



PAPER

Effects of joint attention on long-term memory in 9-month-old infants: an event-related potentials study

Franziska Kopp and Ulman Lindenberger

Max Planck Institute for Human Development, Berlin, Germany

Abstract

Joint attention develops during the first year of life but little is known about its effects on long-term memory. We investigated whether joint attention modulates long-term memory in 9-month-old infants. Infants were familiarized with visually presented objects in either of two conditions that differed in the degree of joint attention (high versus low). EEG indicators in response to old and novel objects were probed directly after the familiarization phase (immediate recognition), and following a 1-week delay (delayed recognition). In immediate recognition, the amplitude of positive slow-wave activity was modulated by joint attention. In the delayed recognition, the amplitude of the Pb component differentiated between high and low joint attention. In addition, the positive slow-wave amplitude during immediate and delayed recognition correlated with the frequency of infants' looks to the experimenter during familiarization. Under both high- and low-joint-attention conditions, the processing of unfamiliar objects was associated with an enhanced Nc component. Our results show that the degree of joint attention modulates EEG during immediate and delayed recognition. We conclude that joint attention affects long-term memory processing in 9-month-old infants by enhancing the relevance of attended items.

Introduction

Joint attention reflects 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). An infant's ability to attend to an event jointly with an adult includes being able to alternate gaze between the social partner and the event and may be accompanied by emotional facial expressions, vocalizations, and gestures such as pointing. Recent research has shown that vocal cues (Parise, Cleveland, Costabile & Striano, 2006) and eye contact (Cleveland, Schug & Striano, 2007; Parise, Reid, Stets & Striano, 2008) are critical aspects of joint-attention interactions.

There is an ongoing debate on the onset of joint attention abilities in the course of the first year of life. Tomasello and colleagues proposed that infants engage in joint-attentional interactions when they understand other persons as intentional agents. Based on their research, they argued that infants before the age of 9 months may not be able to understand and share goals and perceptions with others (Tomasello, Carpenter, Call, Behne & Moll, 2005), and that infants before the age of 12 to 15 months may not be able to participate in fully coordinated joint-attention behavior (Carpenter, Nagell & Tomasello, 1998; Moll, Carpenter & Tomasello, 2007). At the same time, recent evidence suggests that the skills

leading to and the systematic use of joint attention develop gradually at earlier ages. For instance, neonates preferred faces with gaze directed at them over faces with averted gaze (Farroni, Csibra, Simion & Johnson, 2002). Three-month-old infants were able to follow an adult's gaze to an external object (Striano & Stahl, 2005). Finally, joint attention had an effect on object processing in 7-month-olds (Cleveland *et al.*, 2007).

There are good reasons for assuming that joint attention promotes cognitive development. From an evolutionary perspective, Csibra and Gergely (2006) proposed that humans are adapted to transfer knowledge to and receive knowledge from conspecifics through teaching. Infants as learners may be predisposed to interpret ostensive communicative signals of a teacher as evidence for novelty and relevance of the knowledge content (Gergely & Csibra, 2006). Joint-attention interactions may reflect this adaptation, and may help to specify what information is new and relevant for an infant.

Despite the generally accepted importance of joint attention for cognitive development, direct evidence regarding links between joint attention and cognitive performance is sparse. Individual differences in joint attention have been found to relate to cognitive, linguistic, and social aspects of development (Carpenter *et al.*, 1998; Strid, Tjus, Smith, Meltzoff & Heimann, 2006). To strengthen this correlational evidence, process-related links between joint attention and cognitive

Address for correspondence: Franziska Kopp, Center for Lifespan Psychology, Max Planck Institute for Human Development, Lentzeallee 94, 14195 Berlin, Germany; e-mail: kopp@mpib-berlin.mpg.de

performance can be gathered in experimental studies that use electrophysiological measures.

Event-related potentials as indicators of joint attention

Electrophysiological parameters such as event-related brain potentials (ERPs) help to delineate the neural mechanisms through which joint attention modulates cognitive performance. Reid, Striano, Kaufman and Johnson (2004) and Hoehl, Reid, Mooney and Striano (2008) investigated the role of social cues in object processing in 4-month-olds. ERP responses were different when an adult's gaze was directed toward an object as compared to when the gaze was averted from an object. Apparently, uncued objects were perceived as less familiar than objects previously cued by the gaze direction of an adult. Striano, Reid and Hoehl (2006) investigated neural correlates of joint attention in 9-month-old infants using an interactive-live paradigm. An adult gazed at the infant's face and then to a novel object in one condition, and gazed only to a novel object but not at the infant in the other condition. They found that the Nc component of the ERP had larger amplitudes during episodes with high joint attention than with low joint attention.¹ Parise *et al.* (2008) repeated this experiment with 5-month-olds using a blocked design. In one block the experimenter engaged the infant with eye contact while three different objects were presented. Immediately after this familiarization, the objects were again presented to the infant. In the other block the experimenter looked only at the infant's chest instead of establishing eye contact. Like Striano *et al.*'s (2006) findings on the recognition of novel items in 9-month-olds, the 5-month-old infants showed ERP differences in the recognition of familiar objects presented under high-versus low-joint-attention conditions. Taken together, these studies suggest that joint attention may influence neural activity typically associated with learning and memory early in the course of infant development.

Components of event-related potentials as indicators of learning and memory

Memory increases in precision and durability during infancy (Bauer, 2006). These increments are closely related to maturational changes in brain structure and function (Johnson & Munakata, 2005; Paterson, Heim, Friedman, Choudhury & Benasich, 2006). To probe learning and memory, infants are typically shown a series of stimuli during the initial encoding phase of the experiment, also termed familiarization phase. In the recognition phase, previously presented stimuli are shown together with novel stimuli. Differences between

behavioral and EEG responses to previously shown and novel stimuli are considered to indicate memory in the generic sense of stimulus-specific effects of earlier experience on brain and behavior.

ERPs are useful complements to behavioral indicators for charting age-related changes in learning and memory. First, behavioral measures in infancy research have often provided unpredictable data that were difficult to interpret. In particular, measures based on visual preference or habituation were found to be confounded by infant age (Hunt, 1970; Wetherford & Cohen, 1973), stimulus complexity (Hunter, Ames & Koopman, 1983; Thiessen & Saffran, 2009), familiarization time (Hunter *et al.*, 1983; Rose, Gottfried, Melloy-Carminar & Bridger, 1982), retention interval (Bahrack, Hernandez-Reif & Pickens, 1997; Bahrack & Pickens, 1995), and introduction of retrieval cues (Bahrack *et al.*, 1997; Hayne, Rovee-Collier & Perris, 1987; Rovee-Collier & Sullivan, 1980). Furthermore, familiarity versus novelty preferences depend on the time course of visual processing (Roder, Bushnell & Sasseville, 2000). The most critical aspect is that null findings do not necessarily reflect forgetting or a lack of memory or discrimination (Bahrack & Pickens, 1995), and may reflect aggregation artefacts (Roder *et al.*, 2000). In contrast, novelty preference findings suggest discrimination and memory. But it was also suggested that longer looking at novel stimuli may merely be a consequence of reduced neural responses to previously encoded items (Snyder, Blank & Marsolek, 2008). In sum, neither novelty nor familiarity nor null preferences are sufficient to clarify the underlying mechanisms of cognitive processes.

Second, ERPs can document differences in the representation of novel and previously presented items in the absence of behavioral manifestations of this difference (de Haan & Nelson, 1997). In adult research it is widely accepted that electrophysiological responses can provide important information on neural processing when behavioral data fail to show any or provide only few or contradictory indicators of cognition (e.g. Barber & Kutas, 2007; Rugg & Curran, 2007). This is even more important in infancy research as behavioral manifestations can hardly be related to relatively precise measures such as reaction time data or error rates as is possible with adults. Third, ERPs provide information on the precise timing and general spatial pattern of brain activation, and thereby point to the underlying neural dynamics and mechanisms of learning and memory. At a more specific level of analysis, three ERP components were found to be linked to memory processes in infancy: Nc, the positive slow wave (PSW), and Pb.

Nc is a pronounced negative component between 400 and 800 ms after stimulus onset with the most prominent deflection over fronto-central electrodes (Ackles & Cook, 1998, 2007; Karrer & Monti, 1995; Reynolds & Richards, 2005; Snyder, Webb & Nelson, 2002). Nc amplitude appears to be sensitive to both stimulus probability and stimulus familiarity (Ackles, 2008; de Haan & Nelson,

¹ In this article, we prefer to speak of *low* versus *high* rather than *present* versus *absent* joint attention, as the complete absence of any form or degree of joint attention in the low-joint-attention condition cannot be ruled out.

1999; Wiebe, Cheatham, Lukowski, Haight, Muehleck & Bauer, 2006). Reynolds and Richards (2005) noted that sensitivity to stimulus probability is restricted to studies not including a familiarization phase before recognition, which is consistent with the interpretation that the processes underlying the Nc component serve a novelty-detection function. However, Nc amplitude was found to be larger when the familiar stimulus was of high salience, such as the favorite toy or the mother's face (de Haan & Nelson, 1997, 1999).

The PSW commences at about 700–800 ms after stimulus onset, and also tends to be larger over anterior than over posterior electrodes (Snyder *et al.*, 2002; Webb, Long & Nelson, 2005). In contrast to other ERP components, this activity lacks a clear peak, therefore mean amplitudes or area scores are typically analyzed. Functionally, this component has been interpreted in terms of refinement of event categories (Courchesne, Ganz & Norcia, 1981), frequency information (Nelson & Collins, 1991, 1992), and the updating of memory representations (de Haan, 2007). Repetition of a stimulus reduces PSW amplitude (Snyder *et al.*, 2002). In 8-month-olds, Nelson, Thomas, de Haan and Wewerka (1998) found greater amplitudes in response to familiar than to novel stimuli. Thus, PSW activity can be seen as reflecting memory updating and, similar to the Nc component, as being sensitive to stimulus frequency and novelty.

Pb consists of a small positive deflection between 200 and 400 ms, and may correspond to the component labelled P2 in older children and adults. It was suggested that Pb activity may propagate from posterior to anterior sites (Karrer & Monti, 1995; Webb *et al.*, 2005). The component has been thought to reflect mechanisms of contextual processing and stimulus expectancy (Hill Karrer, Karrer, Bloom, Chaney & Davis, 1998). Stimulus characteristics influence Pb amplitude, such as three-dimensional versus two-dimensional format of objects (Carver, Meltzoff & Dawson, 2006) and stimulus duration (Hunter & Karrer, 1993). These findings lead some authors to conclude that Pb activity is affected by ease of stimulus processing (Hunter & Karrer, 1993) or the certainty of expecting an event to occur (Karrer & Monti, 1995). Not only memory-related, but also social processes are related to Pb activity. Striano *et al.* (2006) reported differences in Pb amplitude at frontal and central electrodes due to variations in joint attention.

The available evidence on the development of learning and memory in the first year of life documents infants' increasing reliance on top-down control and elaborative encoding. The ERP evidence on the age-graded timing of these changes is somewhat ambiguous. Some authors postulate major transitions in memory development between 4 and 8 months (de Haan & Nelson, 1999; Nelson & Collins, 1992), and some postulate an additional transition around 9 months of age (Bauer, Wiebe, Carver, Lukowski, Haight, Waters & Nelson, 2006; Bauer, Wiebe, Carver, Waters & Nelson, 2003; Carver, Bauer & Nelson, 2000). Bauer *et al.* (2006) reported

age-related differences in encoding and recall between 9 and 10 months. Research using behavioral and EEG measures showed that, in principle, infants aged 9 months or even younger are able to recall memory contents after a delay of 1 week (Bahrnick & Pickens, 1995; Carver *et al.*, 2000; Lukowski, Wiebe, Haight, DeBoer, Nelson & Bauer, 2005). Using ERP, Bauer *et al.* (2003), however, demonstrated that there is also evidence for large interindividual variability at this age.

This study

We examined whether joint attention at initial encoding modulates long-term memory in 9-month-old infants. To address this question, we combined a modified version of the interactive-live paradigm (e.g. Striano *et al.*, 2006) with the standard recognition-memory paradigm suitable for taxing the presence and strength of memory representations in infants. As Striano *et al.* (2006) have shown, 9-month-old infants are able to use the social cues of a joint-attention context for object processing. In addition, after a 1-week delay, 9-month-olds displayed ERP differences that are indicative of memory for earlier presented objects (Bauer *et al.*, 2003). Based on these observations, our study was guided by two hypotheses. First, we expected that 9-month-old infants would be able to form stable memory traces of visually presented objects, and would therefore be able to recognize familiar items after a 1-week delay, as reflected in differential ERP responses to old versus new objects. Second, we expected that the memory processes for familiar objects would be modulated by the degree of joint attention at initial encoding (i.e. during the familiarization phase). In other words, we assumed that joint attention would modulate *how* items are encoded and thereby stored in long-term memory. Due to the limitations of behavioral measures (see above), we assumed that these subtle and specific mechanisms (including immediate versus delayed recognition differences) would be difficult to assess using looking time measures. Therefore we used event-related potentials.

Method

Participants

A total of 62 infants were tested. The final sample included 28 9-month-old infants. All infants were born full term (≥ 38 th week), with birth-weights of 2500 g or more. The mean age at Session 1 was 270 days (range: 259–283 days), and the mean age at Session 2 was 277 days (range: 266–290 days). Of the final sample, 13 infants had been randomly assigned to the high-joint-attention (HI-JA) group, and 15 infants to the low-joint-attention (LO-JA) group. The two groups' average ages neither differed at Session 1 nor at Session 2. The sample included 18 girls and 10 boys. The remaining

34 infants were excluded due to: (a) experimental errors or problems with the video or EEG equipment ($n = 7$); (b) insufficient data for ERP analyses in one or both sessions ($n = 16$); (c) fussiness in Session 1 ($n = 5$), or Session 2 ($n = 1$); (d) inability to participate in Session 2 within the 1-week interval ($n = 5$).

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

Procedure: familiarization

Infants were tested in a quiet, acoustically shielded room, in an area surrounded by white curtains to prevent visual distraction. The infant sat on the parent's lap in front of a computer screen (distance 70 cm). The experimenter sat 60 cm to the side of the screen and 80 cm away from the child. The experimental design included balancing the experimenter's position beside the screen (left vs. right) across babies. However, due to subsequent exclusion of infants (fussiness, EEG artefacts, etc.) this criterion was no longer fully met in the final sample. Six infants in the HI-JA group and five infants in LO-JA group saw the experimenter on the right side, whereas seven infants in the HI-JA group and 10 infants in the LO-JA group saw the experimenter on the left side of the screen. The behavior of the infant, parent, and experimenter was videotaped to later analyze infant behavior during the familiarization phase.

Stimuli were colored pictures of toys as used by Reid *et al.* (2004) and Striano *et al.* (2006). Infants were familiarized with two objects, which were not varied between groups, i.e. the same two objects were shown to all participants. The procedure for the familiarization phase was adapted from Reynolds and Richards (2005). Objects were presented sequentially in an alternating manner at the center of the computer screen. A second experimenter monitored the child's gazing behavior. When the infant had looked at the first object for an accumulated time of 5 s, she switched to the second object. After a cumulative looking time of 5 s she switched again to the first object and so on. This procedure was repeated four times for each stimulus, resulting in 20 s accumulated looking time for each stimulus.

The joint-attention manipulation during familiarization followed the procedures described by Striano *et al.* (2006). In the HI-JA group, a female experimenter alternated her gaze between the infant's face and object and spoke in a positive tone of voice about the objects. She used phrases such as 'oh look at this', 'so many colors', 'what a beautiful toy', and so on (phrases translated from the original German). Additionally, she pointed to the object (for illustration, see Figure 1). 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 (see Figure 2). Instead, the child was presented with infant-directed speech that had been

recorded in previous sessions in the HI-JA group via loudspeakers. 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)).² 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 familiarization, and the infant remained seated on the parent's lap in the same room. Old and new objects were sequentially presented on the computer screen in random order. Each item was presented for 1500 ms with a variable blank-screen intertrial interval of 700–1200 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 stopped looking at the screen, an age-appropriate animated movie was presented to entertain the child. When the infant attended to the screen again, the presentation of objects continued. The session ended when the infant's attention could no longer be attracted to the screen. Within a session a maximum of 160 trials were presented, with 80 trials of old and 80 trials of new objects in random order. That is, each of the two old objects was presented up to 40 times and each of the 12 new items was, on average, presented 6.7 times during the recognition phase.

Delayed recognition (Session 2)

The recognition test phase was repeated in a second session that took place 7–11 days after the first session. The time interval between Session 1 and Session 2 was on average 7.5 days ($SD = 1.2$ days). Infants did not differ between experimental groups in the average time interval between sessions (memory interval), $t(26) = -1.38$, $p = .18$. In the second session, again 80 trials of old and 80 trials of new objects were 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, infants saw 157 presentations in Session 1 and 154 presentations in Session 2. There were no differences in the numbers of viewed presentations between

² Loudness was assessed at the infant head position when the experimenter was interacting with a child in the HI-JA group. Loudness of the speech stimuli during familiarization in the LO-JA group was then adjusted at the loudspeakers with the sound pressure meter indicating approximately 60 dB(A) at the infant head position.



Figure 1 Experimental set-up for familiarization in the high-joint-attention condition. The experimenter alternated gaze between the child and the object on the computer screen, spoke to the child about the objects, and pointed to the screen.



Figure 2 Experimental set-up for familiarization in the low-joint-attention condition. The experimenter looked continuously at the screen but never at the infant, and did not speak or point. Recordings of infant-directed speech were presented through loudspeakers placed to the left and right of the screen.

experimental groups in Session 1, $t(26) = 0.77$, $p = .450$, or Session 2, $t(26) = 1.17$, $p = .251$.

EEG acquisition and data analysis

EEG was continuously recorded at 32 active electrodes. Signals were recorded 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 was placed at AFz. Signals at FP1 and FP2 were monitored to check for vertical eye movements, and signals at F9 and F10 for horizontal eye movements. Impedances were kept below 20 k Ω .

EEG recordings were rereferenced 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, which comprised the infant on the parent's lap and the computer screen as well as an event code on a split screen. All trials in which the infant did not look at the screen were excluded from further analysis. Artefacts 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 artefacts. A detrending procedure and a baseline correction to the 200 ms pre-stimulus baseline

were performed. Finally, individual averages (ERP) and grand averages across subjects were calculated.

For ERP analysis, the minimum criteria for inclusion were 15 trials per stimulus type and session. On average, infants contributed 35.9 trials ($SD = 18.5$) with new stimuli in Session 1, 33.3 trials ($SD = 13.5$) with old stimuli in Session 1, 36.6 trials ($SD = 14.3$) with new stimuli in Session 2, and 34.1 trials ($SD = 14.2$) with old stimuli in Session 2 to grand averages. The number of trials for each session and stimulus type did not differ between experimental groups.

Video recordings

In addition, the child's and the experimenter's behaviors were video-recorded in the familiarization phase with 25 frames per second and coded frame by frame using the software package Interact[®]. Videos of all infants except one were available. Behavioral categories were infant gazing (number of looks and duration of gazing at object and at experimenter), infant smiling, and the experimenter's gazing in the HI-JA group (number of looks and duration of gazing at object and at infant). Moreover, the duration and number of joint gazes to object (experimenter and child look at the objects simultaneously) and sequences of gaze following were coded. One coder who was blind to the experimental design coded 100% of the behavior, a second coder coded 33%.

The inter-rater agreements for infant gaze ($\kappa = .74$) and experimenter gaze ($\kappa = .87$) were satisfactory.

Results

For all analyses, the alpha level was set to $\alpha = .05$. Statistical trends (i.e. $.10 > p > .05$) are reported when they are informative with respect to the hypotheses under investigation.

Behavioral data

To increase the validity of ERP comparisons between the two experimental groups, we examined behavior during the familiarization phase to find out whether infants' behavior differed as a function of experimental condition (Table 1). Following suggestions by Aslin (2007), we focused not only on global measures of looking time, but also on more detailed measures such as sequences and duration of gazing episodes. The amount of time each object was gazed at was assessed to verify off-line that infants had looked at each object for a total of 20 s (one-sample *t*-test for the first object, $t(26) = -0.54$, $p = .593$, for the second object, $t(26) = -0.88$, $p = .385$). The total time until infants reached the cumulative looking criterion of 20 s, i.e. total duration of familiarization, did not differ reliably between the two experimental groups. In addition, there were no reliable differences between HI-JA and LO-JA in the number of looks to the first and to the second object (Table 1).

One might expect that infants in the HI-JA group would look at the experimenter more than infants in the

LO-JA group. For the number of looks to the experimenter, only a trend in the expected direction was observed, $t(25) = 1.95$, $p = .062$. The total gaze durations to the experimenter and the proportion of time spent gazing at the experimenter, relative to the total duration of the familiarization phase, did not differ reliably between the two groups (see Table 1).

Joint gaze at the object by the experimenter and child in HI-JA occurred with a mean frequency of 9.8 times and a mean duration of 1.9 s per gazing episode within the familiarization phase. Gazing episodes in which the infant looked at the object simultaneously with the experimenter were also observed in the LO-JA group, with a mean number of 12.7 times and a mean duration of 2.8 s per episode.³ Note, however, that the experimenter looked towards the monitor continuously and never initiated joint-gaze episodes to objects by gazing at infants assigned to the LO-JA group.

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. In the HI-JA group, the mean number of gaze-following episodes during familiarization in which the experimenter turned her head to the monitor after she had looked at the child was 3.8. Episodes in which the experimenter looked at the screen continuously and the infant followed her gaze occurred 3.2 times on average. The first type of gaze-following episode was absent under LO-JA conditions. When the two types of gaze following were summed (see Table 1), the mean number of total gaze-following episodes did not differ reliably between the two experimental groups.

Because facial expressions can be indicative of the affective quality of an interaction, we also assessed instances of infant smiling during familiarization. A trend for a higher proportion of smiling (total duration relative to total familiarization time) in the HI-JA than in the LO-JA group did not reach statistical significance.

EEG data

Overview of data analysis

Three ERP components were identified: the positive component Pb (interval: 250–350 ms), the large negative deflection Nc (interval: 350–700 ms), and PSW activity between 700 and 1500 ms. In addition, an early negative peak (N1; interval: 150–250 ms) was observed and analyzed due to its distinct and pronounced waveform in the ERP. Dependent variables for statistical analyses were peak amplitude and peak latency for N1, Pb, and Nc, and PSW mean activity (interval: 700–1500 ms).

The data were analyzed with a mixed-model analysis of variance, including the between-subjects factor

³ This finding supports the assumption that the complete absence of any form or degree of joint attention in the LO-JA group cannot be ruled out.

Table 1 Infant behavior during familiarization

Behavior	High-joint-attention group	Low-joint-attention group	Comparison high- versus low-joint-attention	
			<i>t</i>	<i>p</i>
Total duration of familiarization (s)	102.1	130.8	-0.60	.552
Gaze at object				
Number of looks at object 1	8.3	9.5	-0.78	.444
Number of looks at object 2	9.6	9.1	0.31	.757
Gaze at experimenter				
Total gaze (s)	29.9	25.7	0.29	.772
Proportional gaze (%)	26.4	21.7	0.58	.566
Number of looks	13.8	9.0	1.95	.062
Smiling				
Total smiling (s)	4.9	1.2	1.14	.267
Proportional smiling (%)	2.9	0.6	1.84	.077
Number of smiles	2.2	0.86	1.00	.325
Gaze following				
Number of gaze-following episodes	7.0	6.1	0.55	.586

Note: Behavioral differences between the high- and the low-joint-attention groups were tested by performing *t*-tests for independent samples ($df = 25$).

Group (HI-JA vs. LO-JA) and the within-subjects factors Session (1 vs. 2) and Stimulus (new vs. old). Variations of topography were observed in the components to be analyzed (see Figure 3). Therefore, the within-subjects factor Region was included in the analysis with the following regions defined by electrode lines from anterior to posterior: frontal (F7, F3, Fz, F4, F8), fronto-central (FC5, FC1, FC2, FC6), central/temporal (T7, C3, Cz, C4, T8), centro-parietal (CP5, CP1, CP2, CP6), parietal (P7, P3, Pz, P4, P8), and parieto-occipital (PO9, O1, O2, PO10). We found an effect of Region on N1 amplitude, $F(5, 130) = 27.74$, $p < .05$, $\eta^2 = .52$, Pb amplitude, $F(5, 130) = 40.12$, $p < .05$, $\eta^2 = .61$, Pb latency, $F(5, 130) = 16.78$, $p < .05$, $\eta^2 = .39$, Nc amplitude, $F(5, 130) = 75.29$, $p < .05$, $\eta^2 = .74$, Nc latency, $F(5, 130) = 6.86$, $p < .05$, $\eta^2 = .21$, and PSW amplitude, $F(5, 130) = 3.97$, $p < .05$, $\eta^2 = .13$. Post-hoc comparisons indicated that parietal and parieto-occipital electrodes differed from frontal, fronto-central, and central/temporal electrodes with regard to amplitude and latency in all four ERP

components ($p < .05$). In particular, N1 and Nc had more negative peak amplitudes in anterior than posterior electrodes. In contrast, PSW mean amplitudes were more positive in anterior than in posterior electrodes. Pb and Nc latencies were shorter at frontal and central than at parietal and occipital leads.

Based on prior expectations (Striano *et al.*, 2006), and given that all of the relevant components were clearly identifiable in anterior regions, further analyses were performed at frontal, fronto-central, and central/temporal electrodes. To assess variations in topography between hemispheres, the within-subject factor Hemisphere was included in the ANOVA with the following regions of interest: left-hemisphere electrodes (F7, F3, FC5, T7, C3), midline electrodes (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 Hemisphere (left vs. midline vs. right). Figures 4 and 5 illustrate results at the Fz electrode.

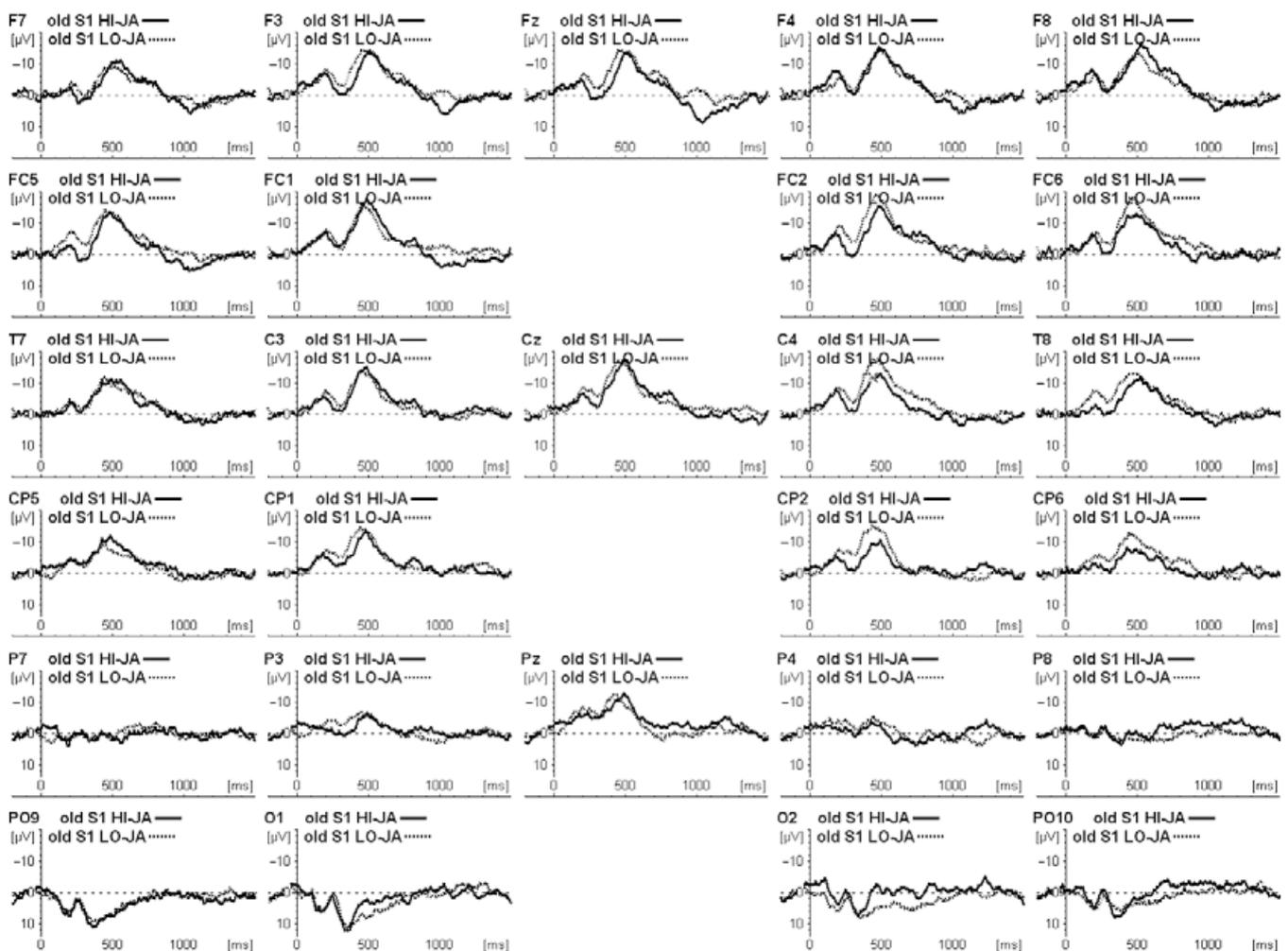


Figure 3 ERP topography for recognition of old objects during immediate recognition for infants in the high-joint-attention group (HI-JA) and for infants in the low-joint-attention group (LO-JA). ERP components differed reliably between anterior and posterior sites. Negative voltage is plotted upwards.

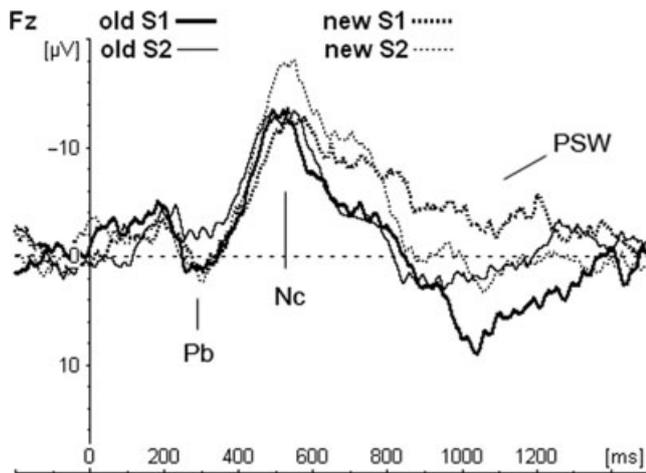


Figure 4 ERPs for infants in the high-joint-attention group at the Fz electrode. The amplitude of the Nc component varied as a function of stimulus novelty. In immediate recognition, reliable differences in positive slow wave (PSW) activity were observed. Negative voltage is plotted upwards.

To test for effects of variables that may contribute variance but were not part of the experimental design, the covariates and between-subjects factors Age (days), Memory Interval (days between Sessions 1 and 2), Gender, and Experimenter's Position (left vs. right side of monitor) were considered in separate control analyses. None of these variables revealed main effects or interactions with Group, Session, or Stimulus on amplitudes or latencies in any of the analyzed ERP components (all $p > .05$). Hence, ERP data were collapsed for further analyses.

N1

No reliable main effects or interactions among the factors of Group, Session, Stimulus, and Hemisphere on peak amplitude or peak latency were found.

Nc

There was a significant main effect of Hemisphere on Nc amplitude, $F(2, 52) = 11.39, p < .05, \eta^2 = .30$. In particular, midline electrodes ($M = -19.87 \mu\text{V}$) had larger (more negative) Nc peak amplitudes than left-hemisphere ($M = -17.38 \mu\text{V}$) or right-hemisphere ($M = -17.37 \mu\text{V}$) electrodes. The analyses also revealed a significant interaction Hemisphere \times Session on Nc amplitude, $F(2, 52) = 4.41, p < .05, \eta^2 = .15$, reflecting larger negative amplitudes at midline electrodes in Session 2 ($M = -20.74 \mu\text{V}$) than in Session 1 ($M = -19.01 \mu\text{V}$). More importantly, a reliable main effect of Stimulus was observed, $F(1, 26) = 4.62, p < .05, \eta^2 = .15$, with new items ($M = -19.09 \mu\text{V}$) eliciting larger Nc amplitudes than old items ($M = -17.33 \mu\text{V}$). This main effect was qualified by an interaction with Session, $F(1, 26) = 5.45, p < .05, \eta^2 = .17$; in Session 2, peak amplitudes were larger (i.e. more negative) for new items ($M = -20.39 \mu\text{V}$)

than for old items ($M = -16.54 \mu\text{V}$; see Figures 4 and 5). In addition to amplitude, Nc latency was also sensitive to stimulus type, $F(1, 26) = 28.24, p < .05, \eta^2 = .52$, with latencies being reliably longer for new items ($M = 520 \text{ ms}$) than for old items ($M = 498 \text{ ms}$). Experimental group had no effect on Nc, nor on amplitude or on latency.

PSW

We found a reliable three-way interaction for Group, Session, and Stimulus, $F(1, 26) = 5.98, p < .05, \eta^2 = .19$. Separate follow-up analyses for the two groups revealed that the Session \times Stimulus was reliable for the HI-JA group, $F(1, 12) = 5.60, p < .05, \eta^2 = .32$, but not for the LO-JA group, $F(1, 14) = 1.99, p > .10$. PSW amplitudes differed reliably between new ($M = 4.44 \mu\text{V}$) and old ($M = 7.40 \mu\text{V}$) stimuli in the HI-JA group in Session 1 (Figure 4), but not in Session 2 (new items: $M = 6.26 \mu\text{V}$; old items: $M = 6.07 \mu\text{V}$).

Pb

The Group \times Session \times Stimulus interaction on Pb amplitude was reliable, $F(1, 26) = 5.63, p < .05, \eta^2 = .18$. Separate follow-up ANOVAs were performed for the HI-JA and the LO-JA groups (see Figures 4 and 5). In the LO-JA group, the Session \times Stimulus interaction was reliable, $F(1, 14) = 10.79, p < .05, \eta^2 = .44$, with old items eliciting larger Pb peak amplitudes in Session 2 ($M = 3.91 \mu\text{V}$) than in Session 1 ($M = .42 \mu\text{V}$) (Figure 5). In the HI-JA group, the Session \times Stimulus interaction was not reliable, $F(1, 12) = 0.58, p > .10$. No significant effects were found for Pb latency.

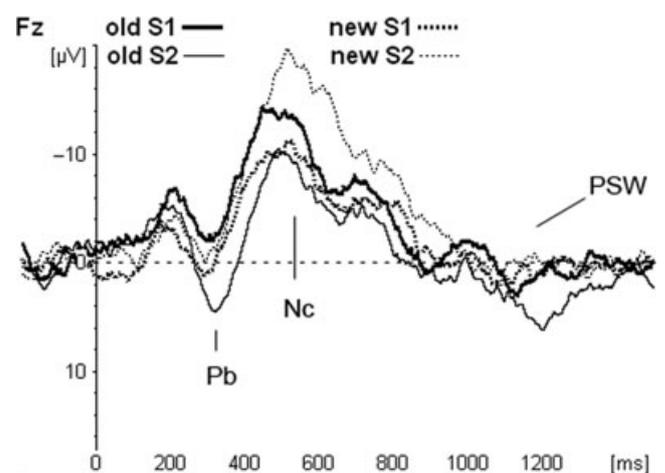


Figure 5 ERPs for infants in the low-joint-attention group at the Fz electrode. The amplitude of the Nc component varied as a function of stimulus novelty. For old objects, the Pb amplitude was significantly larger during delayed recognition than during immediate recognition. Negative voltage is plotted upwards.

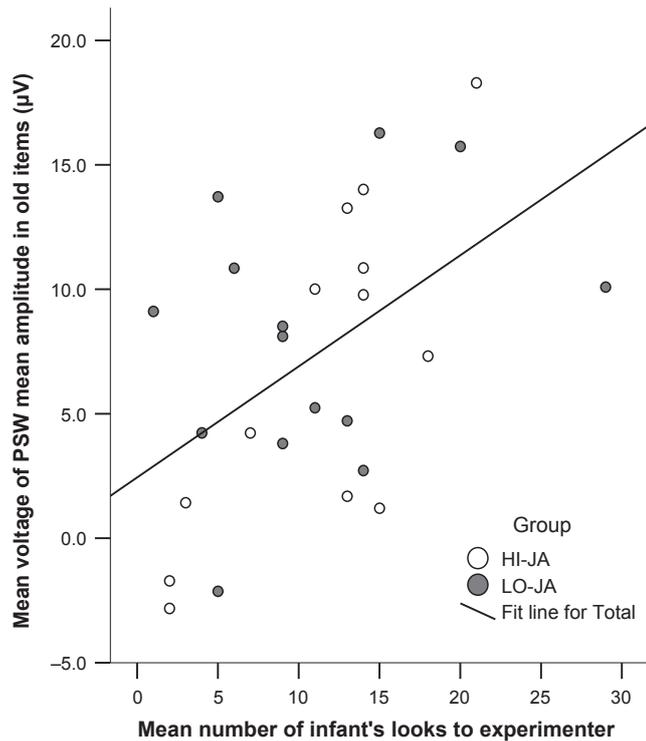


Figure 6 Correlation of mean number of infants' looks to experimenter during familiarization and PSW mean amplitude to old items. There was a significant positive correlation of .51 ($p = .007$).

Correlations between individual differences in behavior and ERP components

Behavioral indicators showing trends for differences between experimental groups, as well as those thought to be indicative of the quality of interaction between experimenter and child during familiarization (HI-JA vs. LO-JA), were included as covariates in the analyses of ERP components. These indicators were total duration of familiarization, number of infant's looks to experimenter, proportional duration of smiling, and the number of all gaze-following episodes. Dependent variables were peak amplitude and peak latency of N1, Pb, and Nc, as well as mean amplitude of PSW.

The number of infant's looks to the experimenter during familiarization was related to PSW mean amplitude during recognition, $F(1, 24) = 5.61$, $p < .05$, $\eta^2 = .19$. This effect was qualified by a significant interaction with Stimulus, $F(1, 24) = 6.19$, $p < .05$, $\eta^2 = .20$. Post-hoc analyses showed that PSW mean amplitude was affected by the number of infants' looks to the experimenter in old items, $F(1, 24) = 8.58$, $p < .05$, $\eta^2 = .26$, but not in new items, $F(1, 24) = 2.06$, $p > .10$. That is, the more often a child had looked at the experimenter during familiarization, the larger the PSW mean amplitude to old items during recognition (Figure 6; Pearson correlation: .51, $p = .007$). This effect did not interact with Group or Session. For the number of gaze-following episodes during familiarization, we observed a trend for

a similar interaction with Stimulus on PSW mean activity, $F(1, 24) = 4.10$, $p = .054$.

Discussion

ERP correlates of immediate and delayed recognition

In line with results from earlier studies (Ackles, 2008; Reynolds & Richards, 2005; Wiebe *et al.*, 2006), new items elicited larger negative amplitudes than old items. In addition, Nc latency proved to be sensitive to stimulus type, with old items eliciting significantly shorter Nc latencies than new. This also replicates earlier work (e.g. Ackles, 2008; Courchesne *et al.*, 1981). Modulations in the Nc component have been interpreted as reflecting attention allocation to salient or novel stimuli (e.g. Courchesne *et al.*, 1981). In 4.5-, 6-, and 7.5-month-old infants, Nc amplitudes increased with attention as measured by heart rate (Richards, 2003). In the same age groups, Nc amplitude varied with attention and stimulus type, but only in infants who had received prior familiarization with two stimuli (Reynolds & Richards, 2005). These authors demonstrated that their Nc effect was due to stimulus novelty rather than to stimulus probability. The paradigm and results of the present study were similar to Reynolds and Richards' findings, thus suggesting that, in the present study, Nc effects do reflect effects of novelty. Not only did new objects elicit larger amplitudes than old objects, but old stimuli were also processed significantly faster than new ones. As Ackles and Cook (2007) pointed out, these Nc effects may indicate a top-down mechanism that allocates attentional resources for further processing.

Nc amplitude and latency effects, however, did not differentiate between the HI-JA and the LO-JA group. This suggests that infants in both groups had formed long-lasting memory traces for old objects. In contrast, Striano *et al.* (2006) and Parise *et al.* (2008) reported reliable variations of the Nc component as a function of joint attention. Note that these two studies did not investigate effects of stimulus familiarity. Hence, one possible reason for the apparent discrepancy between our results and the findings reported by Striano *et al.* (2006) and Parise *et al.* (2008) is that the novelty-related Nc effect in the present study may have overshadowed the potential effects due to joint attention. Alternatively, the present paradigm, which includes variations between old and new objects and between two experimental sessions, may result in ERP responses substantially differing from ERP responses due to joint attention in object processing.

ERP correlates to joint-attention effects on immediate and delayed recognition

We found modulations of brain activity due to joint attention at PSW and Pb. As can be seen in Figure 4, PSW mean amplitudes were significantly larger for old

items than for new items in Session 1 for the HI-JA group. In contrast, there was no Session \times Stimulus interaction in the LO-JA group. Furthermore, Pb amplitudes were significantly larger in old items in Session 2 compared to Session 1 in the LO-JA group. No such interaction was found in the HI-JA group.

The present results suggest that joint attention has differential effects on processes that are associated with PSW and Pb activity for Session 1 versus Session 2, respectively. In particular, PSW, as an indicator for memory updating, was affected in immediate visual recognition, whereas Pb, as an indicator for processes related to stimulus expectancy, was affected in the long run. In the following sections we will discuss these differential short- and long-term effects.

Memory updating responses modulated by joint attention

PSW has been associated with memory updating processes (de Haan, 2007). As reported by Nelson *et al.* (1998), PSW amplitudes were larger for familiar than for novel items in 8-month-old infants after a familiarization procedure. This finding resembles the HI-JA group's results in Session 1 of the present study. In contrast, PSW amplitudes decreased with presentation repetition (Snyder *et al.*, 2002). As old items were more frequently presented in the present experiment, it is unlikely that PSW amplitude modulations are due to repeated presentation. At least for the HI-JA group, old items elicited larger amplitudes. For LO-JA infants there were no differences in immediate recognition between old and new items. This suggests that memory updating processes as demonstrated by Nelson *et al.* (1998) were observed here only when infants were explicitly prompted to attend to the items during familiarization. Infants treated even frequently presented items as relevant for memory updating when these items had previously been cued as important in the interaction with an adult. We propose that this mechanism might reflect the knowledge-transferring function of joint attention (Csibra & Gergely, 2006; Gergely & Csibra, 2006). By this account, ostensive communicative signals might help the infant to identify the relevance of specific content.

Encoding and storage depend on how difficult learning is during familiarization (Thiessen & Saffran, 2009). With high stimulus complexity (Hunter *et al.*, 1983; Thiessen & Saffran, 2009) and short familiarization time (Hunter *et al.*, 1983; Rose *et al.*, 1982), infants may not be able to fully encode the stimuli. The question for the present study is whether a familiarization time of 20 s per object was sufficient to enable full encoding and stable consolidation. Interestingly, infants of the LO-JA group also actively initiated gazes towards the experimenter and followed her gaze to the objects. The number of gaze-following episodes during familiarization did not differ between LO-JA and HI-JA, although the experimenter never initiated gazes to the infant in the LO-JA condition.

Furthermore, the number of looks to the experimenter was positively correlated to PSW amplitude in old items independent of experimental group (Figure 6). A similar trend was observed for the number of gaze-following episodes. That is, memory updating was enhanced when infants had looked to the experimenter more frequently during familiarization. Even when infants were placed in a LO-JA situation, some of them initiated more gazing to the experimenter than others and this correlated to memory updating processes as reflected in PSW amplitude. This result indicates that individual social interaction capacities could possibly contribute to interindividual variability in memory among infants at the age of 9 months (Bauer, 2006). In this sense, our findings are consistent with the theoretical framework by Mundy *et al.* (2009; see also Chapman, 1991). Accordingly, joint attention is considered a self-organizing system that facilitates information processing in support of social learning. This constructivist approach proposes that children help create social-learning opportunities for themselves. Infants learn about the world from their self-generated actions with other people.

Expectancy and joint attention

Pb modulations in memory-related paradigms were described as reflecting contextual processing and stimulus expectancy (Hill Karrer *et al.*, 1998) and, more specifically, the certainty of expecting the occurrence of an event (Karrer & Monti, 1995).

Items are relevant for infants when they are novel. Repeated presentation of old items may be a violation of expectancy for LO-JA infants. These children have not learned the link between the familiarized objects and the interactive cues provided by the adult (Csibra & Gergely, 2006). In contrast, HI-JA infants have learned that the familiarized items are important. Thus, one could argue, priority has shifted from novelty to importance as cued by an adult. Therefore, their expectancy for the occurrence of old items was not violated when they saw the cued and thereby relevant items repeatedly. One could speculate that repeated presentation might even consolidate expectancy. As Pb amplitude in the HI-JA group was the same for old and new items in both sessions, similar processing at this early stage (around 300 ms) could be inferred. Higher Pb amplitudes in the LO-JA group suggest an interference effect for old items in Session 2. On the one hand, the repeated occurrence of old items in recognition might cause them to put more effort into stimulus encoding. The unresponsive behavior of the experimenter during familiarization, on the other hand, may be a source of insufficient and uncued stimulus encoding.

To follow up on these speculations, the mechanisms connecting joint attention to memory need to be investigated in greater detail. For instance, one may induce specific expectations about the occurrence of stimuli by manipulating social interactive parameters, and test how

these expectations affect brain activity and behavior (e.g. using an anticipatory looking paradigm). We think that online measures might be more useful, in general, to delineate the specific mechanisms of social learning than global behavioral measures. The present results show that Pb amplitude is sensitive to long-term memory effects of joint attention. In particular, recognition of old items in LO-JA in Session 2 was affected. These ERP modulations suggest an influence at a very basic cognitive level. In this experiment, Pb and Nc revealed distinct and even dissociable activity patterns with respect to the factors Session, Stimulus, and Group. Results of previous studies, however, indicate that Pb modulations might co-occur or even trigger Nc modulations (Striano *et al.*, 2006; Webb *et al.*, 2005). But with the present experiment, we were able to demonstrate that the two ERP components reflect different cognitive processes, as indicated by their sensitivity to expectancy and salience, respectively. With higher Nc amplitudes for new than for old objects in both HI-JA and LO-JA, forgetting seems unlikely between immediate and delayed recognition. Rather the link between item relevance, as cued by the experimenter, and object processing may interfere with long-term retention. In the present study, cognitive mechanisms reflecting PSW and Pb activity seem to be dissociable within experimental sessions. At the same time, the mechanisms represented by the two ERP components appeared to interact over time, as expectancy of previously not cued but repeatedly presented familiar items was influenced in the LO-JA infants' delayed session.

Clearly, more research is needed to specify the functional relevance of the Pb component. Some previous studies did not analyze Pb modulations, although visual inspection of the data suggests a strong contribution of Pb. Striano *et al.* (2006) reported differential activity in the Pb amplitude as a result of joint attention. Thus, the results of our study converge with Striano *et al.*'s (2006) findings regarding the observation that the Pb component appears to be a reliable electrophysiological indicator of joint attention in infancy.

In sum, we propose the following integrative view: First, joint attention during initial stimulus encoding may be associated with a priority shift from novelty to relevance as cued by an adult. Second, conditions of high joint attention may be related to enhanced memory updating in immediate recognition. Third, novelty and relevance are dissociable aspects of memory as reflected in modulations of Nc and Pb in the infant ERP. Finally, repeated object presentation can interfere with stimulus expectancy in long-term retention if the link to the relevance of items has not been established during encoding.

Limitations of the present study and outlook

With the present paradigm, the various dimensions of the experimenter's behavior that contribute to differences between the HI-JA and LO-JA conditions cannot be disentangled. Direct eye contact between infant and

experimenter is certainly relevant for joint attention (Cleveland & Striano, 2007), as are vocal cues (Parise *et al.*, 2006). Further experimental variations are needed to explore in detail which components of joint attention influence retention in memory at behavioral and neural levels.

Furthermore, in the present study, effects of novelty and stimulus frequency/probability cannot be fully separated (Reynolds & Richards, 2005). Specifically, two familiar items were repeatedly presented together with 12 novel items in the recognition phase of each session in order to keep the familiarization and recognition procedure comparable to the Reynolds and Richards (2005) study. This set of novel items increased the infant's attention during the experiment and, hence, provided a sufficient number of trials for ERP analysis. However, it is known that repeated presentation alters ERP components over time (Snyder *et al.*, 2002; Wiebe *et al.*, 2006). Further studies could investigate to what extent novelty and frequency contribute to brain activity patterns, for example by holding probabilities constant across conditions. In this context, it is worth noting that Reynolds and Richards (2005) were able to show that the effects they observed in the Nc amplitude were due to stimulus novelty rather than stimulus probability. In the present study, novelty and frequency were not varied between groups. Therefore, main effects of stimulus frequency do not offer a viable explanation for memory-related differences between the two attention conditions.

Moreover, the presentation of familiarized items in immediate recognition might have affected delayed recognition. In fact, the significant Session \times Stimulus interaction for Nc peak amplitude suggests that new items in Session 2 might have been perceived as more novel in relation to old items than those in Session 1. In addition, it remains unclear to what extent the presentation of old items in Session 2 interfered with effects that were due to the degree of joint attention as identified in Pb activity. Again, further experimental manipulations could help to separate these aspects. For example, one could investigate the influence of joint attention only in the delayed recognition of old and new items, that is without immediate recognition, to avoid re-exposure effects. However, a direct comparison between immediate and delayed recognition would be difficult using a within-subjects design. Alternatively, infants could be familiarized with objects that are specifically probed together with new items in immediate recognition and with other items specifically for delayed recognition. Note, however, that stimulus presentation was held constant across groups in the present experiment. Hence, this specific experimental procedure alone cannot account for ERP differences between the two joint attention conditions. Joint attention effects were present in the PSW in Session 1, in the Pb component in Session 2, and generally absent in the Nc component, suggesting that the neural mechanisms related to novelty and those related to joint attention are separable.

Conclusion

In sum, the present study demonstrated that subtle processes such as modulation of long-term memory by joint attention can be tracked using electrophysiological parameters. Nine-month-old infants were familiarized with two objects in a high-joint-attention versus low-joint-attention context. PSW and Pb amplitudes reflected modulations of old and new object recognition due to joint attention immediately and after a 1-week delay, respectively. The results of this study show that it is not only adult interaction with a 9-month-old infant that is important; it is also its manner. Children at this age can make use of learning strategies to form long-lasting memory traces based on the relevance and salience of memory contents. Further neurophysiological experiments may help to increase our understanding of the social foundations of cognitive development.

Acknowledgements

This work was supported by the Ernst Rudolf Schloessmann Foundation. The authors thank Gergely Csibra for comments on an earlier version of this paper. We also wish to thank the members of the BabyLab at the Max Planck Institute for Human Development, and the parents and infants who participated in this study. Parts of this article were written while UL was a fellow at the Center for Advanced Study in the Behavioral Sciences at Stanford University.

References

- Ackles, P. (2008). Stimulus novelty and cognitive-related ERP components of the infant brain. *Perceptual and Motor Skills*, **106**, 3–20.
- Ackles, P.K., & Cook, K.G. (1998). Stimulus probability and event-related potentials of the brain in 6-month-old human infants: a parametric study. *International Journal of Psychophysiology*, **29**, 115–143.
- Ackles, P.K., & Cook, K.G. (2007). Attention or memory? Effects of familiarity and novelty on the Nc component of event-related brain potentials in six-month-old infants. *International Journal of Neuroscience*, **117**, 837–867.
- Aslin, R.N. (2007). What's in a look? *Developmental Science*, **10**, 48–53.
- Bahrack, L.E., Hernandez-Reif, M., & Pickens, J.N. (1997). The effect of retrieval cues on visual preferences and memory in infancy: evidence for a four-phase attention function. *Journal of Experimental Child Psychology*, **67**, 1–20.
- Bahrack, L.E., & Pickens, J.N. (1995). Infant memory for object motion across a period of three months: implications for a four-phase attention function. *Journal of Experimental Child Psychology*, **59**, 343–371.
- Barber, H.A., & Kutas, M. (2007). Interplay between computational models and cognitive electrophysiology in visual word recognition. *Brain Research Reviews*, **53**, 98–123.
- Bauer, P.J. (2006). Constructing a past in infancy: a neuro-developmental account. *Trends in Cognitive Sciences*, **10**, 175–181.
- Bauer, P.J., Wiebe, S.A., Carver, L.J., Lukowski, A.F., Haight, J.C., Waters, J.M., & Nelson, C.A. (2006). Electrophysiological indexes of encoding and behavioral indexes of recall: examining relations and developmental change late in the first year of life. *Developmental Neuropsychology*, **29**, 293–320.
- Bauer, P.J., Wiebe, S.A., Carver, L.J., Waters, J.M., & Nelson, C.A. (2003). Developments in long-term explicit memory late in the first year of life: behavioral and electrophysiological indices. *Psychological Science*, **14**, 629–635.
- Carpenter, M., Nagell, K., & Tomasello, M. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the Society for Research in Child Development*, **63** (4, Serial No. 255).
- Carver, L.J., Bauer, P.J., & Nelson, C.A. (2000). Associations between infant brain activity and recall memory. *Developmental Science*, **3**, 234–246.
- Carver, L.J., Meltzoff, A.N., & Dawson, G. (2006). Event-related potential (ERP) indices of infants' recognition of familiar and unfamiliar objects in two and three dimensions. *Developmental Science*, **9**, 51–62.
- Chapman, M. (1991). The epistemic triangle: operative and communicative components of cognitive competence. In M. Chandler & M. Chapman (Eds.), *Criteria for competence: Controversies on the conceptualization and assessment for children's abilities* (pp. 209–228). Hillsdale, NJ: Erlbaum.
- Cleveland, A., Schug, M., & Striano, T. (2007). Joint attention and object learning in 5- and 7-month-old infants. *Infant and Child Development*, **16**, 295–306.
- Cleveland, A., & Striano, T. (2007). The effects of joint attention on object processing in 4- and 9-month-old infants. *Infant Behavior and Development*, **30**, 499–504.
- Courchesne, E., Ganz, L., & Norcia, A.M. (1981). Event-related brain potentials to human faces in infants. *Child Development*, **52**, 804–811.
- Csibra, G., & Gergely, G. (2006). Social learning and social cognition: the case for pedagogy. In Y. Munakata & M.H. Johnson (Eds.), *Processes of change in brain and cognitive development* (pp. 249–274). Oxford: Oxford University Press.
- de Haan, M. (2007). Visual attention and recognition memory in infancy. In M. de Haan (Ed.), *Infant EEG and event-related potentials* (pp. 101–143). Hove: Psychology Press.
- de Haan, M., & Nelson, C.A. (1997). Recognition of mother's face by six-month-old infants: a neurobehavioral study. *Child Development*, **68**, 187–210.
- de Haan, M., & Nelson, C.A. (1999). Brain activity differentiates face and object processing in 6-month-old infants. *Developmental Psychology*, **35**, 1113–1121.
- Farroni, T., Csibra, G., Simion, F., & Johnson, M.H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences, USA*, **99**, 9602–9605.
- Gergely, G., & Csibra, G. (2006). Sylvia's recipe: the role of imitation and pedagogy in the transmission of cultural knowledge. In N.J. Enfield & S.C. Levinson (Eds.), *Roots of human sociality: Culture, cognition, and human interaction* (pp. 229–255). Oxford: Berg Publishers.
- Hayne, H., Rovee-Collier, C., & Perris, E.E. (1987). Categorization and memory retrieval by three-month-olds. *Child Development*, **58**, 750–767.

- Hill Karrer, J., Karrer, R., Bloom, D., Chaney, L., & Davis, R. (1998). Event-related brain potentials during an extended visual recognition memory task depict delayed development of cerebral inhibitory processes among 6-month-old infants with Down syndrome. *International Journal of Psychophysiology*, **29**, 167–200.
- Hoehl, S., Reid, V., Mooney, J., & Striano, T. (2008). What are you looking at? Infants' neural processing of an adult's object-directed eye gaze. *Developmental Science*, **11**, 10–16.
- Hunt, J.M. (1970). Attentional preference and experience. I. Introduction. *Journal of Genetic Psychology*, **117**, 99–107.
- Hunter, M.A., Ames, E.W., & Koopman, R. (1983). Effects of stimulus complexity and familiarization time on infant preferences for novel and familiar stimuli. *Developmental Psychology*, **19**, 338–352.
- Hunter, S.J., & Karrer, R. (1993). ERPs indicate event duration effects on infants' visual attention and recognition memory. *Electroencephalography and Clinical Neurophysiology*, **87**, S38–S41.
- Johnson, M.H., & Munakata, Y. (2005). Processes of change in brain and cognitive development. *Trends in Cognitive Sciences*, **9**, 152–158.
- Karrer, R., & Monti, L.A. (1995). Event-related potentials of 4–6-week-old infants in a visual recognition memory task. *Electroencephalography and Clinical Neurophysiology*, **94**, 414–424.
- Lukowski, A.F., Wiebe, S.A., Haight, J.C., DeBoer, T., Nelson, C.A., & Bauer, P.J. (2005). Forming a stable memory representation in the first year of life: why imitation is more than child's play. *Developmental Science*, **8**, 279–298.
- Moll, H., Carpenter, M., & Tomasello, M. (2007). Fourteen-month-olds know what others experience only in joint engagement. *Developmental Science*, **10**, 826–835.
- Mundy, P., Sullivan, L., & Mastergeorge, A.M. (2009). A parallel and distributed-processing model of joint attention, social cognition and autism. *Autism Research*, **2**, 2–21.
- Nelson, C.A., & Collins, P.F. (1991). An event-related potential and looking time analysis of infants' response to familiar and novel events: implications for visual recognition memory. *Developmental Psychology*, **27**, 50–58.
- Nelson, C.A., & Collins, P.F. (1992). Neural and behavioral correlates of recognition memory in 4 and 8 month old infants. *Brain and Cognition*, **19**, 105–121.
- Nelson, C.A., Thomas, K.M., de Haan, M., & Wewerka, S.S. (1998). Delayed recognition memory in infants and adults as revealed by event-related potentials. *International Journal of Psychophysiology*, **29**, 145–165.
- Parise, E., Cleveland, A., Costabile, A., & Striano, T. (2006). Influence of vocal cues on learning about objects in joint attention contexts. *Infant Behavior and Development*, **30**, 380–384.
- Parise, E., Reid, V.M., Stets, M., & Striano, T. (2008). Direct eye contact influences the neural processing of objects in 5-month-old infants. *Social Neuroscience*, **3**, 141–150.
- Paterson, S.J., Heim, S., Friedman, J.T., Choudhury, N., & Benasich, A.A. (2006). Development of structure and function in the infant brain: implications for cognition, language and social behaviour. *Neuroscience and Biobehavioral Reviews*, **30**, 1087–1105.
- Reid, V.M., Striano, T., Kaufman, J., & Johnson, M.H. (2004). Eye gaze cueing facilitates neural processing of objects in 4-month-old infants. *NeuroReport*, **15**, 2553–2555.
- Reynolds, G.D., & Richards, J.E. (2005). Familiarization, attention, and recognition memory in infancy: an event-related potential and cortical source localization study. *Developmental Psychology*, **4**, 598–615.
- Richards, J.E. (2003). Attention affects the recognition of briefly presented visual stimuli in infants: an ERP study. *Developmental Science*, **6**, 312–328.
- Roder, B.J., Bushnell, E.W., & Sasseville, A.M. (2000). Infants' preferences for familiarity and novelty during the course of visual processing. *Infancy*, **1**, 491–507.
- Rose, S.A., Gottfried, A.W., Melloy-Carminar, P., & Bridger, W.H. (1982). Familiarity and novelty preferences in infant recognition memory: implications for information processing. *Developmental Psychology*, **18**, 704–713.
- Rovee-Collier, C.K., & Sullivan, M.W. (1980). Organization of infant memory. *Journal of Experimental Psychology: Human Learning and Memory*, **6**, 798–807.
- Rugg, M.D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences*, **11**, 251–257.
- Snyder, K.A., Blank, M.P., & Marsolek, C.J. (2008). What form of memory underlies novelty preferences? *Psychonomic Bulletin & Review*, **15**, 315–321.
- Snyder, K., Webb, S.J., & Nelson, C.A. (2002). Theoretical and methodological implications of variability in infant brain response during a recognition memory paradigm. *Infant Behavior and Development*, **25**, 466–494.
- Striano, T., Reid, V.M., & Hoehl, S. (2006). Neural mechanisms of joint attention in infancy. *European Journal of Neuroscience*, **23**, 2819–2823.
- Striano, T., & Stahl, D. (2005). Sensitivity to triadic attention in early infancy. *Developmental Science*, **8**, 333–343.
- Strid, K., Tjus, T., Smith, L., Meltzoff, A.N., & Heimann, M. (2006). Infant recall memory and communication predicts later cognitive development. *Infant Behavior and Development*, **29**, 545–553.
- Thiessen, E.D., & Saffran, J.R. (2009). How the melody facilitates the message and vice versa in infant learning and memory. *Annals of the New York Academy of Sciences*, **1169**, 225–233.
- Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: the origins of cultural cognition. *Behavioral and Brain Sciences*, **28**, 675–735.
- Webb, S.J., Long, J.D., & Nelson, C.A. (2005). A longitudinal investigation of visual event-related potentials in the first year of life. *Developmental Science*, **8**, 605–615.
- Wetherford, M.J., & Cohen, S.B. (1973). Developmental changes in infant visual preferences for novelty and familiarity. *Child Development*, **44**, 416–424.
- Wiebe, S.A., Cheatham, C.L., Lukowski, A.F., Haight, J.C., Muehleck, A.J., & Bauer, P.J. (2006). Infants' ERP responses to novel and familiar stimuli change over time: implications for novelty detection and memory. *Infancy*, **9**, 21–44.

Received: 12 March 2009

Accepted: 21 July 2010