, 13) = 6.86$, $p = .021$, $\eta^2 = .13$. A similar pattern was observed for Stimulus \times Proportional Duration in the LO-JA group, $F(1, 13) = 10.02$, $p = .007$, $\eta^2 = .44$. Again, Pb peak amplitudes increased with lengthening gaze duration at the

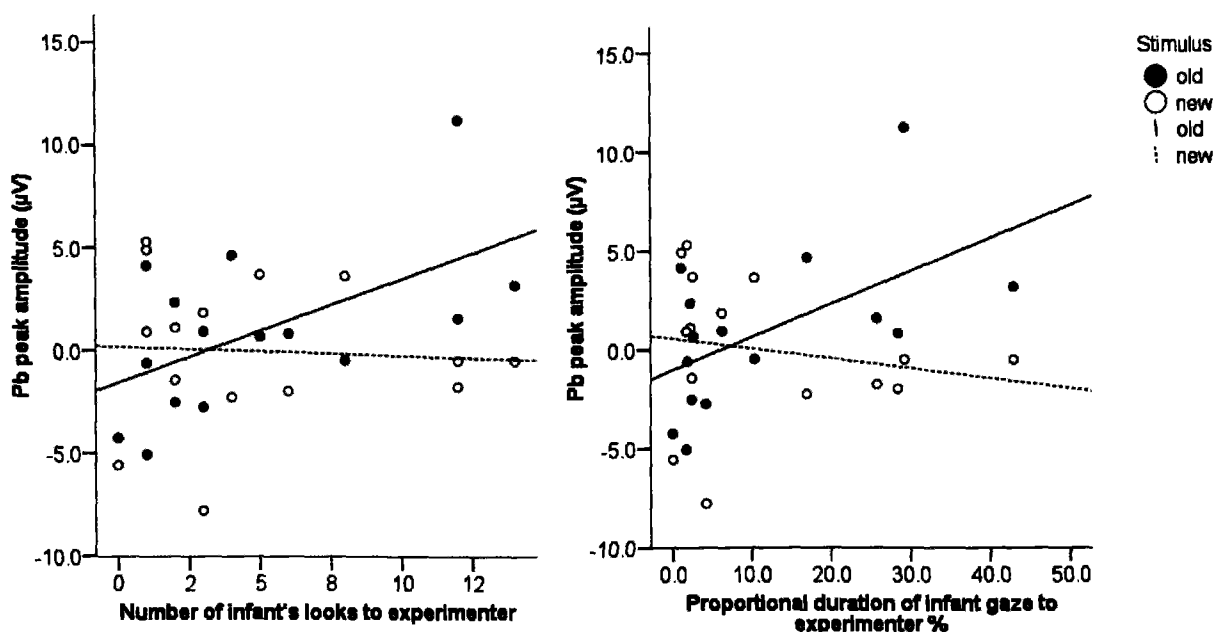


Figure 5. Infant gaze to experimenter during familiarization and Pb amplitude in the LO-JA group. The correlation was .564 ($p = .029$) between frequency of gaze and Pb amplitude, and .558 ($p = .031$) between proportional duration of gaze and Pb amplitude in old items. Both behavioral measures were not significantly correlated with Pb amplitude in new items.

experimenter in old items, $F(1, 13) = 5.87$, $p = .031$, $\eta^2 = .31$, but not in new items, $F(1, 13) = 1.40$, $p = .359$ (Figure 5). In contrast, there were no effects of infant gaze during familiarization on Pb amplitudes in the HI-JA group— Stimulus \times Frequency of Gaze at Experimenter: $F(1, 13) = 0.07$, $p = .790$; Stimulus \times Proportional Duration: $F(1, 13) = 0.41$, $p = .532$.²

In addition, the Nc component proved to be influenced by infant gaze. The higher Proportional Duration was, the larger were the Nc latencies in the HI-JA group, $F(1, 13) = 4.88$, $p = .046$, $\eta^2 = .27$; LO-JA group: $F(1, 13) = 0.54$, $p = .475$. This effect was independent of stimulus and session (Figure 6). Unlike gaze at experimenter, frequency of gaze following episodes was not correlated with ERP activity.

DISCUSSION

Long-term memory in 4-month-old infants

ERPs in visual recognition paradigms have been characterized as reliable tools for detection of memory-related processes in very young infants (e.g., Bauer,

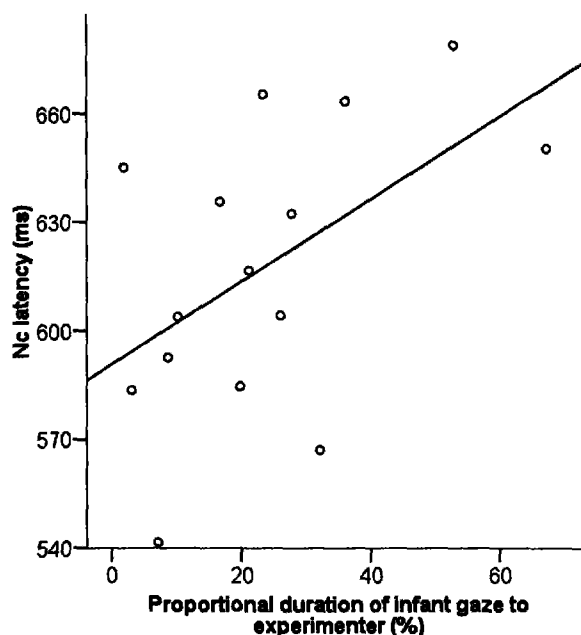


Figure 6. Proportional duration of infant gaze to experimenter during familiarization and Nc latency in the HI-JA group. The correlation between infant gaze and Nc latency was .523 ($p = .046$).

2006). Nc amplitude or latency has been observed to vary with probability and novelty of presented items (Ackles & Cook, 1998, 2007; Courchesne et al., 1981; Webb et al., 2005) as well as with stimulus salience (de Haan & Nelson, 1997, 1999). Ackles (2008) concluded

² Note that frequency and proportional duration of infant gaze to the experimenter were highly correlated ($r = .89$, $p < .001$).

that Nc reflects a top-down or controlled processing mechanism involved in the allocation of attentional resources.

In comparison to our previous study with 9-month-olds using the same paradigm (Kopp & Lindenberger, 2011), the results of the present study revealed both similarities and differences. Similar to 9-month-olds, Nc activity was modulated by memory in the present study. However, in contrast to the data from the 9-month-old infants, Nc latency, but not Nc amplitude, varied with novel versus familiar stimuli. The present results suggest faster processing of new compared to old items in both experimental sessions.

Nc amplitude modulations due to memory have been reported in 4.5-month-old infants in a study by Reynolds and Richards (2005) but have not been observed in other studies with 4-month-old or younger infants (Karrer & Monti, 1995; Richards, 2003; Webb et al., 2005). Webb et al. (2005) reported ERP differences between novel and familiar items in the PSW activity of 4-month-olds. Our results, however, and those reported by Nelson and Collins (1992) converge on the observation that such PSW modulations can not be identified at this age. Webb et al. (2005) used highly familiar and presumably overlearned stimuli, which could have affected memory-updating processes as reflected in PSW activity. Furthermore, they showed that these PSW modulations interacted with the type of stimuli (faces vs. objects) only in 4-month-olds, indicating age-specific stimulus processing.

In some infant ERP studies, Nc latency was not analyzed (Nelson & Collins, 1991, 1992), although ERP waves suggest differential contributions by memory (Richards, 2003). In children aged 6 months or older, Nc latency to novel stimuli was shown to be longer than to familiar stimuli (Ackles, 2008; Kopp & Lindenberger, 2011), indicating faster processing of the familiar ones. In contrast, 4-month-old infants of the present study showed the opposite pattern, suggesting faster processing of novel stimuli. Similar Nc latency responses were observed in 4- to 7-week-old infants by Karrer and Monti (1995), while Nc amplitude remained unaffected. They interpreted their data as reflecting more extensive memory search processes in more familiar stimuli to discriminate features over repeated presentations. According to this interpretation, very young infants efficiently discriminate less familiar stimuli based on salient features. This view and results of the present study suggest that infants aged 4 months or younger might process familiar items at a deeper cognitive level than new items. Behavioral observations, according to which familiar items are often preferred over novel items in visual preference tasks in very young infants, particularly with

short familiarization time, complex stimuli, and long memory intervals, are in line with this assumption (see Introduction of this paper; Roder et al., 2000). In contrast, Bauer et al. (2003) reported longer Nc latencies to old than to new events in 9-month-olds in a deferred imitation paradigm 1 week after exposure to action sequences. Thus, later in the first year of life, infants seem to process familiar events for longer than novel events when reintegration of memory traces is required in delayed recognition after a complex familiarization situation (Bauer et al., 2003).

In the present experiment, a reliable Session \times Stimulus interaction on Nc latency indicated that the difference between old and new stimuli was particularly large in Session 2. One might assume that re-exposure to old items in immediate recognition led to an increase in familiarity (Snyder, Webb, & Nelson, 2002; Wiebe et al., 2006), leading to consolidated memory representations for items presented after a retention interval of 1 week. The novel ERP finding of a long-term memory effect after the delay of 1 week extends ERP results reporting immediate visual item recognition in infants aged 4 months or younger (Courchesne et al., 1981; Pascalis et al., 1998; Webb et al., 2005). Our data suggest that 4-month-old infants are able to recognize familiar objects 1 week after familiarization with these items.

With the present experimental design, familiarity effects cannot be separated from stimulus frequency effects. To compare our results to previous findings, the general procedure of this study followed that of Reynolds and Richards (2005), Striano et al. (2006), and our own assessment of 9-month-old infants (Kopp & Lindenberger, 2011). It would certainly be desirable to control for frequency effects. However, a clear dissociation of familiarity and frequency effects might be difficult, as familiarity tends to increase with frequency. For example, Wiebe et al. (2006) demonstrated that infants' ERP responses to repeatedly presented novel stimuli resembled those to repeatedly presented familiar stimuli in the course of an experimental session, whereas only responses to trial-unique novel stimuli remained unaffected over time.

Previous research and the analysis of Nc latency in the present study suggest developmental changes in memory processes between the ages of 4 and 6 months. First, Webb et al. (2005) demonstrated in a longitudinal assessment that Nc latencies became shorter between 4 and 8 months, presumably indicating a general speed-up of memory-related processes, such as allocation of attentional resources or familiarity-related mechanisms. Second, Nelson and Collins (1991, 1992) proposed a transitional period

around 6 months. They showed that ERP amplitude differences due to memory were similar in 6-month-olds and 8-month-olds (Nelson & Collins, 1991, 1992), but absent in 4-month-olds (Nelson & Collins, 1992). Thus, the transition could be assumed to take place before the age of 6 months. Third, memory-related PSW response shifts were observed from 4 to 6 months (Webb et al., 2005). The authors proposed that this could reflect the preference shift from familiar to unfamiliar stimuli. Finally, as discussed above, Nc latency responses to familiar versus novel stimuli varied with age. In infants of 6 months or older, novel stimuli had longer Nc latencies than familiar stimuli during visual recognition (Ackles, 2008; Kopp & Lindenberger, 2011) while the opposite pattern could be observed in infants aged 4 months or younger (this study; Karrer & Monti, 1995).

Social cues at initial memory encoding

From early on, infants are sensitive to social cues. Newborns look longer and more frequently at a face with gaze directed at them versus averted gaze, and neural processing is enhanced for direct as compared to averted gaze in 4-month-olds (Farroni et al., 2002). Using ERP, Reid et al. (2004) demonstrated that 4-month-old children use adults' eye gaze cues for object learning.

Behavioral analyses of the present study confirm infants' sensitivity to social cues at the age of 4 months. Frequency of gaze at the experimenter distinguished between HI-JA and LO-JA interactions. At the same time, total duration of familiarization, proportional duration, and mean duration of gazing episodes at the experimenter did not differ reliably between the groups, indicating that the number, not the duration of instances of engagement, was the key differentiating element. Infants in the LO-JA condition also looked at the experimenter, but less often than children in the HI-JA context. These 4-month-olds were able to initiate instances of sharing by alternating their gaze to and from a responsive adult who showed signs of interactive behavior including eye contact and pointing (cf. Mundy et al., 2007).

To assess developmental variations in the use of social cues in joint attention, we combined the gazing behavior of the 4-month-olds and that of the 9-month-olds from our previous study (Kopp & Lindenberger, 2011) in one ANOVA. Both infant age, $F(1, 52) = 4.48, p = .039, \eta^2 = .08$, and experimental group, $F(1, 52) = 8.84, p = .004, \eta^2 = .15$, had a statistically significant effect on frequency of infant gaze at the experimenter, but they did not interact with each

other, $F(1, 52) = 0.02, p = .600$. Thus, while the interactive gazing behavior increased with age and with a highly activating joint attention context, the effect of joint attention did not differ reliably between the two age groups. Interestingly, frequency of gaze following episodes did not show systematic variations with age or joint attention. This comparison confirms earlier findings whereby gaze following could be observed at very young ages (Scaife & Bruner, 1975), but infants' self-initiated gaze is yet another dimension of joint attention that seems to show different developmental trajectories (Mundy et al., 2007, 2009).

Joint attention and object learning

Based on our results in 9-month-old infants, we predicted that PSW amplitude would vary with joint attention in immediate recognition. This hypothesis was not confirmed in 4-month-olds. Rather, PSW activity was not systematically affected by any experimental manipulation. Our data suggest that the specific functions of PSW might not have fully developed at this age. This finding is in line with some results at 4 months (Courchesne et al., 1981; Nelson & Collins, 1992; Richards, 2003) or even at 6 months (Ackles, 2008; Ackles & Cook, 1998, 2007) but also contradicts other results (Reid et al., 2004; Webb et al., 2005). As discussed above, stimulus material could have been a source of memory updating effects in the study by Webb et al. (2005). Together with effects in delayed recognition (see below), the lack of PSW effects associated with joint attention in 4-month-old infants is unlikely to reflect a lack of these children's capacity to process and use joint attentional cues.

In this present study, no reliable indications for a contribution of joint attention to immediate recognition were found. There was an overall trend for Group on the attention-sensitive Nc component with more negative Nc amplitudes in HI-JA than LO-JA children. This pattern of activation, however, did not differentiate reliably between familiarized and novel stimuli. In other words, during recognition, HI-JA children tended to allocate more attentional resources to all stimuli than LO-JA children, be it new or old objects (for further discussion, see also the section on long-term joint attention effects below).

We did not observe a comparable trend in 9-month-olds in our earlier study. The trend in the present sample of 4-month-olds resembles previously reported data on joint attention effects on object processing. For instance, Striano et al. (2006) found significantly larger Nc amplitudes in a joint-attention than in a no-joint-attention condition at fronto-central midline electrodes

in 9-month-old infants. Parise et al. (2008) demonstrated more negative Nc amplitudes in a joint attention condition with direct eye contact than without eye contact at left fronto-central sites in 5-month-olds. Separate analyses for different locations in the present study with 4-month-olds also indicated a higher joint attention contribution at left and midline electrodes.

The question arises why this Nc amplitude effect was not statistically significant in the present study. First, it has been repeatedly reported that intra- and interindividual EEG variability is particularly high in infants aged 4 months or younger (Karrer & Monti, 1995; Nelson & Collins, 1992). Thus, it seems difficult to reveal EEG modulations as a function of relatively subtle experimental variations. Second, it would be interesting to test whether longer familiarization times would also increase the influence of joint attention. It could be argued that with longer exposure to the stimuli in a joint attention interaction, more attention might be allocated to these relevant stimuli and this could affect later processing and retrieval. Third, joint attention effects in Parise et al.'s (2008) study were demonstrated during recognition of familiar items, whereas effects in Striano et al.'s study (2006) were shown during processing of novel objects. Thus, the complex manipulation of familiarity, joint attention, and long-term memory in the present study might have obscured potential effects. Larger and preferably longitudinal samples are needed to follow up these speculations.

Long-term joint attention effects

Based on data of the 9-month-olds tested with the same paradigm, we predicted that long-term effects of joint attention would be reflected in modulations of Pb responses. This hypothesis was confirmed. We found a reliable Session \times Group interaction on Pb amplitude, with more positive amplitudes in LO-JA children than in HI-JA children in Session 2. Again, the direction of this effect was comparable to the 9-month-olds' data. In addition, Session \times Group was also significantly related to Pb latency, with shorter Pb latencies in LO-JA than HI-JA infants in Session 2 and shorter Pb latencies in LO-JA infants in Session 2 than in Session 1. Thus, both Pb amplitude and Pb latency responses suggest different object recognition mechanisms of 4-month-old LO-JA infants in Session 2.

In our previous article (Kopp & Lindenberger, 2011), we suggested that joint attention would help infants to cue items as relevant during learning (Csibra & Gergely, 2006). Thereby, visual recognition processes might be affected, both immediately and after

longer retention. Pb activity as an indicator of processes of stimulus expectancy (Hill Karrer et al., 1998; Karrer & Monti, 1995) might reflect mechanisms through which the relevance of learned contents, as manipulated by HI-JA versus LO-JA, is coded in long-term memory. Differential recognition mechanisms related to the individual's expectations about the probability of stimulus occurrence might result in Pb modulations. These ERP differences around 300–400 ms after stimulus onset point to the operation of early cognitive mechanisms that might not necessarily be associated with variations of familiarity or attentional orienting as reflected in Nc activity (Kopp & Lindenberger, 2011).

The present differences in Pb amplitude and Pb latency in Session 2 indicate that the LO-JA context during familiarization had an influence on how novel and familiarized items were recognized after a 1-week delay. One could assume that the LO-JA interaction was very distracting for the 4-month-olds, with the complexity of a triadic context between infant, an adult, and objects presented on a screen as well as the unresponsive behavior of the adult. Therefore, interferences with stimulus encoding and object learning are conceivable. In contrast to the 9-month-olds, however, the Session \times Group interaction effect on Pb amplitude was independent of stimulus type in 4-month-olds. A similar result was observed in Pb latency where Session \times Stimulus \times Group did not reach statistical significance. Apparently, joint attention influences encoding on a more general situational level, making the experimental item presentation and recognition as such important for the child.

Recently, Wu and Kirkham (2010) proposed a similar line of reasoning in the context of a study with 4- and 8-month-old infants. They investigated effects of facial cues on learning of audiovisual events and measured infants' predictions of the event locations after familiarization. Infants' looking times showed that children of both age groups followed the face cue but that only 8-month-olds reliably predicted correct event locations. In contrast, 4-month-old infants showed general spatial learning to cued locations regardless of the specific event. Wu and Kirkham concluded that depth of learning and processing (e.g., Craik & Lockhart, 1972) differed between the two age groups as a function of how they had learned to use social cues.

As we have discussed above, longer Nc latencies in old than in new items might indicate that familiar stimuli are processed on a deeper cognitive level in infants at 4 months or younger (Karrer & Monti, 1995). This is in accordance with the behavioral observation that an initial preference for familiar items directs sufficient

attention to these items to form consolidated representations, as suggested by results from Roder et al. (2000) in 4.5-month-old infants. Likewise, modulations due to the degree of joint attention in the present study might account for interference with processing depth and speed as reflected in shorter Pb latencies in the LO-JA group in Session 2 compared with Session 1 and with the HI-JA group. Separate analyses for the two sessions indicated differences between immediate and delayed object recognition in the LO-JA group. In Session 1, shorter Pb latencies in recognition of old than of new stimuli suggest that indeed the familiarized items had shorter processing times in immediate recognition. In Session 2, after 1 week, there were no Pb latency differences between old and new stimuli, revealing that all stimuli had shorter Pb latencies in the LO-JA group.

Furthermore, interindividual differences in infant gazing behavior during familiarization interacted with stimulus type in Pb activity. The more frequently and the longer LO-JA infants had looked at the adult, the larger were the Pb amplitudes in recognition of the familiarized but not the novel stimuli. The influence of stimulus type was not revealed in group-level analyses as it was in the 9-month-olds and refines the understanding of Pb amplitude modulations in LO-JA infants. First, these modulations document some degree of variability among LO-JA infants in the interaction with an adult. Second, they support the assumption that the unresponsive behavior of the experimenter might have interacted with recognition processes. Third, they reveal that joint attention is, in fact, related to initial memory encoding, as only familiarized stimuli were affected.

In the HI-JA group, the similarity of Pb amplitudes and Pb latencies in Sessions 1 and 2 suggest that the interactive learning situation evoked similar immediate and delayed object recognition mechanisms. The Stimulus \times Group interaction on Pb latency was only a trend, but separate Group analyses showed that old stimuli had generally longer Pb latencies than new stimuli. Again, longer latencies might reflect deeper processing levels here. Therefore, this result might indicate that HI-JA children were able to benefit from the activating triadic social interaction context during their familiarization where they learned about the relevance of memory content. This in turn may have resulted in more elaborated encoding and storage.

In addition, the stimulus-sensitive Nc component was found to have longer latencies in recognition with longer proportional gaze at the experimenter during familiarization. As described above, Nc latency was longer in old than in new items, with even larger differences in delayed recognition, where previous repeated

exposure might have increased familiarity further. HI-JA infants who demonstrated more self-initiated gazing at the experimenter than others in their group had the longest Nc latencies. In line with other findings of the present study, this result indicates a facilitating effect of interactive behavior in joint attention situations whereby processing depth of the relevant items could be increased. According to Mundy and colleagues (2009), infants use social situations to create social learning opportunities for themselves. This might be even more important in very young infants who need more learning opportunities to reach the same level of performance as older infants and toddlers (Howe & Courage, 1997).

Open questions

The results of the present study pose a series of questions that should be pursued further. First, the effects of infant age, retention interval, and familiarization time on memory and memory-relevant ERP components need to be observed across a wider range to better understand the development of familiarization and storage in memory. The same holds true for the effects of joint attention and other social interactive cues.

Second, as mentioned above, our experimental design confounded novelty and frequency effects. Clearly, long-term retention with re-exposure to familiarized items during immediate recognition needs to be studied in greater detail. However, stimulus presentation during familiarization and recognition did not vary between the two experimental groups. That is, effects of item presentation alone cannot account for the joint attention effects observed in this study.

Third, with the present HI-JA versus LO-JA manipulation, it is difficult to assess which dimensions of adult behavior are critical for joint attention effects. For example, direct eye contact (Cleveland & Striano, 2007) and vocal cues (Parise, Cleveland, Costabile, & Striano, 2006) are important aspects. However, it is unknown how these behavioral dimensions affect short- and long-term retention. Moreover, it would be interesting to find out how the aspect of live versus pre-recorded speech and the experimenter's verbal behavior, such as lip movements, would influence the degree of joint attention and long-term memory. Finally, the functional significance of infant ERP components in visual recognition needs to be clarified, particularly at very young ages.

In sum, we found evidence for long-term effects of joint attention on object recognition. So far, the effects of social cues (Wu & Kirkham, 2010) or joint attention

(Cleveland & Striano, 2007) on item recognition in 4-month-olds could not be reliably demonstrated. Here we show such effects, using ERP. The self-initiated infant gaze at the experimenter was critical for memory encoding. We conclude that joint attention helps infants as young as 4 months to specify what is relevant for them to learn.

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