Electrophysiological correlates of auditory semantic priming in 24-month-olds

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Abstract

While the N400 component in adults is sensitive to both semantic incongruity and semantic relatedness between stimulus items, the N400 in toddlers has only been shown as an incongruity effect so far. The present event-related potential (ERP) study aimed to investigate whether the N400 in toddlers also indexes semantic relatedness between single words. To address this issue, we developed a unimodal auditory experiment with semantically related and unrelated word pairs, comparable to behavioral semantic priming tasks used with adults. In 24-month-old children, target words which were preceded by a semantically unrelated word elicited a broadly distributed N400-like effect compared to target words which were primed by a semantically related word. For related words, toddlers displayed a negativity in the 200–400 ms interval, indicating facilitated lexical-phonological processing. Results of the present study suggest that the N400 in toddlers is functionally equivalent to the adult component in indexing relatedness as well as semantic incongruity between stimulus items. Moreover, the study demonstrates an instrument for investigating semantic relatedness priming in young children, for whom behavioral tasks are often inappropriate.

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1. Introduction

Children master the task of word recognition at a remarkably early age. Already from birth infants are able to discriminate the phonetic detail used to distinguish between words in natural language, and by 7–8 months they can extract word forms from the speech stream and remember these for extended periods of time (Cheour et al., 2002; Dehaene-Lambertz & Pena, 2001; Jusczyk & Hohne, 1997; Jusczyk, Houston, & Newsome, 1999; Kujala et al., 2004). Associating these word forms with meaning, however, appears to be a more protracted process. Although children begin to form stable word–object associations around the onset of the second year (Campbell & Namy, 2003; Woodward & Hoyne, 1999; Woodward, Markman, & Fitzsimmons, 1994), their productive use of words at this stage suggests that word meanings differ from those of adults: Between ages 1 and 3, one-third of the vocabulary may involve overextensions (Rescorla, 1980). Underextensions of words are also common, as are situation bound uses of general terms and over-reliance on certain features of objects (such as shape) when extending words to a set of referents (for a review of production errors, see Clark, 1993). However, it is not known whether these atypical uses of words are restricted to the production domain or whether the same differences between adults and young children are also found in language comprehension. There are relatively few studies of word comprehension with children in this age group, perhaps due to productional and motivational obstacles which often lead to low internal reliability of behavioral comprehension measures (Bates, 1993). However, one robust finding is that children under the age of three have a very limited understanding of superordinate terms (Golinkoff, Shuff-Bailey, Olguin, & Ruan, 1995; Liu, Golinkoff, & Sak, 2001), indicating that not only word meanings in themselves, but also their organization may differ between adults and toddlers.

In adults, a principal source of information about organization of word meanings is semantic priming experiments where subjects are presented with pairs of words (sets of primes and targets) that are either semantically related or unrelated. Typically, prime–target pairs are presented in the context of a lexical decision task where subjects have to determine whether the target is a word or not. In these tasks, the semantic priming effect is measured as an advantage in reaction time or accuracy for the lexical decision. By now it is well-established that subjects react faster to targets which have been primed by a semantically related word than targets which are preceded by a semantically unrelated word (for a review, see Neely, 1991).

With an extensive literature on adult findings, priming tasks seem a promising tool for investigating the semantic relations between words in children. Unfortunately reaction time studies are not appropriate for toddlers and young children who are often unable or unwilling to give reliable behavioral responses in such tasks. Looking time measures have been widely used with infants, and although a body of valuable information regarding word learning has been gathered in such studies, these measures may not have the temporal accuracy necessary for many semantic priming tasks. Additionally, looking time measures are seldom employed with healthy adults, making developmental comparisons difficult.

However, as neuroimaging techniques improve and the equipment becomes more widespread, new possibilities arise for assessing semantic priming in children and comparing adults and children within the same testing paradigm.

Due to their excellent temporal resolution, electrophysiological techniques are particularly well suited to semantic priming tasks. Moreover, they are appropriate for
toddlers as they are non-invasive and more robust to motion artifacts than most other neuroimaging methods. A common electrophysiological method is event-related potentials (ERPs) where the brain response to many presentations of one stimulus type is averaged, thereby canceling out unrelated activity and noise. The waveform resulting from this average, the ERP, is assumed to be a reflection of the brain’s processing of the stimulus event in question. In the data analysis, researchers normally focus on some particular feature of the ERP, referred to as an ERP component. Components are typically defined in terms of their polarity (whether they are positive or negative-going), latency (when after stimulus onset they occur), and sometimes their scalp topography or properties of the stimulus material.

The N400, a negative ERP component peaking around 400 ms after stimulus onset in adults, is one of the most studied components in the ERP literature. It was first described by Kutas and Hillyard (1980) as a response to semantic anomaly in sentence context. A prominent negative brain response peaking around 400 ms was observed when subjects read the last word in senseless sentences such as *He spread the warm bread with socks*, but not when reading sensible sentences such as *It was his first day at work* or sentences with a physically deviant (uppercase) last word such as *She put on her high heeled SHOES*. Subsequent studies have shown that the N400 is not a general response to linguistic anomalies, as it does not occur for syntactic violations (Kutas & Hillyard, 1983). Neither is it a purely linguistic effect, as an N400-like negativity has also been observed during processing of pictures, environmental sounds and odors, and thus appears to reflect the brain’s detection and interpretation of meaningful items in general (for a review, see Kutas & Federmeier, 2000).

In language studies, the N400 has been found in a wide variety of experimental tasks. It is well established that words which are anomalous or implausible in a sentence or discourse context elicit an N400. However, it appears the N400 is sensitive to semantic relationships between words even when subjective plausibility in the sentence context is controlled for (Federmeier & Kutas, 1999a, 1999b; Kutas & Hillyard, 1984). An independent effect of semantic category membership on the N400 was demonstrated in a study where subjects were exposed to two types of sentence completions which were equally anomalous in the immediate context, but which differed in the semantic relationship to the expected completion (Federmeier & Kutas, 1999b). For example, subjects were presented with the following context: *They wanted the hotel to look more like a tropical resort. So along the driveway they planted rows of palms (expected completion)/ pines (within-category violation)/tulips (between-category violation)*. Although both violation types were equally implausible in this context, between-category violations elicited a significantly larger N400 than within-category violations.

The N400 is also found in the absence of a sentence or discourse context, as a response to single words (Bentin, Kutas, & Hillyard, 1995) and phonotactically legal non-words (Deacon, Dynowska, Ritter, & Grose-Fifer, 2004). The amplitude of the N400 reflects the word’s usage frequency (Van Petten & Kutas, 1990), and is reduced with repetition (Van Petten, Kutas, Kluender, Mitchiner, & Mcisaac, 1991). If the semantic relation between single words is manipulated in terms of category membership, words out of category elicit a larger N400 than words from a preceding established category (Boddy, 1981; Neville, Kutas, Chesney, & Schmidt, 1986). In addition, it has been shown that among words that fit a certain category (bird), atypical members (such as ostrich) elicits larger N400 amplitude than typical members (such as pigeon) (Heinze, Muente, & Kutas, 1998).
It appears that the N400 response is qualitatively similar whether it is elicited by single words or a sentence context. Kutas (1993) compared, in the same set of subjects, N400 amplitude to a similar set of word stimuli serving as terminal words in a sentence reading paradigm and as target words in a single word semantic priming paradigm. These words differed in the degree to which they were semantically related to the preceding word or sentence fragment. In both paradigms, the N400 components had a similar distribution and latency. However, the components differed in amplitude, with the word level effect being smaller than the sentence level effect.

The fact that the N400 is modulated by a number of different experimental features (e.g. semantic anomaly, usage frequency, semantic category membership) has made the component difficult to interpret in terms of underlying cognitive processes. The dominating view in the literature appears to be that the N400 as a response to word stimuli reflects the difficulty of integrating a word into a given semantic context, whether this context is created by preceding single words, sentences, discourse or images (Koelsch et al., 2004; Kutas & Federmeier, 2000; Van Petten & Kutas, 1991). However, a number of recent studies have claimed that in addition to integrative processes (which start upon, but not before, the occurrence of stimulus items), predictive processes also influence the N400 response. This anticipatory processing can be predictions for semantic features of upcoming stimuli, but also for specific word forms (DeLong, Urbach, & Kutas, 2005).

In recent years, ERP studies of the N400 has become an important complement to lexical decision tasks in the study of semantic priming. A number of studies have found that words which are primed by a semantically unrelated word elicit a larger N400 than words which are primed by a semantically related word (Anderson & Holcomb, 1995; Bentin, Maccarthy, & Wood, 1985; Holcomb, 1988; Holcomb & Neville, 1990, 1991; Rossel, Price, & Nobre, 2003). A similar finding in toddlers would point towards the N400 as a functional measure in the study of organization of word meanings in early development.

Only in the last few years has an N400-like incongruity effect been demonstrated in children in their second year of life (Friedrich & Friederici, 2004, 2005a, 2005b, 2005c; Mills, Conboy, & Paton, 2005; Torkildsen et al., 2006). Except for the study by Friedrich and Friederici (2005c), all these experiments have used a combination of auditory and visual stimuli. More specifically, they have employed a design where a picture was displayed on a screen and subsequently a word that either matched or did not match the picture was presented. Infants from 13 months upwards showed an N400-like negativity for incongruous words in these cross-modal mismatch tasks (Friedrich & Friederici, 2004, 2005a; Mills, Conboy et al., 2005; Torkildsen et al., 2006), but 12-month-olds failed to display an incongruity effect (Friedrich & Friederici, 2005b). Friedrich and Friederici (2005c) were the first to show a purely auditory N400 in this age group. In this study, 19- and 24-month-olds listened to semantically appropriate sentences (e.g. The child rolls the ball) and sentences where the object noun violated the selection restriction of the verb (e.g. The cat drinks the ball). Semantically inappropriate sentence endings elicited a long-lasting N400 in both age groups. In sum, these earlier studies of the N400 in toddlers have in common that the observed N400 effect was the result of semantic anomaly, either a naming violation or violation of the selection restriction of the verb. However, as the N400 in adults has been shown to be sensitive to various stimulus characteristics other than semantic anomaly (e.g. the degree of semantic relatedness between stimulus items), there is reason to investigate the N400 in toddlers in a wider range of experimental paradigms than...
what has been done so far. This is necessary to determine whether the N400 component in early development is functionally equivalent to that of adults, and thus whether studies of the N400 can be used to investigate the same set of questions in children as in adults.

The present study aimed to investigate whether the N400 in toddlers is sensitive to semantic relatedness between single words. To address this question, we designed a simple unimodal priming task. The stimulus material was auditorily presented basic level noun-pairs, where the first noun functioned as a prime and the second noun as a target. Half of the targets were from the same superordinate category as the prime (e.g. ‘dog–horse’) and half from a different superordinate category (e.g. ‘car–apple’). The brain response to unrelated targets was compared to the response to related targets. In this regard, the present study differs from earlier studies of the N400 in toddlers in two ways.

Firstly, the current investigation focused on the N400 as a modulation of the degree of relatedness between two stimulus items rather than the N400 as an index of anomaly. In previous toddler studies the N400 has been elicited in response to either incongruous word-picture pairs (Friedrich & Friederici, 2004, 2005a, 2005b; Mills, Conboy et al., 2005; Torkildsen et al., 2006) or semantically incongruous sentences (Friedrich & Friederici, 2005c). An N400 distinguishing between related and unrelated targets in the present study will reflect knowledge of the degree of relatedness between object words, while the N400 in previous toddler studies reflects detection of incongruity (i.e. the realization that ‘apple’ is an ill-fitting label for the presented object or that the sentence “The cat drinks the ball” is ill-formed).

Only one earlier study of this age group has compared ERP responses to stimulus items from the same semantic category to items from different semantic categories (Torkildsen et al., 2006). However, that study used a graded mismatch paradigm where the study of semantic relationships was combined with a naming violation (contrasting a congruous condition, a between-category violation and a within-category violation), making it difficult to isolate effects of semantic relatedness from effects of naming incongruity. Moreover, this study found only limited effects of semantic relatedness. Even though between-category violations of a lexical expectation gave rise to a larger N400-like incongruity effect than within-category violations, this effect was found only in the left frontal brain region, as opposed to the broadly distributed effect normally found in adults (e.g. Anderson & Holcomb, 1995; Holcomb & Neville, 1990; Rossel et al., 2003). This limited effect of semantic relatedness found in Torkildsen et al. (2006) might have been due to the tasks’ strong focus on incongruity between words and pictures, concealing more subtle effects of semantic relatedness. Thus, a simpler task where the mismatch aspect is removed might yield different results.

Secondly, the present study differs from earlier studies of the N400 in toddlers by investigating the relationship between single words rather than the relationship between words and pictures (Friedrich & Friederici, 2004, 2005a, 2005b; Mills, Conboy et al., 2005; Torkildsen et al., 2006) or words in sentence context (Friedrich & Friederici, 2005c). More specifically, the present experiment employs a design comparable to classical semantic priming tasks used with adults where a single prime word is followed by a target word which is either related or unrelated to the prime (Neely, 1991). If children show an N400 in such a task, it would allow comparison with behavioral and electrophysiological semantic priming studies of adults, and thus enable researchers in language acquisition to draw on a large literature of adult findings.
2. Method

2.1. Participants

Twenty-four typically developing children (12 girls) participated in the study. All subjects were recruited through newspaper advertisements. Participants were healthy, full-term (>36 weeks of gestation) 24-month-olds (+14 days) from monolingual Norwegian-speaking homes and had no known visual, hearing, or neurological deficits. According to parental report, none of the subjects had a family history of dyslexia or other language impairments. Seven of the 24 participants were excluded from the final analysis due to excessive artifacts in the EEG-recording, leaving 17 children (8 girls) in the final sample.

Parents completed the Norwegian adaptation (Smith, unpublished) of the MacArthur--Bates Communicative Development Inventory (MCDI) (Fenson et al., 1993) no more than 1 week prior to EEG testing. In addition, parents answered a questionnaire about the pregnancy, birth, and illnesses as well as possible disabilities of the child. According to parental responses on the MCDI, children in the final sample had a mean productive vocabulary of 337.7 words (SD = 198.3 words, range from 40 to 676 words).

On average participants produced 49 of the 70 words used in the experiment. No questionnaire or behavioral task aimed to measure receptive vocabulary was included in the study, as parents’ report of word comprehension is no longer considered accurate at 24 months (Fenson et al., 1993) and the internal reliability of behavioral comprehension tasks tends to be low with this age group (Bates, 1993). However, all the words used were chosen with the intention that two-year-olds would understand them.

2.2. Stimuli and procedure

Stimuli were 70 common one-, two- and three-syllable basic level words taken from the following six categories of the MacArthur Communicative Development Inventory: animals, food items, clothes, body parts, furniture, and vehicles. The words, which had a mean duration of approximately 700 ms, were spoken in a female voice, and were digitized at 16 bits with a 44.1 kHz sampling rate.

Words were grouped in pairs and divided into two prime–target conditions: (1) the two words were from the same superordinate category (related pairs, e.g. dog–horse) (2) the two words were from different superordinate categories (unrelated pairs, e.g. car–apple).

Each child was presented with a randomized mix of 70 word pairs where half the pairs were unrelated and half the pairs were related. Each word appeared once as target and once as prime. Four pictures of cartoon characters were used in addition to the words to keep the children’s attention. Before the presentation began participants heard the following instructions over the speaker: “Now you will see four characters: [a cartoon-like drawing of each of the characters was shown on the screen as it was introduced]. These characters will say some words to you. Listen carefully to what they have to say.” After this introduction, each word pair was presented by one of the characters in the following way: The cartoon character appeared on the screen for 1000 ms. Next, the screen went blank and there was a pause for 1000 ms before the prime was presented. The stimulus onset asynchrony (SOA) between the prime and the target was 1200 ms, and the screen remained blank as the two words were played. After a 1200 ms inter-trial interval, a
A different character appeared on the screen and the procedure was repeated. The four pictures were presented in a fixed sequence so that the same picture was displayed every four trials.

The experimental session lasted about 8 min.

2.3. EEG-recording

The EEG-recordings took place in a sound-attenuated room. Auditory stimuli were presented at an intensity of 70 dB SPL and visual stimuli were displayed on a 30 × 40 cm computer monitor. Both monitor and speakers were placed approximately 1 m in front of the participants. During the experimental session a curtain blocked every object except the speakers and the computer screen from the child's view. Participants were video-monitored during the experiment and were given a short break when they became fussy or looked away from the screen.

The whole session lasted approximately 45 min including familiarization, capping and impedance measures.

Silver-silver chloride electrodes (EasyCap, Falk Minow) were placed according to the international 10–20 system at the following locations: Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T3, C3, Cz, C4, T4, TP7, CP3, CPz, CP4, TP8, T5, P3, Pz, P4, T6, O1, Oz, O2. The vertical electrooculogram (VEOG) was recorded from electrodes placed above and below the right eye, and the horizontal electrooculogram (HEOG) was recorded from electrodes placed lateral to the left and the right eye. All electrodes were referenced to the average of the left and the right mastoids. Impedances were kept below 5 kΩ for all electrodes.

The EEG was recorded with a 0.1/70 Hz band pass filter at a sampling rate of 500 Hz, and amplified with a Neuroscan Nuamps amplifier.

2.4. Data analysis

Baseline correction (prestimulus interval) and a zero-phase band pass filter from 0.3 to 20 Hz were applied to the EEG. Epochs of 1200 ms were computed with a pre-stimulus baseline of 100 ms. All trials contaminated by high amplitude activity (> 150 μV) on any channel, including the HEOG and VEOG channels, were removed. In addition, a linear detrend procedure was performed on each epoch and each channel to remove slow DC shifts from the waveforms. The slow shifts removed were mainly drifts from fronto-temporal electrode sites caused by HEOG.

There were at least 20 artifact-free trials per condition (mean = 27.8, SD = 1.4). After visual inspection of ERPs, nine regions of interest were selected for analyses: left frontal (F3, FC3), midline frontal (Fz, FCz), right frontal (F4, FC4), left central (C3, CP3), midline central (Cz, CPz), right central (C4, CP4), left parietal (P3), midline parietal (Pz), and right parietal (P4).

2.5. Statistical analysis

As earlier studies of the N400 in comparable age groups have shown substantial variation with regard to the latency of the component (cp. Friedrich & Friederici, 2004, 2005a, 2005b; Mills, Conboy et al., 2005; Torkildsen et al., 2006), no pre-defined time-
windows were selected for analysis. Instead, the effects of the experimental manipulation were analyzed in consecutive time intervals of 200 ms duration, from 200 to 1200 ms, using mean amplitude values.

For each 200 ms interval, three-way ANOVAs with semantic relatedness (related, unrelated), electrode site (frontal, central, parietal) and laterality (left, midline, right) were performed. Separate two-way ANOVAs were also carried out for each of the three electrode sites and each of the three lateral domains. Significant three-way interactions were followed up by one-way ANOVAs of each electrode site-laterality combination.

The Greenhouse–Geisser correction (Greenhouse & Geisser, 1959) was applied when evaluating effects with more than 1 degree of freedom in the numerator.

3. Results

Visual inspection of the ERPs of 24-month-olds showed that there was a pronounced positive deflection peaking at about 150 ms for both conditions. A negativity for related words appeared at approximately 200 ms in all brain regions, and lasted until about 400 ms at left electrodes sites and around 500 ms at right electrode sites. The negativity for related words was followed by a larger N400-like negative deflection for unrelated words in the 500–800 ms interval (Figs. 1 and 2). The negative response to unrelated words started earlier at left and central sites than at right sites and was larger in frontal than in parietal brain regions (Fig. 3).

Fig. 1. Grand average ERPs for related targets (black line) and unrelated targets (gray line).
Fig. 2. Difference between related and unrelated targets in two selected time intervals. Bars represent mean amplitude values for all electrodes in the six regions of interest and error bars represent standard error of mean.

Fig. 3. Difference between related and unrelated targets at frontal, central and parietal electrode sites in the 600–800 ms time interval. Bars represent mean amplitude values and error bars represent standard error of mean.

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Inspection of individual averages showed that 15 of 17 children showed an ERP pattern where unrelated targets were more negative than related targets in frontal and central brain regions in the 500–800 ms interval. In one child related words were generally most negative, and in one child there was no systematic difference between conditions. Statistical analyses yielded a significant main effect of semantic relatedness for target words in the 200–400 ms interval where related targets were more negative than unrelated targets (Table 1). This effect was broadly distributed, as confirmed by a lack of interactions with electrode site or laterality in this time interval. However, separate analyses for the three electrode sites showed that while the effect was strong in central areas ($F(1, 16) = 11.91, p = 0.003$), and robust in frontal areas ($F(1, 16) = 6.16, p = 0.025$), there was only a trend towards an effect in parietal areas ($F(1, 16) = 2.70, p = 0.12$).

In the 400–600 ms interval, there was no reliable main effect of semantic relatedness. However, there was a significant three-way interaction between semantic relatedness, electrode site and laterality ($F(4, 64) = 5.27, p = 0.004$). Follow-up analyses for the different electrode site-laterality combinations yielded a significant effect of semantic relatedness in the frontal midline region, where unrelated words were more negative than related words ($F(1, 16) = 5.24, p = 0.036$). There were no effects of semantic relatedness in the other brain regions.

There was a significant main effect of semantic relatedness in the 600–800 ms interval ($F(1, 16) = 6.53, p = 0.021$). In this time window, unrelated words were more negative than related words, and thus the effect went in the opposite direction of that found in the 200–400 ms interval, but the same direction as the effect at frontal midline sites in the 400–600 ms interval. There were no significant main effects or interactions.

In order to interpret the differences between targets primed by related and unrelated words, it was important to establish that there were no differences between the ERPs to the primes. Thus, ERPs to prime words were tested in the same time intervals as the targets (200–1200 ms) with the same three-way ANOVAs. There was no difference between the words that primed related targets and words that primed unrelated targets in any time intervals ($F(1, 16) = 0.171–0.442, p = 0.515–0.684$), and no significant interactions.

Table 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Main effect $F(1, 16)$</th>
<th>Direction of relationship</th>
<th>Left $F(1, 16)$</th>
<th>Midline $F(1, 16)$</th>
<th>Right $F(1, 16)$</th>
<th>Frontal $F(1, 16)$</th>
<th>Central $F(1, 16)$</th>
<th>Parietal $F(1, 16)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200–400</td>
<td>6.18**</td>
<td>Related words more negative</td>
<td>4.29 ($p = 0.055$)</td>
<td>5.68*</td>
<td>6.73**</td>
<td>6.16**</td>
<td>11.91***</td>
<td></td>
</tr>
<tr>
<td>400–600</td>
<td>6.53**</td>
<td>Unrelated words more negative</td>
<td>7.26** ($p = 0.050$)</td>
<td>4.50</td>
<td>3.96</td>
<td>11.43***</td>
<td>7.92**</td>
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<td>800–1000</td>
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<td>1000–1200</td>
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</table>

*p < 0.05 **p < 0.03 ***p < 0.01.
In order to test whether productive vocabulary had an impact on the observed ERP effects, bivariate correlations between productive test vocabulary and priming effects in the 200–400 and 600–800 ms time window were carried out. The measure of test vocabulary used in the analyses was the number of stimulus words produced by each participant according to the MCDI. Priming effects were calculated by subtracting the mean amplitude in the unrelated condition from mean amplitude in the related condition for each individual child. Mean amplitude in the two conditions was calculated by averaging the amplitude of all electrodes in the nine regions of interest in the two time intervals.

There was no correlation between test vocabulary and ERP effects in neither the 200–400 ms interval (Pearson correlation \( r = 0.153 \), \( p = 0.602 \)) nor in the 600–800 ms interval (Pearson correlation \( r = 0.182 \), \( p = 0.535 \)).

4. Discussion

4.1. N400-like semantic priming effect

The present ERP study investigated whether the N400-like response in toddlers could be present in a task manipulating the semantic relatedness between words, but where no semantic anomaly was involved. An N400 component in the absence of semantic anomaly is well-established in adults, but has to our knowledge not been shown in this age group earlier. The experimental paradigm used was a traditional semantic priming task with related and unrelated word pairs, comparable to behavioral and electrophysiological semantic priming tasks used with adults.

Previous toddler studies of the N400-like component as a modulation of semantic incongruity have found that this component appears to be functionally similar to the adult N400. A finding of a similar component distinguishing related and unrelated target words in the present design would be additional evidence that the N400-like component in toddlers is functionally comparable to the N400 in adults. Moreover, such a result in a design which is highly similar to the semantic priming tasks which have been used with adults for several decades, would allow researchers in language acquisition to draw on a large literature of adult findings and make developmental comparisons.

Results of the present study showed that basic level words which were preceded by a basic level word from a different superordinate category elicited an N400-like negativity compared to basic level words which were primed by another basic level word from the same superordinate category. This effect was statistically significant in the 600–800 ms interval after stimulus onset. Although the effect was broadly distributed across the scalp, it was more pronounced in fronto-central than posterior brain regions, and larger over the left than the right hemisphere. The N400-like effect appeared at frontal midline sites around 390 ms and reached significance here already in the 400–600 ms interval. Subsequently, the priming effect emerged in the left hemisphere around 450 ms and in the right hemisphere approximately 550 ms after stimulus onset. As a control procedure, ERPs to the primes were also analyzed, showing no difference between words preceding semantically related and unrelated words. Thus, the differences found between target words in the present study appear to be an effect of priming.

The priming effect was obtained in a wholly auditory task where single words primed other single words with a SOA of 1200 ms. Such a unimodal priming paradigm with single words has to our knowledge not been employed with pre-school children earlier. The
design is, however, almost identical to the auditory part of an adult study by Holcomb and Neville (1990), except that this study included a lexical decision component, using both words and non-words as stimuli. In the Holcomb and Neville (1990) experiment, the SOA between prime and target words was 1150 ms, i.e. only 50 ms shorter than in the present study. In a comparison of results, this similarity is of particular relevance since prime–target SOA has been shown to have a significant influence on ERPs in semantic priming tasks (e.g. Anderson & Holcomb, 1995; Holcomb & Anderson, 1993). As in the current study, Holcomb and Neville (1990) found that target words preceded by a semantically unrelated word elicited an N400 component compared to semantically primed targets. The difference between related and unrelated targets was significant already in the 150–300 ms in adults (but lasted until 750 ms), suggesting that the adults were faster at exploiting information from the primes than the 24-month-old children in the present experiment. As in the current study, the N400 in the experiment by Holcomb and Neville was visible on all scalp electrodes. However, the effect was largest in parietal and temporal areas, as opposed to the frontal-central focus found in 24-month-olds. A possible reason for this topographical difference is that the N400 component in toddlers overlapped with a frontally distributed negativity (Nc), which has been associated with attentional processing in a number of infant and child studies (for an overview, see Nelson & Monk, 2001). It is also important to keep in mind that the lexical decision task included in the study by Holcomb and Neville (1990), but not in the present experiment, introduced additional cognitive processing which may have contributed to differences between the two studies.

When comparing adult and toddler priming studies one must also consider the possibility that the relative contributions of automatic and controlled mechanisms may differ between age groups. According to Neely (1991), who reviewed a large number of semantic priming studies, at least three mechanisms may be involved in the semantic priming effect. One of these mechanisms is regarded as automatic, while the two others are viewed as controlled. The first mechanism is automatic spreading activation between related word representations. This is a process which is believed to have a relatively brief time span, and contributes to semantic priming only when the SOA between prime and target is short (usually less than 400 ms) (Neely, 1977; Posner & Snyder, 1975). When the SOA is longer than 400 ms, there is enough time for controlled processing, in which at least two different strategies are employed. Expectancy-based priming, results from subjects using primes to generate an expectancy set consisting of potential targets which are semantically or associatively related to the prime (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). Targets included in the expectancy set are recognized more quickly than targets which are not in this set. It has been shown that semantic expectancies are made more prominent when the proportion of related word pairs in an experiment is increased (de Groot, 1984). Semantic matching is another controlled process where subjects match primes and targets for semantic similarity (de Groot, 1984; Neely, Keefe, & Ross, 1989). As opposed to automatic spreading activation and expectancy-based priming which lead to the semantic priming effect by speeding access to the target in the lexical access stage, semantic matching occurs after lexical access to targets. ERP studies have indicated that the N400 is sensitive to both automatic and controlled processing mechanisms, as priming effects are seen at SOAs from 0 to at least 1200 ms (Anderson & Holcomb, 1995; Holcomb & Neville, 1990).

The 1200 ms SOA used in the present study is considered too long for the relatively short-lasting effect of automatic spreading activation in adults. However, in toddlers ERP
latencies of components assumed to reflect word processing are often considerably longer than their adult counterparts (e.g. Friedrich & Friederici, 2004, 2005a, 2005b; Torkildsen et al., 2006). Thus, it is possible that the N400 in the present study reflects automatic spreading activation. Moreover, it appears that controlled processing is at best partially developed in the relevant age group (Diamond, 2002; Richards, 2003), rendering an account in terms of automatic processes more plausible.

Earlier investigations of the N400 in comparable age-groups (Friedrich & Friederici, 2004, 2005a, 2005b, 2005c; Mills, Conboy et al., 2005; Torkildsen et al., 2006) have either used a cross-modal picture–word incongruity paradigm or a sentence processing paradigm quite different from the unimodal priming task employed in the current study. For this reason, specific features of the N400-like component in the present experiment, such as latency and topography, cannot be directly compared to those of previous investigations. However, while the studies by Mills, Conboy et al. (2005) and Friedrich and Friederici (2004, 2005a, 2005b) only distinguished between congruous and incongruous picture–word pairs, assessing the N400 solely as a response to a naming violation, the study by Torkildsen et al. (2006) also examined the degree of semantic relatedness between stimulus items as it compared congruous picture–word pairs (e.g. dog–‘dog’) to both within-category violations where the target word was semantically related to the picture (e.g. dog–‘horse’) and between-category violations where the target word was unrelated to the picture (e.g. dog–‘car’). Thus, the difference between these two violation types has a functional similarity to the difference between related and unrelated words in the present study. Although Torkildsen et al. (2006) did find evidence that between-category violations elicited a larger negativity than within-category violations, this difference was only reliable in the left frontal brain region in the 850–950 ms interval. In the present study, the effect of semantic relatedness was much more broadly distributed and appeared earlier (600–800 ms interval). In other words, when comparing only the part of the N400 which indexed semantic relatedness, the N400-like effect in the present experiment was larger and earlier than in the study by Torkildsen et al. (2006). This difference might have been due to the former tasks’ strong focus on semantic congruity between words and pictures, making children concentrate on the picture–word incongruities and reducing attention to semantic relatedness between stimulus items. The latency difference between the two studies might have been an effect of stimulus modality. In this regard, it is worth noting that in two studies of adults, both using an 800ms SOA between stimulus pair items, the N400 appeared earlier in a purely auditory task than in a comparable cross-modal visual–auditory task (cf. Anderson & Holcomb, 1995; Holcomb & Anderson, 1993). When comparing the results of Torkildsen et al. (2006) with the findings of the current experiment, it should also be kept in mind that subjects were 4 months older in the present study.

As mentioned above, the N400 observed in the present study appears to be the result of primes facilitating the processing of related targets compared to unrelated targets. However, exactly which relations between primes and targets that underlie this priming effect is not clear. In this regard, two sets of distinctions are relevant: the differentiation between semantic and associative relationships on the one hand and the differentiation between lexical and conceptual relations on the other.

A common distinction in the literature on semantic memory is between semantic and associative relations (see e.g. Collins & Loftus, 1975). Semantic relations are based on similarities in meaning, such as shared taxonomic category membership or overlap of
Semantic features. Associative relations, on the other hand, are based on properties of surface forms. Associations between words are often measured by free association norms (Postman & Keppel, 1970) and typically result from co-occurrence in speech, as well as phonological or orthographic similarities. As many words which have a strong associative relation are also semantically related and vice versa, distinguishing the influence of these two on priming is a non-trivial task (Plaut, 1995). For example, if the word ‘chair’ facilitates processing of the word ‘table’ this may be because the word ‘chair’ has semantic features in common with the word ‘table’, because these two words frequently occur together in spoken language, or because of both these relationships between the two words.

In most studies which refer to themselves as ‘semantic priming studies’ effects of associative relationships are not controlled for (Neely, 1991). However, Neely (1991) reviewed three studies which attempted to distinguish between semantically and associatively related word pairs in behavioral lexical decision tasks. All these found effects of “pure” semantic priming as well as associative priming, but the latter effects were stronger than the former. Koivisto and Revonsuo (2001) who made the same distinction in an ERP study, showed N400 priming effects for both semantically similar and lexically associated word pairs, and thus concluded that the presence of either of these two relations between words was sufficient, but not necessary to produce a priming effect.

Unlike many semantic priming studies which have aimed to use word pairs with the strongest possible relation in the related condition (i.e. words which have both a strong associative relationship and share many semantic features, such as ‘doctor–nurse’, ‘cat–dog’), related pairs in the present experiment were selected only on the basis of taxonomic category membership. Thus, the only factor which varied systematically between conditions was semantic relatedness. For this reason we argue that it is reasonable to refer to the study as a semantic priming study. However, associative relations may have contributed to the priming effects. While effects of phonological similarity are unlikely because the pairing of words differed between subjects, the frequency of co-occurrence of taxonomically related words may have had an impact on priming. No attempt was made to control for such frequency-based effects, as we did not have information about co-occurrence of words in speech directed to children in the relevant age group. We believe, however, that the effect of associative relationships on priming is relatively modest, as most of the words within each semantic category had, at least by adult standards, only a weak associative relationship, (e.g. ‘elephant–butterfly’, ‘scarf–socks’).

Whether a semantic or frequency-based effect, it can be questioned if the N400 is due to processes at the lexical level or the conceptual level. Most models of word knowledge distinguish between a conceptual level where the meaning of words are represented, a phonological level where the sounds of words are represented, and a third, lexical level, mediating between the first two (Caramazza, 1996; Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Levelt, Roelofs, & Meyer, 1999). It is, however, debated whether the lexical level is organized semantically or whether it relies on the semantic organization of the conceptual level (cf. Damasio et al., 1996; Levelt et al., 1999). In the present study, a semantic priming effect may either reflect direct connections between words in a semantically organized lexicon or overlap of semantic features between concepts activated by related words. A frequency-based priming effect may be attributed to co-occurrences between words or co-occurrences between concepts activated by the named objects.

Previous studies have shown that the N400 component is modulated by expectations at the conceptual level as well as the word form (phonological or lexical) level (DeLong et al., 1996; Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Levelt, Roelofs, & Meyer, 1999). It is, however, debated whether the lexical level is organized semantically or whether it relies on the semantic organization of the conceptual level (cf. Damasio et al., 1996; Levelt et al., 1999). In the present study, a semantic priming effect may either reflect direct connections between words in a semantically organized lexicon or overlap of semantic features between concepts activated by related words. A frequency-based priming effect may be attributed to co-occurrences between words or co-occurrences between concepts activated by the named objects.

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2005; Federmeier & Kutas, 1999b). Note, however, that even though both Federmeier and Kutas (1999b) and DeLong et al. (2005) refer to “expectations” influencing the N400, they do not claim that these are the result of conscious or strategic processes. The study by Federmeier and Kutas (1999b) demonstrated that the N400 is sensitive to expectancies for semantic features of categories in long-term memory. For example, they showed that the expectation of a particular animal word facilitated the processing of words for other animals which shared semantic features with the expected animal, even though the lexical connection between the two words was judged to be weak in a cloze probability task. On the other hand, a recent study by Delong et al. (2005) demonstrated that the N400 is also modulated by expectancies for concrete word forms. DeLong et al. constructed sentence contexts leading to expectations for specific nouns, but preceded these nouns with either an appropriate indefinite article (e.g. ‘an’) or a semantically identical, sententially congruous, but phonologically inappropriate article (e.g. ‘a’). An unexpected article elicited an N400 compared to an expected article, showing that subjects had predicted a specific word form to appear.

In the present experiment, only single words, not pictures or sentence fragments, were used as primes. Thus, if we assume that lexical items are organized by semantic or associative relatedness, there could be priming occurring at the lexical level as well as on a higher conceptual level. In this regard, the present experiment differs from the earlier cross-modal studies of the N400 in toddlers were pictures were used to prime words (Friedrich & Friederici, 2004, 2005a, 2005b; Mills, Conboy et al., 2005; Torkildsen et al., 2006). In these cross-modal tasks, the priming effect depends entirely on a conceptual level mediating between pictures and words.

The N400 observed in the present study is evidence that words and/or concepts from the same adult superordinate category (e.g. ‘elephant’ and ‘cat’) have closer relations than words and/or concepts from different adult superordinate categories (e.g. ‘elephant’ and ‘car’). As argued above, it is unlikely that the close relations between items from the same adult superordinate category are based solely on frequency of co-occurrence. Thus, the results of our study indicate that children are capable of semantically-based grouping of different basic-level items belonging to the same adult superordinate category. Furthermore, children are able to make use of this grouping in a task where they only receive linguistic input, i.e. in the absence of picture cues or 3-D objects. It is important to keep in mind, however, that children may establish clusters of related basic-level items without having acquired superordinate terms or an understanding of hierarchical relations between words or concepts. No superordinate words (such as ‘animal’ or ‘vehicle’) were used in the present experiment. Thus, the current study does not provide evidence that children have acquired superordinate terms or superordinate categories.

4.2. Lexical priming effect

In addition to the N400-like response to the unrelated targets in the 600–800 ms interval, there was an earlier component distinguishing related and unrelated targets in the present study. In the 200–400 ms time window, related words elicited significantly more negative ERPs than unrelated words. This effect was visible on all dorsal electrodes, but most prominent on frontal electrode sites. The fact that the mean duration of words was 700 ms, and ERPs to related and unrelated words were significantly different already in the 200–400 ms interval, suggests that auditory word recognition in this age group starts well...
before the whole word has been presented. This is in line with earlier evidence from electrophysiological and eye-tracking studies (Fernald, Swingley, & Pinto, 2001; Friedrich & Friederici, 2004, 2005a, 2005b; Mills et al., 2004; Thieriy, Vihman, & Roberts, 2003).

An ERP response in the 200–400 ms interval related to word processing has been observed in a number of studies of children from 10 to 20 months of age (Friedrich & Friederici, 2004, 2005a, 2005b; Kooijman, Hagoort, & Cutler, 2005; Mills, Coffey-Corina, & Neville, 1993, 1997; Mills, Plunkett, Prat, & Schafer, 2005; Molfese, 1989, 1990; Molfese, Wetzel, & Gill, 1993; Sheehan, Nam, & Mills, in press). It appears that this early negativity in children may be modulated by at least four different features of word stimuli: (1) phonotactic familiarity (Friedrich & Friederici, 2005b) (2) lexical familiarity (i.e. amount of previous lexical exposure, Kooijman et al., 2005), (3) lexical priming independently of lexical familiarity (i.e. current activation in memory, Friedrich & Friederici, 2004, 2005a, 2005b), and (4) meaningfulness (i.e. whether words are linked to a referent or not, Mills, Plunkett et al., 2005; Mills et al., 2004; Molfese, 1989).

It is possible that the early negativities to words reported in the above studies should be regarded as different ERP components, as they not only seem to be modulated by distinct features of the stimulus material, but also appear to have different scalp topographies in some cases: In the experiment by Mills et al. (1997), an early negative effect distinguishing between known and unknown words was restricted to temporal and parietal regions of the left hemisphere in 20-month-olds. However, in the study by Mills, Plunkett et al. (2005) of the same age group, but where the early negativity distinguished between novel words which had or had not been paired with an object, the effect was broadly distributed over both hemispheres. In Friedrich and Friederici’s (2004, 2005a, 2005b) studies where the early negative response reflected a lexical priming effect, the scalp distribution was frontal.

Most relevant to the interpretation of this early negative component in the present study are Friedrich and Friederici’s (2004, 2005a, 2005b) three picture–word mismatch studies of 12-, 14- and 19-month-old children. All these studies found that words which were congruous with the picture elicited a frontally-distributed early negativity compared to words which were incongruous with the picture. As the same words were used in the congruous and incongruous condition, this effect could not be a result of differences in lexical familiarity between conditions. Friedrich and Friederici therefore interpreted this phenomenon as an effect of lexical priming. More specifically, they proposed that the early negativity reflected facilitated phonological-lexical processing of an expected word. The early negativity for congruous words was followed by a later negativity for incongruous words which was interpreted as an N400-like semantic incongruity effect.

Above we mentioned that the early negativity has been shown to be modulated by (1) phonotactic familiarity, (2) lexical familiarity (3) lexical priming, and (4) meaningfulness in different studies with children in the relevant age group. In the present study all the stimulus items were common Norwegian words assumed to be highly familiar to the children, and the assignment of words to a condition (either related or unrelated) was randomized. Consequently, the only one of the four factors mentioned above which varied systematically between conditions was lexical priming independently of word familiarity.

Moreover, the early negative response had a frontal dominance similar to the one found in the studies by Friedrich and Friederici (2004, 2005a, 2005b), strengthening the interpretation of the response as a lexical priming effect. On this basis, we suggest that the early negativity reflects facilitated phonological-lexical processing of words which have been pre-activated by priming.
In their discussion of the early negativity as a lexical priming effect, Friedrich and Friederici (2004, 2005a, 2005b) assumed that the effect was the result of a picture influencing the expectation of a specific lexical item. However, as opposed to the studies by Friedrich and Friederici (2004, 2005a, 2005b), where there was an identity relation between the picture and the subsequent word in the congruous condition (e.g. picture of cat, auditory stimulus ‘cat’), prime and target words were merely semantically related (e.g. ‘dog–horse’) in the present study. Thus the findings of the present study suggest that the early negative response is not only sensitive to identity priming, but also to relatedness priming.

Note that the early negativity in infants and young children should not be seen as a functional equivalent of the N200 or the phonological mismatch negativity observed in many adult studies (e.g. Hagoort & Brown, 2000; van den Brink, Brown, & Hagoort, 2001). In fact, the second negative component appears to show complex functional age-related changes well into the school years (Bonte & Blomert, 2004), and the relation between the adult N200 and the child negativity in the same time interval is not well understood at present.

4.3. Conclusion

The N400 component in adults is sensitive to both semantic incongruity and semantic relatedness between stimulus items. Earlier studies have demonstrated the presence of an N400-like effect in young children, but only as an incongruity effect. The present study aimed to investigate the N400 in toddlers as an index of relatedness between single words. To this end, we designed a unimodal auditory semantic priming task with related and unrelated word pairs. The experiment was intended as an electrophysiological counterpart of behavioral semantic priming tasks used with adults.

Results showed that 24-month-olds displayed a broadly distributed N400-like negativity for target words preceded by a semantically unrelated word compared to targets primed by a semantically related word. The N400 thus appeared to reflect processing of semantic relationships, although influence of associative relations cannot be excluded. Another ERP component distinguishing between related and unrelated words was also found in the current experiment. This was a negativity for related compared to unrelated targets in the 200–400 ms interval, and was interpreted as a lexical priming effect reflecting facilitated phonological-lexical processing of words which had been pre-activated by the presentation of a related word.

More generally, results of the present study suggest that the N400 in toddlers is functionally equivalent to the adult component in indexing relatedness as well as incongruity between stimulus items. Furthermore, the study demonstrates an instrument for measuring semantic relatedness priming in young children, for whom behavioral tasks are often inappropriate.

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