Word Learning in 6-Month-Olds: Fast Encoding–Weak Retention

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Abstract

■ There has been general consensus that initial word learning during early infancy is a slow and time-consuming process that requires very frequent exposure, whereas later in development, infants are able to quickly learn a novel word for a novel meaning. From the perspective of memory maturation, this shift in behavioral development might represent a shift from slow procedural to fast declarative memory formation. Alternatively, it might be caused by the maturation of specific brain structures within the declarative memory system that may support lexical mapping from the very first. Here, we used the neurophysiological method of ERPs to watch the brain activity of 6-month-old infants, when repeatedly presented with object–word pairs in a cross-modal learning paradigm. We report first evidence that infants as young as 6 months are able to associate objects and words after only very few exposures. A memory test 1 day later showed that infants did not fully forget this newly acquired knowledge, although the ERP effects indicated it to be less stable than immediately after encoding. The combined results suggest that already at 6 months the encoding process of word learning is based on fast declarative memory formation, but limitations in the consolidation of declarative memory diminish the long lasting effect in lexical-semantic memory at that age. ■

INTRODUCTION

Early Word Learning

Word learning requires the constitution of memory structures for both word forms and word meanings and the establishing of referential connections between these newly acquired memory representations. Behavioral research has shown that at 6 months infants already associate the words *mama* and *papa* with the faces of their mother and father (Tincoff & Jusczyk, 1999). Around 8–10 months, infants comprehend their first words (Bates, Thal, & Janowsky, 1992; Benedict, 1979). Thus, well before their first birthday, infants are able to build up memory structures for phonological and semantic representations and to establish associative links between them. During this early stage, word learning is assumed to be a slow and time-consuming process that requires very frequent exposure to the word form and the appropriate referent. Shortly after their first birthday, however, infants become able to quickly learn a novel word for a novel meaning after only a few exposures (Schafer & Plunkett, 1998; Woodward, Markman, & Fitzsimmons, 1994). This fast mapping ability is the basis of the rapid increase in vocabulary, the so-called vocabulary spurt that sets in at around 18 months (e.g., Reznick & Goldfield, 1992; Goldfield & Reznick, 1990). Several cognitive, linguistic, and sociocommunicative factors such as the development of categorization abilities, the development of working memory, the referential understanding of a word, or changes in social interactions are discussed to be related to infants' word learning rate (for reviews, see Nazzi & Bertoncini, 2003; Woodward et al., 1994). Computationally, it has been demonstrated that the qualitative shift in word learning at the behavioral level might not necessarily be caused by a qualitative shift in the learning mechanisms at the neural level (McMurray, 2007). In the same way, some researchers assume that the vocabulary spurt is a more gradual increase in word learning rate that does not require specialized cognitive or linguistic abilities but rather general abilities that exist for other purposes too (e.g., Bloom, 2004).

Fast mapping precedes the vocabulary spurt for several months. It may be seen as general learning ability that does not only occur in mapping words but also facts and events. The present study is part of a series of studies to explore what kind of changes in the neural mechanisms of perceptual and semantic processes accompany this behaviorally observed qualitative shift from slow to fast mapping and whether these changes at the neural level are indeed qualitative or still quantitative in their nature. As successful learning always requires long-term memory, we particularly aimed to explore which role memory plays in the development of the fast mapping ability.

Memory Development

Neuroscientists have identified two distinct forms of memory, declarative and procedural memory (e.g., Eichenbaum, 2000; Graf & Schacter, 1985; Cohen & Squire, 1980). Procedural memory includes a heterogeneous group of implicit

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learning abilities like motor skills, habits, or kinds of statistical learning, which have no feature in common, but are rather defined as to be nondeclarative. Declarative memory is the explicit memory for facts and events, which is available to multiple response systems and can be consciously and verbally retrieved. An important difference between declarative and procedural memory is the time course of learning. In contrast to procedural memory that is established slowly by the gradual and accumulative acquisition of novel skills, declarative memory is uniquely characterized by the rapid acquisition of novel knowledge, which may lead to the formation of memory even after a single event. This rapid memory formation critically depends on the integrity and the intact function of medial-temporal lobe (MTL) structures, in particular, the hippocampus.

Word learning, that is, the arbitrary mapping of phonological and semantic representations, is commonly considered to be based on declarative memory involving MTL functions (Ullman, 2004). In principle, however, these lexical mappings could also be learned by slow associations without involvement of MTL structures. Thus, it might be the case that early slow word learning rests upon frequency-based learning, that is, on implicit procedural memory, whereas later fast word learning requires explicit declarative memory. Alternatively it might be possible that declarative memory supports word learning from the beginnings and that the behavioral shift from slow to fast word learning is mainly attributed to the maturation of specific MTL structures, which limits the full functioning of the declarative memory system during initial developmental stages.

For the development of memory, the classical view is that implicit procedural memory is managed by an early developing neural system that is already functional at birth and that explicit declarative memory emerges when the late developing memory system matures (Schacter & Moscovitch, 1984). As a precursor of the explicit memory system, a hippocampus-dependent "pre-explicit" memory system is assumed to mature in the first months, whereas the adult-like explicit memory is established between the ages of 8–12 months (Nelson, 1995).

Behavioral research has shown that pre-explicit memory abilities develop early in infancy (for reviews, see Richmond & Nelson, 2007; Bauer, 2004). Even 6-month-old infants show successful performance in visual paired comparison and deferred imitation tasks, which both depend on MTL functions and are, therefore, viewed as to reflect rudimentary declarative memory in infancy. Generally, older infants encode information faster than younger infants, and they also remember longer than younger infants. The increase in processing speed during encoding appears to reflect a domain-general mechanism such as myelination that rapidly occurs during the first year of life. The development of long-term retention and retrieval, however, is attributed to the maturation of specific brain structures within the declarative memory system. Because much of the hippocampal formation develops early in gestation, and the parahippocampal region (entorhinal, perirhinal, and parahippicampal cortices) seems to be functional at birth, the dentate gyrus of the hippocampus is the most obvious candidate to account for the limitations of declarative memory functions. Compared with other MTL structures, the dentate gyrus has a prolonged maturation; its cytoarchitecture appears adult-like by the end of the first postnatal year. There is, moreover, experimental evidence that the dentate gyrus is particularly involved in the consolidation of new memories (see Richmond & Nelson, 2007; Bauer, 2004). Thus, although the whole network involved in declarative memory formation becomes fully functional at the end of the first year of life, even during early infancy, one might expect some support of declarative memory in the acquisition of lexical mappings, in particular, for the process of encoding.

ERP Correlates of Word Processing in Infants

Within the last decade, several infant ERP studies have identified two ERP components related to word processing in infants and toddlers: A lateral distributed negativity in the 200–500 msec range (N200–500) was found to be affected by perceptual word form familiarity. Early studies have shown that, in 14- and 20-month-old infants, the N200–500 is enhanced to known as compared with unknown words (Mills, Coffey-Corina, & Neville, 1993, 1997). More recent studies demonstrated that the frontal N200–500 emerges in the ERP of 7- and 10-month-olds during the familiarization with initially unfamiliar word forms (Kooijman, 2007; Kooijman, Hagoort, & Cutler, 2005). In addition, several studies have shown that the lateral frontal N200–500 is not only affected by prior familiarity or by repetition-based familiarization in unimodal studies but also by unimodal word–word priming or by cross-modal picture–word priming (Torkildsen, Svangstu, Simonsen, Moen, & Lindgren, 2007; Friedrich & Friederici, 2004, 2005a, 2005b, 2005c). The observed increase in the N200–500 amplitude in response to primed words in these studies indicates that both pictures and words can facilitate the perceptual processing of contextually expected word forms. A similar increase in negativity with earlier latency and left frontal to temporal distribution has also been observed in adults (Friedrich & Friederici, 2004, 2005b).

The second ERP component related to word processing in infants and toddlers is the N400, the centro-parietally distributed negative wave that reflects semantic processing of a meaningful stimulus (Kutas & Hillyard, 1980; for a review, see Kutas & Federmeier, 2000). A reduction in the amplitude of the N400 indicates that an expectation triggered by a prime word, a sentence, or any other context like a picture has facilitated semantic processing of a target stimulus. This N400 semantic priming effect has been shown to be present in 14- to 24-month-olds, but it failed to appear in normally developing 12-month-olds, as well as in 19- and 20-month-old children with delayed language development (Torkildsen et al., 2007; Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007; Friedrich & Friederici, 2004, 2005a, 2005b, 2005c, 2006). Because the same 12- and 19-month-olds who did not show the N400 priming effect exhibited an N200–500 priming effect (Friedrich & Friederici, 2005a), the missing N400 in these children cannot be attributed to the full missing of lexical-semantic knowledge. For 12-month-olds with particularly early word production skills, we moreover observed an N400 priming effect (Friedrich & Friederici, 2010). From the results of these studies, we conclude that the N400 semantic priming effect requires sufficiently stable memory structures, whereas the N200–500 perceptual priming effect occurs even in the case of weak associations in memory (for a discussion, see Friedrich, 2008, 2010; Friedrich & Friederici, 2010). Thus, the N400 can be viewed as the more mature ERP response that indicates the existence of relatively strong lexical-semantic connections. Moreover, because lexical knowledge is assumed to be declarative and semantic priming is generally seen as process operating over declarative memory structures, the centro-parietal N400 is posited to represent a neural mechanism that is particularly involved in declarative memory processes (Ullman, 2004).

Infant ERP Studies on Word Learning

As yet, only very few ERP studies investigated word learning in infants. Mills and colleagues (2005) trained 20-month-olds with four novel words. In the training session, two words were paired with each a novel object and two words were not paired with an object. In a test phase subsequent to training, all words were presented without an object. During this pure acoustic word presentation, the N200–500 discriminated between the word conditions, suggesting that object–word pairings have facilitated the perceptual encoding of word forms during training.

So far, only two infant ERP studies explored the on-line learning of object–word pairs, that is, the changing brain responses during the encoding process itself and the retention of the newly acquired lexical mappings in memory. In one study, Torkildsen and colleagues (2008, 2009) used 10 blocks to train 20-month-olds with 30 novel words for 30 novel cartoon pictures. Within each training test block, they presented three novel picture–word pairs for each five times. After these five presentations they presented the trained words with pictures that had been paired with other words during training. For the training phase, they observed an increase in N200–500 amplitude after three presentations in 20-month-olds with high productive vocabulary and after five presentations in 20-month-olds with low productive vocabulary (Torkildsen et al., 2009). In the 20-month-olds with high productive vocabulary, the presentation of trained words in unexpected picture contexts during the test phase elicited an N400 when compared with the fifth presentation of the same words during training (Torkildsen et al., 2008). Although in this training design the N200–500 effect might be caused by both repetition-based increased word form familiarity and learning-related word form priming, the N400 priming effect in the test phase indicates the successful encoding of object–word mappings.

Friedrich & Friederici (2008) trained 14-month-olds with 16 novel word and 16 novel objects. Half of the stimuli were presented in a constant pairing condition, in which a certain word was consistently paired with a certain object such that the mapping of eight object–word pairs could be learned. The other half of the stimuli were presented in a rotated pairing condition, in which objects and words were presented for the same number of times to control for repetition effects, but in which each object was paired with each word, such that mappings could not be learned. In the second half of the training phase, that is, for the fifth to eighth word presentations, both a lateral frontal N200–500 perceptual priming effect and a parietal N400 semantic priming effect differentiated between constant and rotated pairing conditions. These priming effects indicate that infants had acquired the mappings for the constant pairings within the first four presentations. Moreover, the N200–500 effect was even observable within the first half of the training phase, suggesting that some lexical-semantic memory formation has taken place after only two to three presentations. Additionally, 1 day after training, infants participated in a memory test, in which words of the constant condition were presented each four times either in the congruous picture context, that is, with the object with which they were trained, or in an incongruous context, that is, with objects of the rotated condition. For the memory test, we also observed an N400 priming effect indicating that the 14-month-old infants had consolidated the newly acquired mappings in lexical-semantic memory.

The Present Study

The aim of the present study was to explore the limitations of fast mapping in early infancy and the involvement of declarative memory in the formation of lexical-semantic associations within the first year of life. We particularly asked whether even younger infants show ERP correlates of the rapid encoding of arbitrary mappings between objects and words and whether they show similar correlates indicating long-term memory for the newly acquired lexical knowledge at an age when they do not show signs of fast mapping at the behavioral level. For that reason, we applied the same ERP learning paradigm to 6-month-old infants, which we had successfully used with 14-month-olds (Friedrich and Friederici, 2008). This design allows to watch the encoding process, that is, the initial formation of lexical-semantic memory during training. Here, we adapted the visual stimuli to the infant's younger age of 6 months. Pictured objects were characterized by only a few salient features that were brightly colored to maximally grasp and sustain the infants' attention (Figure 1).

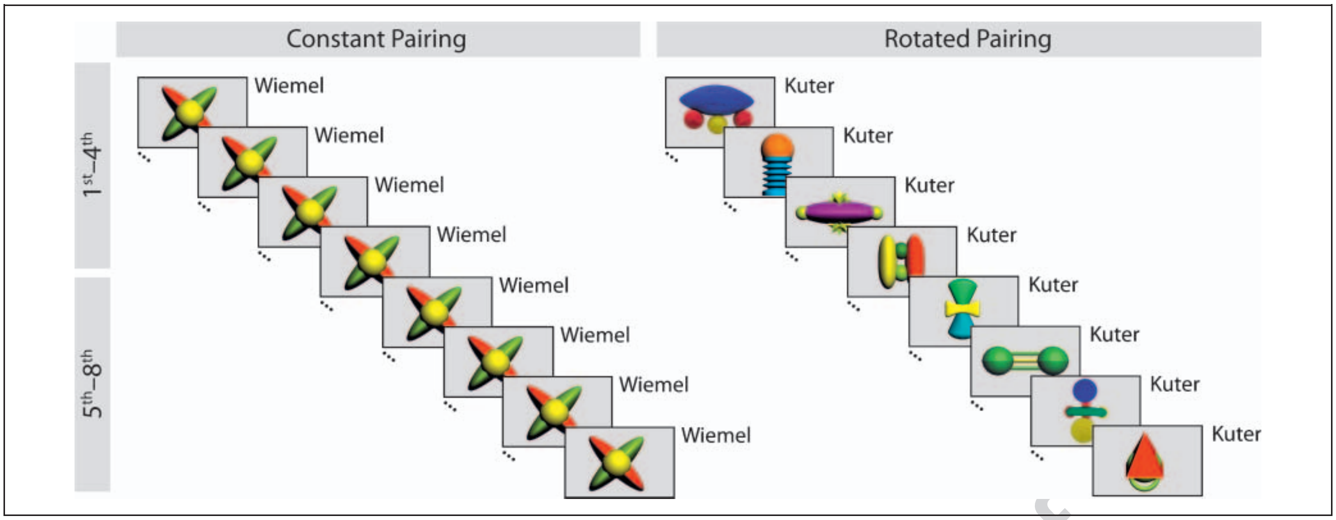

Figure 1. The experimental design of the training phase (for a description, see text).

Moreover, to test memory 1 day after training, we presented infants only with those objects and words for which mappings could have been learned during training. These object and word stimuli were combined either in a congruous condition that was identical to the constant condition or in an incongruous condition, in which the previous mappings were violated.

The combination of training and memory test of the present study should give information about whether only the long-term storage or even the fast encoding process of lexical mappings is limited in 6-month-old infants. If infants are able to sufficiently encode object–word mappings within the first half of the training phase, in the second half of the training phase, we expect to observe ERP effects in the N200–500 time window reflecting perceptual word form priming and in the N400 time window reflecting semantic priming. Similar ERP priming effects in the memory test 1 day later would indicate the successful retention of this newly acquired knowledge. In the case that fast declarative memory is not involved in word learning at 6 months of age, the present study should indicate what the precursors of fast mapping are.

METHODS

Participants

Training data were obtained from 44 infants (25 boys and 19 girls) at an age of 6 months (mean = 6 months and 4 days) and memory test data from 39 infants (22 boys and 17 girls).

Procedure

The experimental study consisted of two parts, a training session and a test session performed 1 day after training. During the training session, infants were presented with picture–word pairs of 16 unknown objects and 16 unknown words (pseudowords). Eight words and eight objects were presented in a constant pairing condition, in which each word was paired with the same pictured object eight times, such that eight object–word mappings could be learned. In the rotated pairing condition, each of the eight words were presented with each of the eight objects once, such that mappings could not be learned. Thus, in both conditions each stimulus was repeated eight times (Figure 1). Constant and rotated conditions were presented in a mixed version, that is, the eight repetitions of the eight consistently paired object–word pairs were interspersed with the presentation of the 64 individual object–word pairs of the rotated condition. The assignment of the stimuli to the two conditions was balanced between infants. To emphasize the referential relationship between novel pseudowords and novel objects and to make the training session comparable to that of older infants, additionally, eight real words were presented four times, each together with the picture of an object commonly named by the word. Here, real words were not included in the analyses. During the memory test session, trained words of the constant pairing condition and real words were presented each seven times in one of the two conditions, either in congruous (trained) or in incongruous (untrained) picture context. The difference between incongruous condition of the test phase and rotated condition of the training phase consisted only in the fact that during testing objects and words of the incongruous condition were the same as in the congruous condition, whereas during training all stimuli of the rotated condition were different from that of the constant condition.

At each trial, a colored picture of a single object appeared for 3500 msec on the screen. After an interval of 800 msec from picture onset, the German indefinite article *ein* (masculine/neuter) was presented to refer to the pictured object in a natural way and to increase the children's attention to the acoustically presented pseudoword that followed the article at 1700 msec postpicture onset. The training session lasted for about 9 min, and the memory test session lasted for 12 min.

Stimuli

Pictures were brightly colored illustrations of pseudo-objects created by Autodesk 3ds Max software (Figure 1). Word stimuli were 16 disyllabic pseudowords. All pseudowords were phonologically and phonotactically legal in German, had a consonant–vowel onset, were stressed on the first syllable as common in German, and had typical masculine or neuter endings. They were slowly spoken by a young woman with mean duration of 763 msec, digitized at a rate of 44 100 Hz, and presented through loudspeaker with an intensity of approximately 65 dB sound pressure level.

ERP Recording and Averaging

The EEG was continuously recorded from silver–silver chloride electrodes at sites F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2 as well as left and right mastoids attached to an elastic electrode cap (Easy Cap, Falk Minow). During the recordings, the ERP electrodes were referenced to CZ. EOG electrodes were recorded bipolar. Electrode impedances were mostly below 10 kΩ, at least below 20 kΩ. The EEG was amplified with PORTI-32/MREFA (Twente Medical Systems; with input impedance of 10^{12} Ω and analogue first-order low-pass filter of 5 kHz), digitized on-line at a rate of 500 Hz (AD converter with 22 bit, digital filter from DC to 125 Hz), and stored on hard disk.

Off-line, the EEG was algebraically rereferenced to the average of left and right mastoids. A zero-phase digital band-pass filter ranging from 0.3 to 20 Hz (−3 dB cutoff frequencies of 0.37 and 19.93) was applied to increase the signal-to-noise-ratio by removing slow drifts and muscle artifacts. All trials were individually checked for artifacts. Manually defined blinks and horizontal eye movements were corrected by a computer algorithm. All other artifacts were rejected manually. Epochs of 1200 msec from word onset were averaged according to a 100-msec prestimulus baseline. A minimum of 10 artifact-free trials for constant and rotated condition with at least five trials in first half and second half of the training session were required for an individual average to be included in further analyses. The mean number of accepted trials was 23 for the constant condition and 22 for rotated condition of the training session, 12 for the congruous, and 13 for the incongruous condition of the test session. These numbers did not differ between conditions.

Data Analyses

According to both visual inspection of the ERPs and experience from previous studies, mean amplitudes within the time window from 100 to 200 msec were calculated for evaluating the P100, from 200 to 800 msec for the frontal N200–500 effect, from 300 to 500 msec for the parietal N300-500, and from 600 to 900 msec for the infant N400 priming effect.

To discover the establishing of object–word mappings, the constant pairing condition was compared with the rotated pairing condition for the first and the second four word presentations separately by three-way repeated measure ANOVAs with condition (constant vs. rotated), hemisphere (left, right), and region (outer lateral frontal [F7/8], frontal [F3/4], fronto-central [FC3/4], temporal [T7/8], central [C3/4], centro-parietal [CP5/6], parietal [P3/4], and outer lateral parietal [P7/8]). To assess the effect of repetition based word familiarization, we analyzed initial with subsequent word presentations by three-way repeated measure ANOVAs with repetition (first-to-second vs. third-to-fourth for the conditions pooled, first-to-fourth vs. fifth-to-eighth for constant and rotated conditions separately), hemisphere, and region. For the memory test, three-way ANOVAs with condition (congruous vs. incongruous), hemisphere, and region were conducted. For midline sites, two-way ANOVAs with condition/repetition and region (frontal, central, and parietal) were performed for each analysis. Significant interactions, including the factors condition or repetition, were analyzed by one-way ANOVAs for single-electrode sites. In all ANOVAs, the Greenhouse–Geisser correction (Greenhouse & Geisser, 1959) was applied, whenever there was more than one degree of freedom. Here, we report uncorrected degrees of freedom and adjusted p values.

RESULTS

Because changes in the perceptual and semantic word processing during learning may be affected by both the acquisition of the word form and the mapping of this word form onto a meaning, different analyses were conducted for training and test phases. First, to grasp priming effects indicating the successful *encoding of object–word mappings*, we compared the constant and the rotated condition separately for the first and the second half of the training phase (Figure 2). Second, to characterize changes in the perceptual and lexical processes because of increased *word form familiarity over the course of training*, we analyzed how the ERP responses change with repetition. We compared both the first and second with the third and fourth word presentations for the conditions pooled indicating *early familiarity effects* (Figure 3) and the first-to-fourth with the fifth-to-eighth word presentations separately for each condition indicating *later familiarity effects* (Figure 4). Third, to assess potential priming effects indicating the retention of the newly acquired *knowledge in lexical-semantic long-term memory*, we compared congruous and incongruous conditions of the memory test performed 1 day after training (Figure 5).

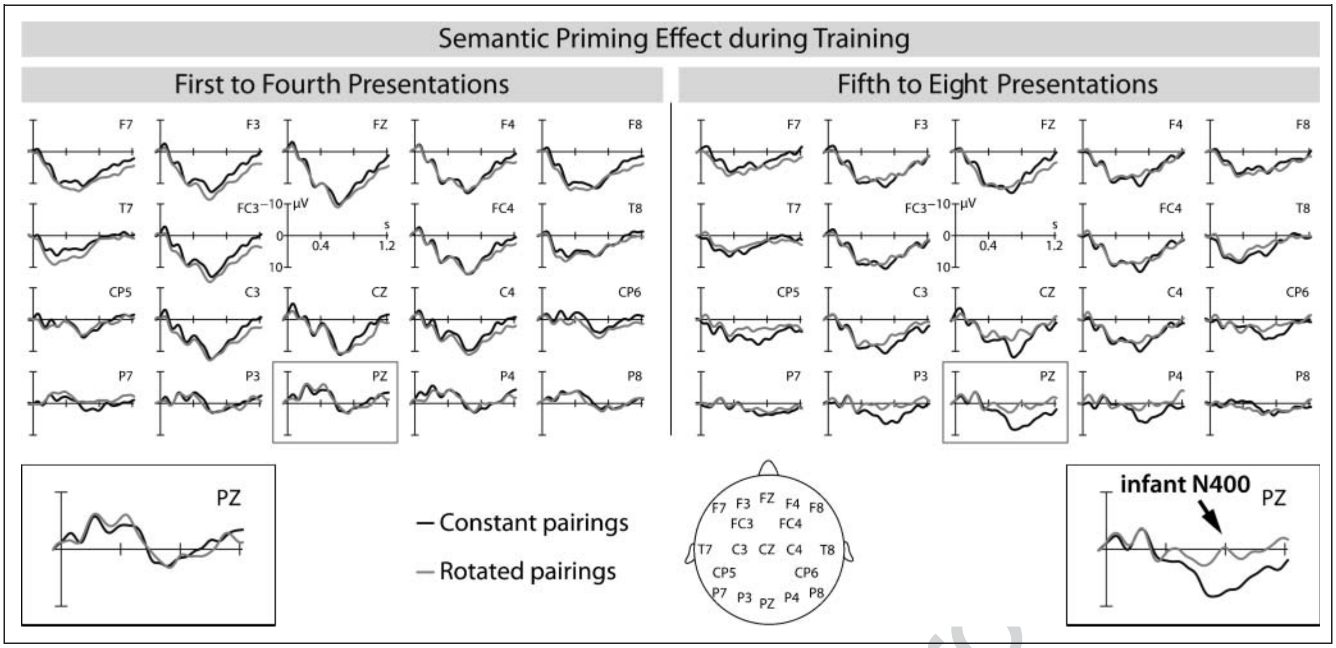

Figure 2. The ERPs of 6-month-old infants on the first four word presentations (left) and on the second four word presentations (right) during training. Black lines indicate constant object–word pairings; gray lines indicate rotated object–word pairings.

Encoding of Object–Word Mappings: Semantic Priming Effect

Constant vs. Rotated Condition for the First-to-Fourth Word Presentations

Within the first four presentations (Figure 2, left), no significant differences between constant and rotated conditions were observed.

Constant versus Rotated Condition for the Fifth-to-Eighth Word Presentations

Within the second four presentations, constant and rotated conditions significantly differed in the time window from 600 to 900 msec (Figure 2, right bottom; lateral: condition by region $F(7, 301) = 2.129$, $p < .041$; midline: condition by region $F(2, 86) = 3.449$, $p < .041$). Within this time window, the rotated condition elicited more negative responses over parieto-central and left parietal regions (PZ: $F(1, 43) = 5.741$, $p < .021$; P3: $F(1, 43) = 4.828$, $p < .033$) and marginally over adjacent brain regions (P4, CZ, CP5, CP6: $F(1, 43) = 2.898$–3.847, $p < .061$–$.096$). This reduction in negativity resembles an infant N400 priming effect.

Familiarity over the Course of Training: Repetition Effects

Early Training: First-to-Second versus Third-to-Fourth Word Presentations

Within the first four presentations, the constant and rotated conditions did not significantly differ, but three effects were observed when comparing the first two (first–second) and the second two (third–fourth) presentations of the conditions pooled (Figure 3). First, the most conspicuous effect of early repetition was a frontally to centrally broadly distributed decrease in the positivity (Figure 3, top) from 200 to 800 msec (lateral: repetition $F(1, 43) = 7.530$, $p < .009$; repetition by region $F(7, 301) = 20.390$, $p < .0005$; midline: repetition $F(1, 43) = 5.002$, $p < .031$; repetition by region $F(2, 86) = 14.094$, $p < .0005$). This effect was present at 12 of 19 electrode sites ($F(1, 43) = 4.375$–38.288, $p < .0005$–$.042$), and it was most prominent at outer lateral frontal sites. It resembles the familiarity effect reported in earlier studies. Second, an increase in the infant P100 that had a latency of around 150 msec (Figure 3, top left and bottom) was found for the second two presentations (lateral: repetition $F(1, 43) = 9.464$, $p < .004$; midline: repetition $F(1, 43) = 3.965$, $p < .061$). And third, there was a spatially and temporally clearly defined decrease in negativity between 300 and 500 msec (Figure 3, bottom right) for the second two presentations (lateral: repetition by region $F(7, 301) = 20.486$, $p < .0005$; midline: repetition by region $F(2, 86) = 18.920$, $p < .0005$), which was present over parietal regions (PZ $F(1, 43) = 6.031$ $p < .018$; P3: $F(1, 43) = 5.917$, $p < .019$, P8 $F(1, 43) = 6.330$, $p < .016$).

Later Training: First-to-Fourth versus Fifth-to-Eighth Word Presentations

Rotated condition. From the first four to the second four presentations of the rotated condition, we observed both a decrease in the frontal positivity from 200 to 800 msec

(Figure 4, top right; lateral: repetition by region $F(7, 301) = 7.307$, $p < .0005$; midline: repetition by region $F(2, 86) = 3.813$, $p < .028$) with significant effects at F7, F8, T7, F3, FZ, FC3 ($F(1, 43) = 4.846$–12.975, $p < .001$–$.033$) and a decreased negativity from 300 to 500 msec (Figure 4, bottom right; lateral: repetition by region $F(7, 301) = 8.009$, $p < .0005$; midline: repetition by region $F(2, 86) = 3.333$, $p < .044$) at parietal sites (PZ, P3, P4, P7, P8: $F(1, 43) = 4.421$–10.671, $p < .002$–$.041$). The P100 did not change from the first-to-fourth to the fifth-to-eighth presentations.

Constant condition. For the constant condition, again, we observed a decrease in the frontal positivity from 200 to 800 msec (Figure 4, left top; lateral: repetition by region $F(7, 301) = 6.819$, $p < .0005$; midline: repetition by region $F(2, 86) = 4.640$, $p < .017$) and the parietal decrease in negativity between 300 and 500 msec (Figure 4, bottom left; lateral: repetition by region $F(7, 301) = 7.208$, $p < .0005$; midline: repetition by region $F(2, 86) = 4.771$, $p < .016$) from the first four to the second four presentations. In this comparison, however, the frontal effect was spatially more restricted than for the rotated condition. There were only effects at outer lateral frontal sites (F7: $F(1, 43) = 7.304$, $p < .010$; F8: $F(1, 43) = 4.959$, $p < .031$). This might possibly be caused by an overlap with the more centro-parietally distributed inversed N300–500 effect (PZ, P3, CP5, CP: $F(1, 43) = 5.516$–8.777, $p < .005$–$.024$), which leads to the extinction of the effects at overlapping sites.

As crucial difference to the rotated condition, in the constant condition we additionally found a decrease in the

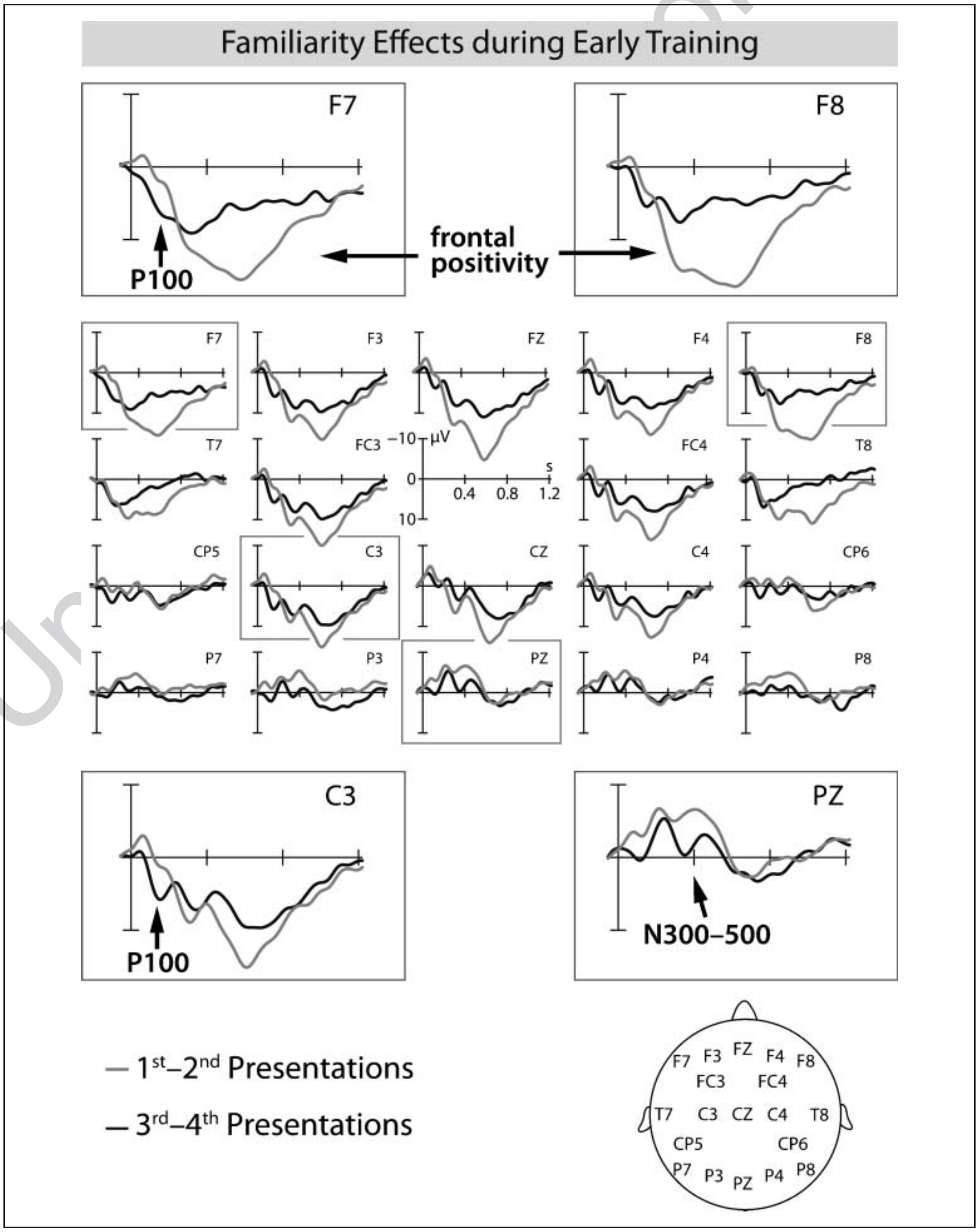

Figure 3. The ERPs of 6-month-old infants within the first four object–word presentations of the conditions pooled. Gray lines represent the ERPs on words of the first two presentations, and black lines represent the ERPs on words of the second two presentations.

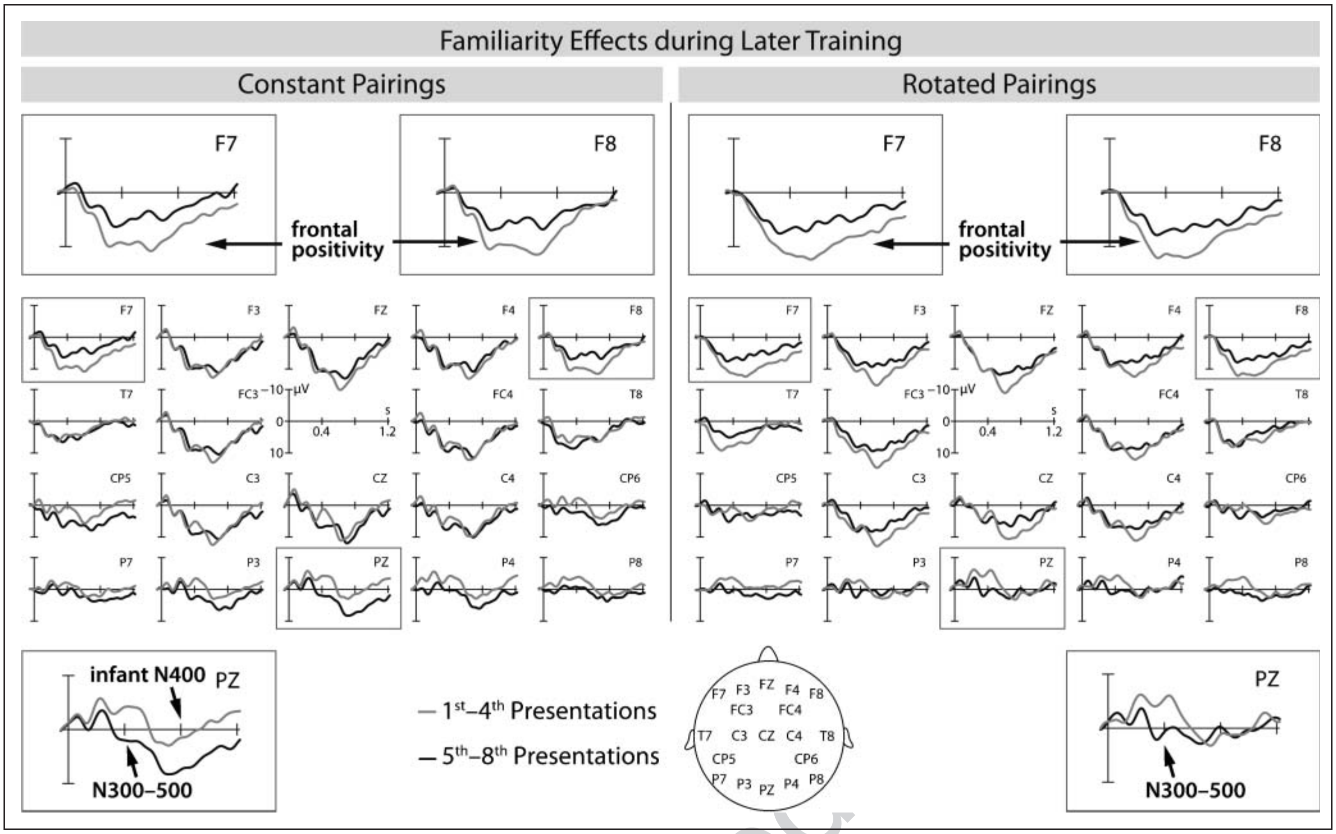

Figure 4. The ERPs of 6-month-old infants on words of the constant object–word pairing condition (left) and on words of the rotated object–word pairing condition (right) during training. Gray lines indicate the first four word presentations, and black lines indicate the second four word presentations.

parietal negativity from 600 to 900 msec (Figure 4, bottom left; lateral: repetition by region $F(7, 301) = 4.202$, $p < .005$; midline: repetition by region $F(2, 86) = 4.823$, $p < .012$) for the second four compared with the first four presentations. This reduction in negativity for the constant condition at parietal sites (PZ: $F(1, 43) = 4.346$, $p < .043$; CP5: $F(1, 43) = 4.853$, $p < .033$) caused the priming effect in the comparison between the fourth-to-eighth presentations of the constant and the rotated conditions.

Long-term Memory: Priming Effects

Congruous versus Incongruous Condition

In the ERP data of the memory test applied 1 day later, the congruous as compared with the incongruous condition was characterized by an increased P100 amplitude (Figure 5, top right and bottom left; lateral: condition $F(1, 38) = 13.162$, $p < .001$, condition by region $F(7, 266) = 3.604$, $p < .009$; midline: condition $F(1, 38) = 3.873$, $p < .056$) at eight electrodes sites ($F(1, 38) = 5.265$–15.107, $p < .0005$–$.027$), by a decreased frontal positivity (Figure 5, top left; lateral: condition by region $F(7, 266) = 3.323$, $p < .014$) at left outer lateral and left temporal sites (F7: $F(1, 38) = 7.779$, $p < .008$; T7: $F(1, 38) = 4.503$, $p < .040$) and by a decreased negativity between 300 and 500 msec (Figure 5, bottom right; lateral: condition by region $F(7, 266) = 5.814$, $p < .001$; midline: condition by region $F(2, 86) = 3.378$, $p < .045$) over parietal brain regions (PZ: $F(1, 38) = 6.946$, $p < .012$; P3: $F(1, 38) = 11.801$, $p < .001$). There was no parietal effect between 600 and 900 msec, that is, in the infant N400 time window.

DISCUSSION

The present study explored word learning and memory retrieval in 6-month-old infants. Analyses during learning (training phase) and during memory retrieval (test phase 1 day after learning) revealed the following observations.

Encoding of Object–Word Mappings during Training: Semantic Priming Effect

For the 6-month-olds of the present study, a clear difference was observed between constant and rotated pairings within the second half of the training phase, that is, the fifth-to-eighth presentations indicating that infants have encoded object-to-sound mappings when presented in a constantly paired fashion. We observed a more negative going wave for the rotated than for the constant pairing condition. The overall similarity, in particular, latency, parietal distribution, and polarity, of this effect to that observed in the highly developed 12-month-olds for picture–word priming (Friedrich & Friederici, 2010) and in 14-month-olds for the same learning paradigm (Friedrich & Friederici, 2008) strongly suggests that it represents an infant N400 priming effect. In the 6-month-olds of the present study, the N400 occurred between 600 and 900 msec, indicating a slightly later onset than in 12-month-olds and an even later onset than in 14-month-olds. This decrease in N400 onset latency because of age might be caused by general maturational factors increasing processing speed during the first year of life, such as myelination. The presence of an N400 semantic priming effect in 6-month-olds during the second half of the training phase indicates that these young children have rapidly acquired a least some of the object–word mappings within only about four paired presentations.

Familiarity over the Course of Training: Early and Late Repetition Effects

In the present object–word training study with 6-month-old infants, we found three word repetition effects in the ERP, one of them was already known from previous studies with older infants and toddlers and two of them were not yet reported. The most prominent and stable effect of both early and late repetitions was a frontally to centrally broadly distributed decrease of the initial positivity from 200 to 800 msec. The polarity and distribution of the effect clearly identifies this decrease in positivity as repetition-based increase in negativity, that is, as the

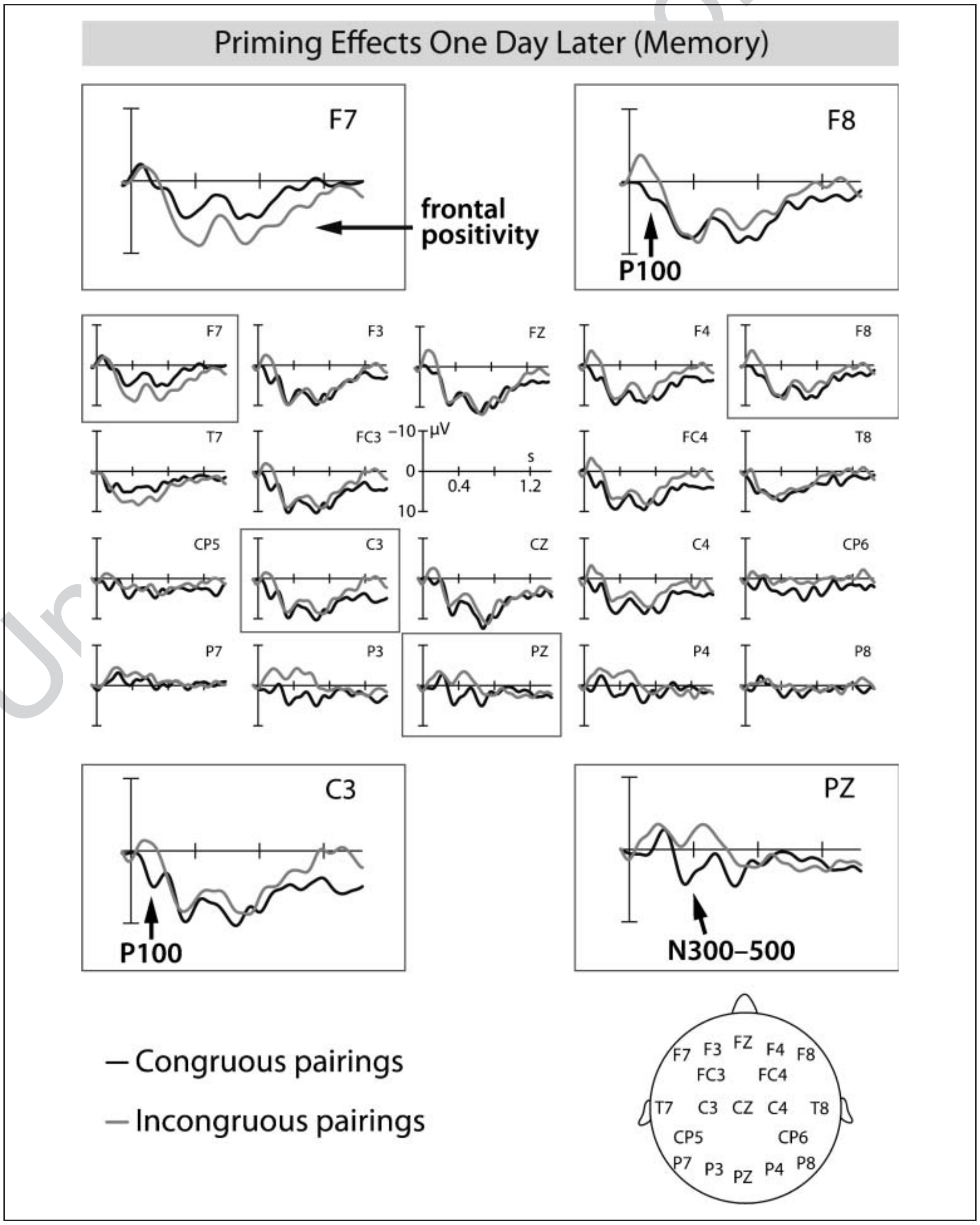

Figure 5. The ERPs of 6-month-old infants on words during the memory test. Black lines indicate congruous object–word pairings, and gray lines indicate incongruous object–word pairings.

N200–500 familiarity effect, which occurs with an extended duration in these young infants as compared with studies with older infants (Kooijman, 2007; Kooijman et al., 2005; Thierry, Vihman, & Roberts, 2003; Mills et al., 1993, 1997). In contrast to other authors who suggest that the N200–500 indicates some kind of word recognition (Torkildsen et al., 2009; Mills et al., 2004), we interpret the strong N200–500 increase even during early training phases as unconscious facilitation of perceptual word form processing because of the repeated activation of phonological features.

For early, but not later, repetitions, we moreover observed an increase in the infant P100. As yet, the functional relevance of the infant P100 is not clear, but an early developmental increase in P100 has been observed from birth to 3 months (Kushnerenko et al., 2002). Here, the early repetition-related increase in P100 amplitude during initial training may reflect some tuning to the temporal characteristics of stimulus presentation, in particular, the expectation of word onset.

During both early and later repetitions, a decrease in the negativity over the parietal region between 300 and 500 msec was additionally observed. From the present database, we do not know what this N300–500 familiarity effect stands for. It might represent variations in the P350 or the N450, both observed during acoustic presentation in infants (Kushnerenko et al., 2002), it might be an early part of the N400 that is reduced by repetition priming like in adults (Rugg, 1985, 1987) or it might be a completely different infant ERP component. Future studies comparing infant and adult ERP responses in the same paradigms may clarify the functional relevance of this component.

Priming Effects during the Memory Test

Surprisingly, all effects indicating increased repetition-based familiarity during training, that is, increased P100, increased frontal N200–500, and decreased parietal N300–500, appeared as priming effects in the memory test. Thus, several word processing stages that were affected by repetition during training were similarly affected by priming 1 day later. In particular, words presented in congruous picture context were processed as they would be more familiar than the same words presented in incongruous picture context.

The N200–500 assumed to reflect specific phonological word form processing is already known to be increased by both familiarity and lexical priming (Friedrich, 2008; Kooijman, 2007; Friedrich & Friederici, 2004, 2005a; Kooijman et al., 2005; Mills et al., 1993, 1997). In contrast to the training phase, the N200–500 was clearly left lateralized in the memory test. This might be caused by the spatio-temporal overlap of the three effects observed during the test phase. Alternatively, one might speculate that the overnight consolidation of lexical memory is attended by hemispheric specialization.

For the P100 and the first observed parietal N300–500, the present finding of similar effects of repetition-based familiarity and lexical priming is new. If the increase in P100 during early repetitions will indeed indicate the unspecific expectation of word onset, then the P100 priming effect would reflect the specific expectation of the onset of the appropriate congruous word. For the parietal N300–500, one might presume that it indicates some kind of lexical word status or lexical access, which is affected by both the repeated presentation of a word in semantic picture context and the expectation of a lexical element from a certain meaning. Although we do not definitely know what kind of processing is reflected by P100 and N300–500 priming, together with the frontal N200–500 priming effect, these effects indicate that in 6-month-old infants newly acquired object–word mappings affect specific stages of word processing even 1 day after their encoding. Thus, the occurrence of the repetition-based familiarity effects as lexical priming effects in the memory test indicates that some lexical knowledge is still present in infants' long-term memory.

The infant N400 semantic priming effect around 800 msec was not observed in the memory test.[1] One might argue that the N400 difference between training and testing is caused by the fact that, in the incongruous test condition, words were the same as in the congruous test condition, whereas in the training phase the words of the constant and rotated conditions were from different sets. However, the N400 effect during training did not emerge due to an increased negativity of the rotated condition. Rather it originated from the decreased negativity of the primed constantly paired words that were the same as in the congruous condition of the test phase. If 1 day later the long-term memory representations of the trained object–word mappings were sufficiently stable to trigger semantic priming, then the negativity would have been decreased in the congruous condition, and therefore, the N400 priming effect should have emerged in the test phase too. Thus, the disappearance of the N400 during the memory test can be interpreted as missing semantic priming.

At least for the comparison with the frontal N200–500 perceptual priming effect we know that the N400 represents the higher developed response that operates over declarative knowledge (Ullman, 2004) and requires sufficiently stable memory structures to be elicited (Friedrich & Friederici, 2005a, 2006, 2010). The missing N400 priming effect together with the presence of other, at least partly, more immature priming effects suggest that the memory representations 1 day after their encoding are still present, but they are weaker than immediately after encoding. This result indicates that some forgetting has taken place, and it suggests that the development of memory consolidation lags behind that of the encoding process.

General Discussion

The aim of the present study was to explore the limitations of fast mapping in early infancy and the involvement of declarative memory in the formation of lexical-semantic connections within the first year of life. Most importantly, we observed an N400 semantic priming effect during the training phase,[2] indicating 6-month-olds' successful encoding of object–word mappings after a very few presentations. Thus, although before their first birthday infants do not show signs of fast mapping at the behavioral level, the neurophysiological result of the present study indicates that, at 6 months, infants are already able to rapidly associate novel words with novel meanings and to retain this newly encoded knowledge in STM.

In the present study, infants learned mappings between words and objects that did not vary in their features over the whole course of training and testing. From this design, we cannot conclude that infants have acquired referential linguistic knowledge. Here, infants may have build up proto-words (Nazzi & Bertoncini, 2003), that is, associative representations between specific temporally co-occurring objects and speech sounds. However, the very fast encoding process argues against the establishing of simple associative memory. Moreover, the presence of N400 semantic priming implies some kind of reference. Thus, at least temporarily, infants might have established referential connections in the sense that a word stands for a meaningful event even if this event is actually not present. Further studies will more explicitly address the difference between associative and referential memory during first word learning and may answer the question, whether and how associative connections and referential knowledge differ at the representational neural level.

The presence of an N400 priming effect in 6-month-olds in response to immediately acquired object–word mappings is a striking new finding, because, so far, the N400 in response to known object–word pairs has not been observed in normally developing 12-month-olds (Friedrich & Friederici, 2005b). The result of the memory test 1 day after training, in which 6-month-old infants did not show N400 priming although, like in 12-month-olds, N200–500 priming was present, clarifies matters. The pattern of results can be interpreted in the following way: During encoding, initially established memory structures become temporary sufficiently strengthened such that the N400 neural mechanisms can operate over these memory structures. However, this short-term strengthening is not consolidated in 6-month-olds, such that 1 day later, memory representations are not sufficient to elicit the N400 priming effect, although several other ERP priming effects indicated that at least some lexical knowledge is retained. Similarly, the N400 does not occur in response to "known" words in 12-month-old infants, to which they were exposed in the past but have not immediately been strengthened. On this note, the emergence of the N400 in 6-month-olds during the training phase of the present study confirms our previous interpretation that it is indeed the weaker knowledge base and not the immature brain structures that is responsible for the missing N400 in 12-month-old infants (Friedrich, 2010). The results of the present study imply that those familiar words that recently have been heard in appropriate semantic context should elicit an N400 in 12-month-olds and possibly even in younger infants.

The observation of fast encoding and weak retention receives additional support from research in infant categorization. Generally, the developmental course of categorization abilities undergoes a shift from global (e.g., animal) to basic level (e.g., dog) to subordinate categories (e.g., poodle; e.g., Younger & Fearing, 2000). However, results on categorization in infancy strongly depend on the behavioral method used (for a review, see Mareschal & Quinn, 2001). In studies that do not require a familiarization phase, when infants have to use their long-term knowledge, they categorize only into imprecise global categories and show first signs of more precise basic level knowledge at the end of their first year of life. In contrast, in studies that require a familiarization phase, when infants have the possibility to form categories during the familiarization within the experiment itself, even 3- to 4-month-old infants are able to establish precise basic-level categories (French, Mareschal, Mermillod, & Quinn, 2004). Thus, detailed short lasting knowledge can be encoded at a very early age, but the representations in long-term memory are much broader and more imprecise, and they remain in this form for a relatively long time. The much weaker knowledge in long-term memory than in STM might be caused by the immature dentate gyrus that is assumed to play a role particularly in the consolidation of declarative memory (Richmond & Nelson, 2007; Bauer, 2004).

From the result of the training phase of the present study, in particular from the very fast encoding indexed by the N400 component, we conclude that declarative memory is involved in the encoding process of object–word mappings in 6-month-old infants. The result of the test phase suggests that the newly acquired content in declarative memory is only partly consolidated. However, the combined results do not necessarily imply that procedural memory is not involved in early word learning. In principle, it might be possible, that for the same learning material declarative and procedural memory are built in parallel and the weaker content of slow procedural memory is fully consolidated whereas the stronger content of fast declarative memory is not consolidated at all. In either case, the present data shows that fast declarative memory supports the encoding process and is, therefore, involved in infants' earliest word learning stages.

Conclusion

The present study was intended to explore what kind of neural changes are associated with perceptual and semantic word learning during early infancy and, in particular, which role the development of declarative memory plays for the development of the fast mapping ability. Here, for the first time, we showed that even 6-month-old infants are able to rapidly encode arbitrary mappings between objects and words, but in contrast to 14-month-olds, they are not able to sufficiently consolidate this lexical-semantic knowledge in long-term memory. Thus, fast declarative memory is involved in the encoding of object–word mappings, but a substantial part of this new content in declarative memory appears to be lost 1 day after its encoding. The results reported here suggest that it is not the encoding process but the rapid forgetting or the partial consolidation of declarative memory that limits the lexicon during early infancy.

UNCITED REFERENCE

Houston-Price, Plunkett, & Harris, 2005

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Notes

1. The temporally clearly defined N300–500 effect is not interpreted as infant N400 because, in the 6-month-olds of the present study, the N400 of the training phase had a latency of 600–900 msec.
2. The N200–500 was not affected by priming during training. One reason for this missing priming effect might be that word form processing was already maximally facilitated by repetition, which leads to a kind of saturation.

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