Brain responses to lexical-semantic priming in children at-risk for dyslexia

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Abstract

Deviances in early event-related potential (ERP) components reflecting auditory and phonological processing are well-documented in children at familial risk for dyslexia. However, little is known about brain responses which index processing in other linguistic domains such as lexicon, semantics and syntax in this group. The present study investigated effects of lexical-semantic priming in 20- and 24-month-olds at-risk for dyslexia and typically developing controls in two ERP experiments. In both experiments an early component assumed to reflect facilitated lexical processing for primed words was enhanced in the at-risk group compared to the control group. Moreover, an N400-like response which was prominent in the control group was attenuated or absent in at-risk children. Results suggest that deficiencies in young children at-risk for dyslexia are not restricted to perceptual and lower-level phonological abilities, but also affect higher order linguistic skills such as lexical and semantic processing.

Keywords: Familial risk for dyslexia; Lexical-semantic processing; Event-related potentials (ERP); N400

1. Introduction

Developmental dyslexia is a disorder manifested by difficulty in learning to read despite conventional techniques of instruction and intelligence within the normal range (Critchley, 1970). Of the various hypotheses about the underlying cognitive deficits in dyslexia, the phonological deficit hypothesis is probably the one with the most empirical support (Beaton, 2004). According to this hypothesis dyslexics have an impaired “phonological awareness”, a term referring to skills involved in discriminating and manipulating speech sounds. Tests of phonological awareness include such tasks as asking a child to tap the number of sounds in a word (Bradley & Bryant, 1983) and to delete a syllable or phoneme from a word (Liberman, Shankweiler, Fischer, & Carter, 1974).

Recent investigations have provided extensive evidence that deficiencies in awareness of phonological segments lead to difficulties in the phonological coding of written language, which is a key precondition for word recognition and spelling ability (Beaton, 2004; Bryant & Bradley, 1985; Olson, 1994). A vast number of studies have demonstrated that children with poor phonological awareness also show poor reading ability, and conversely that children who are poor readers have poor phonological awareness (Snowling, 1981; Stanovich, 1988; Stanovich & Siegel, 1994). Many adult dyslexics continue to have problems with phonological awareness tasks (Kinsbourne, Rufo, Gamzu, Palmer, & Berliner, 1991; Scarborough, 1984). In fact, it seems that impaired phonological ability remains the most persistent deficit in adult dyslexics, even the ones who have mostly overcome their
reading difficulties (Pennington, Van Orden, Smith, Green, & Haith, 1990; Watson & Miller, 1993).

However, there is accumulating evidence that dyslexics’ difficulties are not restricted to the phonological domain of language (Been & Zwarts, 2004; Bishop, 1991). Several studies have found that children with dyslexia show deficient naming speed and accuracy for pictured objects (e.g. Faust, Dimitrovsky, & Shacht, 2003; Snowling, Van Wagtendonk, & Stafford, 1988; see Nation, 2005 for a review). Although other naming skills also appear to be compromised in dyslexic subjects, object naming speed appears to be a better predictor of reading skills than other naming-speed tasks such as letter or number naming (Wolf & Goodglass, 1986; Wolf & Obregon, 1992). Moreover, dyslexic children seem to be impaired on object naming tasks even when they are compared to younger children of the same reading age (Nation, Marshall, & Snowling, 2001; Swan & Goswami, 1997). Additional evidence of a naming deficit in dyslexia comes from a recent investigation by De Jong and Van Der Leij (1999) showing that picture naming speed in kindergarten children predicts reading achievement in first grade.

Interestingly, however, dyslexic children tend to perform equally to typically developing children on picture vocabulary tests, i.e. tests in which the child is presented with a word and is asked to select a corresponding picture (Nation, 2005; Snowling et al., 1988). This finding points to a deficit in lexical processing rather than reduced receptive vocabulary as the main reason for naming problems. The difficulty may lie in lexical access, lexical retrieval, or in both these processes (Beaton, 2004). Alternatively, problems with later stages of speech processing, such as motor programming, may lie behind the naming deficit (Nation, 2005).

There is an ongoing debate about whether the naming deviations in dyslexia are simply a consequence of impaired phonological awareness or whether they independently account for variance in performance (Vuovic & Siegel, 2006; Wimmer, Mayringer, & Landerl, 2000; Wolf & Bowers, 1999). No matter what the outcome of this debate, a deficit that appears to be profound, and perhaps even larger than reading level predicts, merits further investigation. In particular, assessing the naming deficit prior to reading instruction would add to its understanding. The present study sought to investigate lexical processing in children at familial risk for dyslexia at an early stage of language acquisition.

As one of the major specific learning disabilities, affecting between 2% and 10% of the school age population, dyslexia has wide-ranging educational, social and emotional consequences (Beichmann et al., 1996; Shaywitz, 1998). Although the defining features of the disorder have been debated for decades, it is now widely believed that dyslexia has a neurobiological basis (Beaton, 2004). A familial component to dyslexia has been recognized for about a century (Fisher, 1905; Stephenson, 1907), and has been thoroughly demonstrated in a number of more recent studies (Lyytinen, 1997; Scarborough, 1989; Vogler & Defries, 1985). A child with an affected parent appears to have about an eight times higher risk of dyslexia than the population mean (Pennington, 1995).

As the hereditary component of dyslexia has become more and more firmly established, there has been a growing interest in investigations of children at familial risk for dyslexia before the onset of reading instruction (Guttorm, Leppänen, Richardson, & Lyytinen, 2001; Leppänen et al., 2002; Lyytinen, Ahonen et al., 2001; Lyytinen, Poikkeus, Laakso, Eklund, & Lyytinen, 2001; Pihko et al., 1999). These studies of pre-school children and infants have certain advantages compared to studies of school-age children. For example, it is difficult to determine the causal relationship between reading and other language difficulties in subjects who have already learned to read. Many of the reported language deficits in school-age dyslexic children could be primarily a consequence rather than a cause of reading problems (Olson, 1994; Stanovich, 1986). Early assessment gives access to subjects who have not yet been affected by compensatory processes and may thus be important in differentiating underlying cognitive deficits and cognitive consequences of the disorder. Moreover, identifying early precursors or markers of dyslexia may make it possible to single out individuals for intervention at an earlier stage with possibilities of a better reading outcome.

Investigations with traditional language assessment batteries have shown some early language delay in dyslexic children (Gallagher, Frith, & Snowling, 2000; Rutter & Yule, 1975). However, language differences between infants and toddlers with and without familial risk of dyslexia tend to be slight (Locke et al., 1997; Lyytinen, Ahonen et al., 2001). In the Jyväskylä Longitudinal Study of Dyslexia which followed children at familial risk for dyslexia and controls from birth, Lyytinen, Poikkeus et al. (2001) found that the earliest single language score that differentiated the groups was maximal sentence length at age 2, measured by the MacArthur Communicative Development Inventories (Fenson et al., 1993). From age 2 to 3 onwards the at-risk group began to show reduced scores on several measures, particularly those assessing phonological, morphological and naming skills.

Although language production inventories may not be able to distinguish children at-risk for dyslexia from typically developing children before the age of 2, brain imaging methods have revealed atypical development in at-risk children at a much earlier age. A large number of the brain imaging studies have employed electrophysiological techniques as these are particularly well-suited for children due to the ease of the recording and the relative robustness to motion. In infants and young children, electrophysiological methods are normally preferable to other imaging techniques such as PET, which requires exposure to radiation, and MRI, where head motion severely degrades the measurable signal (Thomas & Casey, 2003).
The electroencephalogram (EEG) is a non-invasive and painless method for recording brain electrical activity from the scalp surface. Since the procedure measures brain responses, it makes no demands on productive language or motor abilities. In addition, the technique has an excellent time resolution, allowing the study of cognitive processing at the millisecond level. The temporal accuracy is a particular advantage in the study of fast processes such as language comprehension. With infants and young children, the most common EEG-technique is the measure of event-related potentials (ERPs). This method represents a way to separate the brain response to a particular stimulus type from noise and unrelated brain activity. By presenting subjects repeatedly with the same type of stimulus, and subsequently averaging the EEG-response to these stimuli, unrelated EEG-activity is cancelled out. The output of the averaging process is the brain response to the particular stimulus type, or the event-related potential. Typically, several noise-reduction methods are used in addition to the averaging.

The ERP waveform can be subdivided into different features or parts of interest which are referred to as ERP components. Within a given experimental paradigm, ERP components are normally defined in terms of their latency (the time span between stimulus onset and occurrence), polarity (whether they are positive or negative), and topography (in which parts of the brain they are most prominent) (Rugg & Coles, 1995). A number of ERP components have been shown to vary systematically with physical properties of the stimuli (such as duration, pitch, intensity, etc.) or reflecting specific cognitive processes (such as mismatch detection, visual face processing, syntactic integration, etc.) (Fonaryova Key, Dove, & Maguire, 2005).

Studying electrophysiological responses to speech and non-speech sounds in newborns, Molfece (2000) found three ERP-components which distinguished between children who were diagnosed with dyslexia and children who were classified as normal readers at 8 years of age. Several other ERP-studies have found differences between infants at familial risk for dyslexia and controls in the processing of consonant-vowel syllables (e.g. Gutterm et al., 2001; Leppäinen, Pihko, Eklund, & Lyytinen, 1999; Pihko et al., 1999). Common to these studies is the tendency of right hemisphere dominance in the ERP-responses of the at-risk group and left hemisphere dominance in the typically developing group.

Investigations of electrophysiological responses in children at-risk for dyslexia have tended to focus on very young children (newborns and children in their first year of life) and early ERP components indexing phonological discrimination, such as the mismatch negativity (MMN). Studies of late and mid-latency ERP components, which tend to reflect higher order language processes, would provide information about whether the deficit in dyslexia is restricted to lower level auditory or phonological processing or whether lexical, semantic and syntactic skills are also compromised in early language development.

The N400, a negative ERP component peaking around 400 ms after stimulus onset, has been shown to reflect the processing of semantic information. This component was identified by Kutas and Hillyard (1980) in an experiment where adult subjects were visually presented with the words of a sentence one after each other. The last word of the sentence was either semantically congruous (‘It was his first day at work’), semantically incongruous (‘He spread the warm bread with socks’) or physically deviant (uppercase) (‘She put on her high heeled SHOES’) in the sentence context. Incongruous words elicited a large negative deflection which peaked around 400 ms and which was not found in the two other conditions. In a follow-up experiment, Kutas and Hillyard (1983) observed that the N400 component was evoked by semantic, but not syntactic violations. However, later investigations have shown that the N400 is not simply a response to semantic anomaly, as it is also found in response to single words in the absence of a sentence context, where it is larger to infrequent than frequent words (Bentin, Kutas, & Hillyard, 1995) and reduced by repetition of a word (Van Petten, Kutas, Klunder, Mitchiner, & Mcisaac, 1991). Taken together, experimental results imply that the N400 reflects at least two factors: (1) the cost of semantic integration into context and (2) the ease of accessing information from long-term memory (Kutas & Federmeier, 2000). Although the N400 was first shown in a visual paradigm, extensive research in the last two decades has demonstrated that the N400 can be elicited in a variety of modalities, including the auditory (Connolly & Phillips, 1994; Holcomb, Coffey, & Neville, 1992).

Developmental studies of school-age children have shown that both the amplitude and the peak latency of the N400 tends to decline with age (Coch, Maron, Wolf, & Holcomb, 2002; Friedman, Sutton, Putnam, Brown, & Erlenmeyer-Kimling, 1988; Hahne, Eckstein, & Friederici, 2004; Holcomb et al., 1992; Juottonen, Revonsuo, & Lang, 1996). Recently, an N400-like component has also been demonstrated in toddlers and pre-school children (Friedrich & Friederici, 2004, 2005a, 2005b, 2005c, 2006; Mills, Conboy, & Paton, 2005; Silva-Pereyra, Klarman, Lin, & Kuhl, 2005; Silva-Pereyra, Rivera-Gaxiola, & Kuhl, 2005; Torkildsen et al., 2006). Three of these studies compared groups of varying language ability, and found a relation between language skills and the N400-like response: Friedrich and Friederici (2004) showed that when a group of 19-month-olds was split at the median of word comprehension abilities, the low comprehension group displayed only a small and late-coming N400-like incongruity effect concentrated in the left hemisphere, while the high comprehension group showed a large incongruity effect present in both hemispheres and appearing at approximately the same latency as the adult N400. In a similar design, but where children were grouped according to productive vocabulary size, Torkildsen et al. (2006) found that in 20-month-olds with a low productive vocabulary the N400-like incongruity response occurred later and was more concentrated to the left hemisphere than in 20-month-olds with a high produc-
tive vocabulary. A recent longitudinal study by Friedrich and Friederici (2006) demonstrated that the presence of an N400 component at 19 months was associated to later language development. Children with very low scores on the sentence or word production parts of a German language test at 30 months, did not display an N400 at 19 months, while children with age-appropriate language scores at 30 months did show an N400 at this age.

A number of investigations of the N400 component in dyslexic adults and reading-age children have shown abnormalities compared to fluent readers, such as delayed latencies (Brandeis, Vitacco, & Steinhausen, 1994; Helenius, Salmenlin, Service, & Connolly, 1999 (magnetoencephalography study); Neville, Coffey, Holcomb, & Tallal, 1993), reduced amplitude and concentration to frontal areas (Stelmack & Miles, 1990) or elevated amplitudes (Robichon, Besson, & Habib, 2002).

However, it should be noted that a recent study did not find differences between dyslexic and normal children in the N400 response, but did find abnormalities in earlier ERP-components (Bonte & Blomert, 2004).

The present study aimed to investigate whether children at familial risk for dyslexia display early lexical-semantic processing deficits by examining the N400 component. In two experiments, one cross-modal visual-auditory and one unimodal auditory, children at-risk for dyslexia and typically developing controls were compared with regard to this component. On the basis of the behavioral and electrophysiological studies described above, we expected children at-risk for dyslexia to display a lower speed or accuracy in lexical processing than children without such risk. This deficient lexical processing might lead to difficulties with semantic processing in listening comprehension, and may thus manifest itself in a latency delay in the N400 response, or even an absence of the N400 component altogether.

The first experiment used a word-picture paradigm to assess lexical-semantic processing in 20-month-olds and resembled behavioral object-naming tasks in which dyslexic children have been shown to perform poorly (Faust et al., 2003; Nation, 2005; Nation et al., 2001; Snowling et al., 1988; Swan & Goswami, 1997). In the present study, however, no behavioral response on the part of the participants was required. Moreover, the experiment had a comparable design to a series of picture-word priming studies used to investigate semantic processing by Friedrich and Friederici (2004, 2005a, 2005b, 2006).

As the first experiment employed a cross-modal design with words and pictures, it could not distinguish between cross-modal integration problems and lexical-semantic processing deficiencies as explanations for differences between at-risk children and controls. Although there are a number of studies pointing to a lexical processing deficit in dyslexia (Beaton, 2004; Nation et al., 2001; Snowling et al., 1988), there is also some recent evidence that adult and school age dyslexics have a cross-modal temporal processing deficit compared to normal controls, and that combined demands from cross-modal and linguistic processing may give rise to a cumulative deficit (Cestnick, 2001; Laasonen, Tomma-Halme, Lahtinen, Service, & Virtu, 2000; Laasonen, Service, & Virtu, 2002; Meyler & Breznitz, 2005). In order to control for effects of cross-modality on ERP differences between at-risk children and controls, a second unimodal experiment was conducted with 24-month-old children. This experiment was a simple semantic priming task where participants were auditorily presented with pairs of basic level words which were either semantically related or unrelated. As no image-based processing or cross-modal integration was involved, experiment 2 allowed a more concentrated focus on differences in lexical-semantic processing between at-risk children and controls than experiment 1.

2. Experiment 1: Cross-modal presentation

2.1. Methods

2.1.1. Participants

Twenty-seven typically developing children (12 girls and 15 boys) and 9 children at familial risk of dyslexia (5 girls and 4 boys) participated in the study. All subjects were recruited through newspaper advertisements. Participants were healthy, full-term (>36 weeks of gestation) 20-month-olds (±14 days) from monolingual Norwegian-speaking homes and had no known visual, hearing, or neurological deficits. While the 27 typically developing children had no family history of dyslexia or other language impairments, the criterion for being included in the at-risk group was having at least one parent with dyslexia diagnosed during the school years and reading problems that persisted into adulthood. For two of the at-risk children both parents were diagnosed with dyslexia, and six of the at-risk children had least one other close family member who was affected (close family member is defined here as siblings of the child, siblings of the child’s parents, and the child’s grand parents). All affected parents were diagnosed with dyslexia by the municipal school authorities during primary or secondary school and reported that they were still experiencing reading difficulty at the time when their child participated in the study. An additional 16 children were excluded from the study due to refusal to wear the electrocap (N = 5), or too few artifact-free trials (N = 11). A full analysis of the results for the typically developing children is given in a separate article.

Parents completed the Norwegian adaptation of the MacArthur–Bates Communicative Development Inventory (MCDI) (Fenson et al., 1993; Smith, unpublished) no more than one week prior to testing. The one-week criterion was set to ensure that EEG-measures and parental report of vocabulary size would reflect the same stage in language development. In addition, parents answered a questionnaire about the pregnancy, birth, and illnesses as well as possible disabilities of the child. As a study by Snowling (2000) shows that the education level of the mother is one of the most important environmental predictors of later reading performance, we also included questions about parents’ educational background.

In a univariate ANOVA with total productive vocabulary according to the MacArthur–Bates CDI as a dependent vari-
able and group (at-risk and control) as a fixed factor there was no statistically significant difference in vocabulary between the two groups of children \((F(1,35) = 2.01, p = .17)\). However, it should be noted that the means of total productive vocabulary still differed substantially between the groups. The typically developing children had a mean productive vocabulary of 139 words (range from 7 to 419 words, SD = 130), and at-risk children had a mean vocabulary of 64 words (range from 16 to 160 words, SD = 44).

The mean number of years of education beyond primary school was only slightly lower for parents of children in the at-risk group (mothers 7.3 years, SD = 2.4; fathers 6.6 years; SD = 3.4) than parents of children in the control group (mothers 7.8 years, SD = 2.2; fathers 7.2 years, SD = 2.7).

2.1.2. Materials

The stimulus material consisted of 90 Norwegian basic level nouns taken from the Norwegian adaptation of the MacArthur Communicative Development Inventories \((\text{Fenson et al., 1993}; \text{Smith, unpublished})\). The words can be grouped into the following six categories: animals (30 words), food items (19 words), clothes (13 words), body parts (16 words), furniture (7 words), and vehicles (5 words). Words were chosen with the expectation that 20-month-olds would understand practically all of them. The mean duration of the words was approximately 700 ms (range 351–975 ms). Ninety color drawings were used to illustrate each of the basic level words.

The auditory stimuli were spoken in a female voice, digitized at 16 bits, 44.1 kHz sampling rate, and presented at an intensity of 70 dB SPL.

2.1.3. Procedure

The presentation lasted 8 min. Each picture was shown on the screen for 3000 ms, and after 1800 ms a word was presented auditorily. The inter-trial interval was 1000 ms. Each word had one of three types of relation to the picture content: (1) congruous, control condition \((\text{e.g. picture of dog, sound: dog})\), (2) incongruous, within-category violation, i.e. words belonged to the same superordinate level category, but a different basic level category than the picture \((\text{e.g. picture of dog, sound: cat})\), or (3) incongruous, between-category violation \((\text{e.g. picture of dog, sound: car})\).

Every participant was presented with 30 picture-word pairs for each condition. In order to rule out effects for specific words, two different lists of word-picture combinations were created from the same lists of 90 words and 90 pictures. Lists were alternated so that every second child was shown the same combination of stimuli. All pictures and words appeared only once in each list. The words in the three conditions of each list were matched for duration and number of syllables.

2.1.4. EEG-recording

The EEG-recordings took place in a sound-attenuated room. Stimuli were presented on a 30 × 40 cm computer monitor placed approximately 1 m in front of the participants. A curtain blocked every object except the computer from view. Participants were video-monitored during the whole experimental session which lasted approximately 45 min including familiarization, placement of the electrocap, and impedance measures.

Silver–silver chloride electrodes \((\text{EasyCap, Falk Minow})\) 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, A1, A2. The vertical electrooculogram \((\text{VEOG})\) was recorded from electrodes placed above and below the right eye, and the horizontal electrooculogram \((\text{HEOG})\) was recorded from electrodes placed lateral to the left and the right eye. 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.

2.1.5. EEG-analysis

All trials with an amplitude higher than 150 μV or lower than −150 μV were removed. For the remaining trials, the video recording of the participants was used to reject trials where participants were not looking at the screen. Methods which correct the EEG for electrooculogram such as EOG-EEG transfer were not employed, as these techniques have been shown to be unsuitable for children’s EEG \((\text{Somsen & Van Beek, 1998})\). In addition, baseline correction \((\text{pre-stimulus interval})\) and a zero-phase band pass filter from 1 to 20 Hz was applied to the EEG. Epochs of 1250 ms were computed with a pre-stimulus baseline of 100 ms.

There were at least 10 artifact-free trials per condition (mean = 21, SD = 4.7), and the number of accepted trials did not differ significantly between conditions or between at-risk children and normally developing children.

Six regions of interest were used: left frontal (F3 and FC3), right frontal (F4 and FC4), left central (C3 and CP3), right central (C4 and CP4), left posterior (P3 and T5) and right posterior (P4 and T6). These particular six regions were chosen because they correspond to the regions used by \text{Friedrich and Friederici (2004)} in the first study of the N400 in toddlers which had a design comparable to the present study. In addition, data from midline sites \((\text{Fz, FCz, Cz, CPz and Pz})\) and electrodes F7 and F8 were analyzed.

The effects of the experimental manipulation were analyzed in consecutive time intervals of 100 ms duration, from 200 to 1200 ms.

2.1.6. Statistical analyses

In each selected time window and for each group \((\text{at-risk group and control group})\), three-way ANOVAs, with condition \((\text{control condition, within-category violation, between-category violation})\), hemisphere \((\text{left and right})\) and region \((\text{frontal, central and posterior})\) as within-subject factors were conducted using mean amplitude values. Significant interactions were analyzed further by one-way or two-way ANOVAs.

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Planned comparisons were (1) a linear contrast where the control condition > within-category violation > between-category violation (where ‘>’ is used to mean ‘is more positive than’) (2) ANOVA pair wise comparisons of the conditions (control condition vs. within-category violation, control condition vs. between-category violation, and within-category violation vs. between-category violation).

Since visual inspection of the grand averages suggested hemispheric differences with regard to condition, separate two-way ANOVAs with condition and region as within-subject factors were performed for both hemispheres and midline sites.

In order to test the effect of at-risk status on the experimental manipulation, four-way ANOVAs with condition, hemisphere, and region as within-subject factors, and group (at-risk, control) as a between-subject factor were performed.

The Greenhouse–Geisser (Greenhouse & Geisser, 1959) correction was applied when evaluating effects with more than one degree of freedom in the numerator. We report unadjusted degrees of freedom and adjusted $p$ values.

2.2. Results

2.2.1. Comparison of the at-risk group and the whole sample of controls

Fig. 1 shows the grand average ERPs for the control condition, the within-category violation and the between-category violation for children at familial risk for dyslexia. From 200 ms onwards, the control condition and the within-category violation elicited a more negative response than the between-category violation. This pattern was particularly distinct in the 200–400 ms interval where both the control condition and the within-category violation exhibited a pronounced negative peak compared to the between-category violation.

Grand average ERPs for the typically developing children are shown in Fig. 2. There was an early negative peak for all three conditions in the 180–350 ms interval. A marked difference between conditions appeared around 600 ms, and the largest discrepancy between conditions was seen in the 600–700 and 900–1200 ms intervals. On dorsal electrodes a prominent, long-lasting negative wave started around 600 ms for between-category violations in both hemispheres and for within-category violations in the left hemisphere. On frontal electrodes a large negative wave was observed for all three conditions from approximately 700–800 ms onwards.

Visual inspection of individual averages showed that 7 of 9 at-risk children displayed a negativity for the control condition and within-category violation compared to the between-category violation in at least one brain region in the 200–400 ms interval. In the control group, however, only 8 of 27 children exhibited a negativity for these two conditions compared to the between-category violation in the same time window.
As for the later incongruity effect, inspection of individual averages showed that in 2 of 9 at-risk children between-category violations were more negative than the control condition in at least one time window within the 600–1200 ms interval. In comparison, 24 of the 27 control children exhibited a more negative response to between-category violations than the control condition in the same time window. The two at-risk children who displayed an incongruity effect for between-category violations compared to the control condition also displayed a negativity for between-category violations compared to within-category violations in this interval. Between-category violations were more negative than within-category violations in 20 of the 27 control children.

Comparing the at-risk group with the typically developing children in a four-way ANOVA (within-subject factors were condition, hemisphere and region) yielded a significant group × condition interaction in the intervals 300–400 ms, 800–900 ms, and 1100–1200 ms (Table 1). In all these time intervals between-category violations were most positive in the at-risk group and most negative in the typically developing group. In the 500–600 ms interval there was a main effect of group, showing that the ERPs of typically developing children were generally more negative than those of at-risk children.

In the at-risk group, there was no significant effect of condition in a three-way ANOVA (F(2, 8) < 1; ns) or any pair wise comparisons of conditions in any of the selected time intervals. No interactions reached significance. In pair wise comparisons there was, however, a trend indicating that the control condition and the within-category violation were more negative than the between-category viola-
tion in the 200–400 ms intervals ($F(1,8) = 2.22–3.85$, $p = .085–.175$). On electrodes F7 and F8, there was an even stronger trend that the control condition and the within-category violation was more negative than the between-category violation ($F(1,8) = 4.12$ and $4.71$, $p = .077$ and $.062$) in the 200–300 ms interval.

A three-way ANOVA for the control group yielded a significant effect of condition in the 600–700, and 900–1200 ms intervals ($F(2,6) = 3.33–5.57$, $p = .044–.008$). In all these intervals the between-category violation elicited the largest negativity and the control condition was most positive.

### 2.2.2. Comparison of the at-risk group and a low production sub-group of controls

As the differences between the typically developing group and the at-risk group with regard to condition may have been due to a larger (productive) vocabulary in the typically developing group than the at-risk group, we compared the at-risk group to a sub-group of children with a low productive vocabulary, but without a family history of dyslexia. Thus, subjects in the control group were divided into a high production group ($N = 14$) and a low production group ($N = 13$) with the mean of productive vocabulary (97 words) as a cut-off criterion.

Low producers had a mean vocabulary of 37 words and a mean test vocabulary of 8 words, while at-risk children had a mean vocabulary of 64 words and a mean test vocabulary of 16 words. In a univariate ANOVA with total vocabulary as dependent variable and group (low producer, at-risk) as fixed factor, there was a near-significant trend that at-risk children produced more words than low producers ($F(1,21) = 3.23$, $p = .088$).

**Fig. 3** shows the grand average ERPs for the low production sub-group of the typically developing children. Low producers displayed a tendency toward an incongruity effect which peaked around 330 ms, but this effect was only present in left centro-parietal areas. The largest separation between conditions for low producers was in the 1100–1250 ms interval, and the incongruity effect for this group was largest in the left and central areas, and less pronounced in the right hemisphere.

In a four-way ANOVA with condition (control, within-category violation, between-category violation), hemisphere (left and right) and region (frontal, central and posterior) as within-subject factors and group (low production, at-risk) as between-subject factor, there was a significant interaction between condition and group in the 300–400 ms ($F(2,21) = 4.04$, $p < .03$) and 1100–1250 ms ($F(2,21) = 5.74$, $p < .01$) intervals. When groups were tested separately, there was a significant effect of condition ($F(2,12) = 4.80$, $p < .05$) and a significant linear contrast where control > within-category violation > between-category violation ($F(1,12) = 7.48$, $p < .05$) for the low production group in the 1100–1250 ms interval. In the same time interval, there was a tendency in the opposite direction for at-risk children,
with a trend towards a main effect of condition \((F(2,8)=2.10, \ p=.17)\), and a linear contrast where between-category violation > within-category violation > control condition \((F(1,8)=2.61, \ p=.15)\). There were no further significant effects. The condition \times group interaction in the 300–400 ms interval was due to a pattern where the between-category violation elicited the largest negativity in the low production group and the largest positivity in the at-risk group.

2.3. Discussion

2.3.1. Lexical priming effect

Children at-risk for dyslexia generally exhibited a more negative response to the control condition and the within-category violation than the between-category violation. This pattern was particularly apparent in the 200–400 ms interval where both the control condition and the within-category violation exhibited a pronounced negative peak, but these two conditions continued to elicit more negative ERPs than the between-category violation through the whole 1250 ms epoch.

An early or mid-latency negative ERP response has been related to processing of words and word-like stimuli in a number of studies with children from 10 to 20 months of age (Friedrich & Friederici, 2004, 2005a, 2005b, 2006; Kooijman, Hagoort, & Cutler, 2005; Mills, Coffey-Corina, & Neville, 1993, 1997; Mills, Plunkett, Prat, & Schafer, 2005; Molfese, 1989, 1990; Molfese, Wetzel, & Gill, 1993). However, as the experimental paradigms used in these studies are quite heterogeneous, it is difficult to assign one functional interpretation to this response. It appears that the negativity may be modulated by at least four features of word-like 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 familiarity (i.e. current activation in semantic memory, Friedrich & Friederici, 2004, 2005a, 2005b, 2006), and (4) meaningfulness (i.e. whether words are linked to a referent or not, Mills, Coffey-Corina, & Neville, 1997, 2004; Mills, Plunkett et al., 2005; Molfese, 1989).

The only of these four features which can account for the difference between conditions in the present study is lexical priming independently of familiarity, as the assignment of words to either the related or unrelated condition varied between children and all stimulus items were common Norwegian words assumed to be meaningful to the participants. We suggest that the negativity for congruous and within-category picture-pairs compared to between-category pairs results from picture primes facilitating the lexical–phonological processing of words which were related to the picture content.

The interpretation of this negative ERP response as an index of lexical priming is strengthened by the fact that the studies by Friedrich and Friederici (2004, 2005a, 2005b) which had a cross-modal design comparable to the present experiment found a similar lexical priming effect with the same age group. In three experiments investigating processing of picture-word pairs in typically developing children from 12 to 19 months, Friedrich and Friederici found that words which were congruous with the picture content gave rise to an early negativity compared to words which were incongruous with the picture. They interpreted this negativity as the reflection of a priming effect where picture cues facilitated the subsequent phonological–lexical processing of congruous words. In typically developing 12-month-olds the negativity for congruous words was present at frontal, central and temporal electrode sites and lasted from 100 to 500 ms (Friedrich & Friederici, 2005b). In 14- and 19-month-olds, however, the effect was restricted to left lateral frontal and right frontal areas and the 100–400 ms time window (Friedrich & Friederici, 2004, 2005a, 2005b). In addition to the early negativity for congruous words, 14- and 19-month-olds, but not 12-month-olds, displayed a long-lasting N400 effect for incongruous words.

In a recent study using the same cross-modal design, Friedrich and Friederici (2006) investigated whether ERPs at 19 months were related to later language development. More specifically, they retrospectively compared ERPs of children who were found to have very low expressive language scores on the word or sentence production part of a German language test at 30 months (at least one standard deviation below the age norm) to children who displayed age-appropriate productive language abilities at this age. They found that while the negativity for congruous words was spatially restricted to left frontal lateral regions and relatively short-lasting (100–400 ms interval) in the control group, this effect was broadly distributed and temporally extended (100–700 ms) in the low producers. Friedrich and Friederici interpreted this enhanced negativity in children with poor expressive language skills as evidence of more effortful lexical processing in this group.

In the present experiment, the negativities for the control condition and the within-category violations were broadly distributed and long-lasting in at-risk children, and thus similar to the prolonged facilitation effect for lexical processing found in children with poor expressive language skills in the study by Friedrich and Friederici (2006). However, as opposed to the typically developing toddlers in Friedrich and Friederici’s (2004, 2005a, 2005b, 2006) experiments, the control group in the present study displayed no evidence of a picture-induced facilitation effect for lexical processing. In fact, in early time intervals there was a negativity for all three conditions in typically developing children. A possible reason why this early lexical priming effect was not seen in the control group was that it overlapped with the N400-like semantic incongruity response which was somewhat earlier in the present experiment than in the studies by Friedrich and Friederici. For the control group, the N400-like effect was significant in the left hemisphere already from 300 ms in the current study, while it did not reach significance before in the 400–600 ms intervals in Friedrich and Friederici’s experiments. The latency difference for the incongruity effect between the present experi-
ment and those of Friedrich and Friederici may have been due to words being spoken at considerably slower rate in their studies (mean duration of words 1083 ms compared to 690 ms). Slow presentation rates have been shown to increase N400 latencies (Holcomb & Neville, 1991).

In the studies by Friedrich and Friederici (2004, 2005a, 2005b, 2006) the lexical priming effect could be explained as result of identity priming where a picture of a specific basic level object elicited a lexical expectation which in turn facilitated the processing of the upcoming congruous word. These studies contained only two conditions: congruous and incongruous. However, in the current study, which contained three conditions, the facilitation effect in at-risk children was also found for within-category violations, i.e. words which did not refer to the pictured object, but which referred to a semantically related object. Thus, the priming occurring for within-category violations could not be based on identity, but relied on semantic relations between words or concepts. To our knowledge, this type of relatedness priming has not been shown in toddlers before. The observed facilitation effect may either be the result of automatic processes such as spreading activation between semantically related word nodes in a network or a controlled process such as expectancy-based priming (for a review, see Neely, 1991). In expectancy-based priming subjects use primes to generate an expectancy set consisting of potential targets which are semantically related to the prime. Targets included in the expectancy set are recognized more quickly than targets which are not in this set, i.e. the expectation generated by the prime speeds access to the target in the lexical access stage. In adult studies, a priming effect is normally assumed to be the result of controlled rather than automatic processes when the stimulus-onset asynchrony (SOA) between prime and target is long (usually longer than 400 ms) (Neely, 1977; Posner & Snyder, 1975). In the present study, the SOA was 1200 ms and the mean duration of words was 700 ms, meaning that there was a pause of about 500 ms from the offset of the prime to the onset of the target. However, as controlled processing mechanisms are at best partially developed in the tested age-group (Diamond, 2002; Richards, 2003), it is unclear whether the lexical-phonological facilitation effect observed in the current study resulted from controlled or automatic processes.

In the present study, the lexical facilitation response in at-risk children was quite similar for the congruous words (control condition) and the semantically related words (within-category violation). Normally, identity priming produces the strongest effects (Forster, 1998), and one would thus expect to find weaker priming effects for within-category violations than the control condition. One possible explanation for the observed pattern of effects is that the lexical priming induced by the picture was relatively underspecified in the at-risk children. In other words, both the word corresponding to the picture and words which were semantically related to the corresponding word may have been treated as acceptable labels for the referent picture in early time intervals, while words from a different superordinate category were not. We may assume that seeing the picture made the at-risk children activate a cluster of semantically or associatively related words (e.g. words for animals), but that they had difficulty singling out the specific phonological form corresponding to the picture content (e.g. horse). As the target word and other closely related words would have approximately equal activation status, any of these words would be accepted as a label, at least in the initial stages of processing. However, words from a different superordinate category (such as furniture), which have weaker relations with the depicted object, would be significantly less activated, and thus not accepted as a label.

2.3.2. Semantic incongruity effect (N400)

Children in the control group displayed an N400-like incongruity effect for picture-word mismatches, and this negative brain response was larger and earlier for between-category violations than for within-category violations. Children at familial risk for dyslexia, on the other hand, did not show any tendency towards such an incongruity effect. Indeed, in the at-risk group it was the words which were congruous with the pictures as well as the within-category violations which elicited the largest negativity, while the between-category violations generally elicited a positive brain response. When at-risk children were compared to the full group of typically developing children there was a significant interaction between group and condition in several time intervals.

A possible reason for the lack of an incongruity effect in children at-risk for dyslexia was that subjects in the at-risk group had a smaller vocabulary than the subjects in the typically developing group. Therefore, the brain responses of at-risk children were compared with those of the half of the control children who had the lowest productive vocabulary. This low production group had a lower total vocabulary and test vocabulary than the at-risk group. However, differences between controls and at-risk children remained even after the exclusion of the control children with the highest vocabulary. The low production group showed a late-appearing, but statistically significant semantic incongruity response. There was a significant interaction between condition and group in the latest time intervals, where the low production group displayed an incongruity response, while at-risk children displayed a larger negativity for congruent words and within-category violations than between-category violations. Since children without risk for dyslexia but with smaller vocabularies did show an incongruity response, this suggests that a possible processing deficit for lexical-semantic information in at-risk children is larger than what can be predicted from vocabulary size.

The absence of N400 component in 20-month-olds at-risk for dyslexia is in line with the longitudinal study by Friedrich and Friederici (2006) (see Sections 1 and 2.3.1) which showed that a group of children who were classified as having poor expressive language skills at age 30 months...
did not show an N400 at 19 months while children with a typical language development at 30 months did display an N400 eleven months earlier. Previous studies by the same authors have shown that an N400 component can be identified in picture-word match/mismatch tasks in 14-month-olds (Friedrich & Friederici, 2005a), but that 12-month-olds do not appear to show an N400 in such tasks (Friedrich & Friederici, 2005b). These results suggest that the lack of an N400 for the at-risk group in the present experiment represents a developmental delay.

A conceivable explanation for the differences between at-risk children and typically developing children in the present experiment may be deficiencies in cross-modal processing and integration in the at-risk group. A number of recent studies have found a cross-modal temporal processing deficit in dyslexic adults and school age children, and also that combined demands from cross-modal and linguistic processing may give rise to a cumulative deficit (Cestnick, 2001; Laasonen et al., 2000, 2002; Meyler & Breznitz, 2005). In order to investigate whether the observed ERP differences between children at-risk for dyslexia and controls would remain even when the cross-modal integration part of the task was removed, a unimodal experiment was conducted.

3. Experiment 2: Unimodal auditory presentation

3.1. Methods

3.1.1. Participants

Seventeen normally developing children and 9 children at familial risk for dyslexia participated in the experiment. Of these, 15 of the normally developing children and six of the at-risk children also took part in experiment 1. Controls and children at-risk for dyslexia were selected by the same criteria as in experiment 1. One of the children in the at-risk group had two parents diagnosed with dyslexia, while six of the children had at least one close family other than the parents who was diagnosed with dyslexia. Subjects were 24 months (±14 days) at the date of testing. Eight additional children were excluded from the data analysis due to refusal to wear the electrocap (N = 1) or too few artifact-free trials in one of the experimental conditions (N = 7). A more elaborate report of the control group data is given in a separate article (Torkildsen et al., submitted for publication).

Participants in the present experiment were four months older than the subjects in experiment 1. The reason for this was that these two experiments formed part of a larger design where data on language and communicative comprehension were collected from 20-, 24- and 28-month-old children. Some of the participants underwent EEG-testing at all three ages, while others were only tested at one or two of these ages.

Parents completed the same questionnaires as in experiment 1. According to parental report, children in the final sample had a mean productive vocabulary of 249.7 words (SD = 183.5 words, range from 52 to 646 words). In a univariate ANOVA with productive vocabulary as dependent variable and group (at-risk, control) as fixed factor, there was a statistically significant effect of group (F(1,26) = 5.31, p = .032), showing that controls produced more words (mean 337.7, SD = 198.3) than at-risk children (mean 174.6 words, SD = 89.9). However, there was no significant difference between groups in experimental vocabulary (F(1,26) < 1, ns), with controls producing 64% and at-risk children producing 53% of the words used in the experiment. A possible reason why groups differed significantly in total vocabulary and not in experimental vocabulary is that experimental vocabulary was selected among the items of the MCDI which were judged by the experimenters to be the most commonly known words in the relevant age-group. Subjective judgment had to be used since the Norwegian adaptation of the MCDI is not standardized. The large productive vocabulary differences between the at-risk group and the control group prevented the possibility of singling out a sub-group of controls which had a total vocabulary size comparable to that of the at-risk children.

The mean number of years of education beyond primary school was somewhat lower for parents in the at-risk group (mothers 7.1 years, SD = 2.2; fathers 6.4 years, SD = 3.3) than in the control group (mothers 7.8 years, SD = 2.2; fathers 7.7 years, SD = 2.4).

3.1.2. Materials

Stimuli were 70 of the 90 words used in experiment 1 from the following six categories: animals, food items, clothes, body parts, furniture, and vehicles. The words had a mean duration of approximately 700 ms (range 351–975 ms).

3.1.3. Procedure

Participants were presented with 70 word-pairs which were divided into two prime-target conditions: (1) the two words were from the same superordinate category (related targets, e.g. dog–horse) (2) the two words were from different superordinate categories (unrelated targets, e.g. dog–car). An identity condition comparable to the control condition in experiment 1, where the same word served as both prime and target, was not included in experiment 2 because it would not have been a functional counterpart to the control condition (picture of a dog, sound: dog) in experiment 1. More specifically, an identity condition in the auditory modality would not have allowed discrimination of the effect of repetition and the effect of semantic identity.

Each child was presented with a randomized mix of word pairs were half related and half were unrelated. Each of the 70 words appeared once as the prime and once as the target in a word pair.

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’ll 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, and then the screen went blank and there was a pause for 1000 ms before the prime was presented. The 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 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.

3.1.4. EEG-recording and analysis

The EEG was recorded with the same electrodes and settings as in experiment 1.

Baseline correction (prestimulus interval) and a zero-phase band pass filter from 0.3 to 20 Hz were applied to the EEG. Filter settings were different than in experiment 1 because data from the present experiment contained fewer artifacts and thus allowed a lower high pass filter. However, data from the present study was contaminated by slow DC shifts to a larger degree than data from experiment 1. A possible reason for this difference was that visual stimuli were present simultaneously with the auditory stimuli in experiment 1, leading to relatively focused eye-movements, while in the present experiment there were no visual stimuli presented along with the auditory stimuli, resulting in less focused and more wide-ranging eye-movements which may have been responsible for slow drifts on some electrodes. In order to remove slow DC shifts from the waveforms, a linear detrend procedure was performed on each epoch and each channel. Epochs of 1200 ms were computed with a pre-ear detrend procedure was performed on each epoch and focused and more wide-ranging eye-movements which may presented along with the auditory stimuli, resulting in less while in the present experiment there were no visual stimuli experiment 1, leading to relatively focused eye-movements, were present simultaneously with the auditory stimuli in possible reason for this difference was that visual stimuli were present simultaneously with the auditory stimuli in experiment 1, leading to relatively focused eye-movements, while in the present experiment there were no visual stimuli presented along with the auditory stimuli, resulting in less focused and more wide-ranging eye-movements which may have been responsible for slow drifts on some electrodes. In order to remove slow DC shifts from the waveforms, a linear detrend procedure was performed on each epoch and each channel. Epochs of 1200 ms were computed with a pre-stimulus baseline of 100 ms.

Each experimental condition contained at least 20 artifact-free trials (mean 27.5, SD = 2.6). There was no difference between conditions or between at-risk children and normally developing children in number of accepted trials.

After visual inspection of the data, nine regions of interest were chosen for the analyses: left frontal (F3 and FC3), midline frontal (Fz and FCz), right frontal (F4 and FC4), left central (C3 and CP3), midline central (Cz and CPz), right central (C4 and CP4), left parietal (P3), midline parietal (Pz), and right parietal (P4). While the regions of interest in experiment 1 were based on those used by a similar experiment (Friedrich & Friederici, 2004), there was no precedent in the child ERP literature for the present experiment, allowing a different selection of regions. As the effect of the experimental manipulation was evident on all dorsal electrodes, three midline regions were included in the analysis in addition to those used in experiment 1.

3.1.5. Statistical analyses

As in experiment 1, mean amplitude values were calculated for each combination of electrode and experimental condition in every 100 ms time interval from 200 ms to 1200 ms. In each time period, three-way ANOVAs with semantic relatedness (related and unrelated), electrode site (frontal, central and parietal) and laterality (left, midline and right) as within-subjects factors were carried out for each of the groups. In addition four-way ANOVAs with semantic relatedness, electrode site and laterality as within-subjects factors and group (at-risk and control) as between-subject factor were performed. Significant interactions were followed up by one and two-way ANOVAs. Otherwise statistical analyses were conducted and reported in the same way as in experiment 1.

3.2. Results

Grand-average waveforms for children at-risk for dyslexia showed a positive peak for both conditions around 150 ms and a subsequent negativity for related targets compared to unrelated targets in the 300–600 ms interval (Fig. 4). Around 650 ms the response to unrelated words was more negative than the response to related words, and this differentiation between conditions lasted until approximately 800 ms. The negativity for unrelated targets appeared earlier and was more prominent at left and central than right electrode sites.

Typically developing children displayed a positive deflection around 150 ms comparable to that of at-risk children (Fig. 5). However, the negativity for related words in the control group emerged already around 200 ms, and lasted only until approximately 450 ms. In the 500–800 ms time window, there was a prominent component where unrelated words elicited a more negative response than related words, especially at left frontal and central electrode sites. The most striking differences between the grand averages for the at-risk group and the control group was that the negativity for related compared to unrelated targets was larger and temporally more extended in the at-risk group than in controls, while the opposite was the case for the subsequent negativity for unrelated compared to related targets.

The fact that the early negativity for related words lasted much longer in the at-risk group than in the control group, could either be due to greater variability in the onset of this component in at-risk children or that the component generally occupied a longer time span in the at-risk group. To assess these two different explanations, individual data were inspected, supporting the latter hypothesis: All 9 at-risk children displayed a negativity for related words, and for 7 of these 9 children the component was prominent in all three 100 ms intervals from 300 to 600 ms. However, for only two children did the component appear before 300 ms. In comparison, 13 of the 17 controls displayed a negative component for related words, and for 11 of these 13 the component was most prominent in the 200–300 ms interval. Only three of the controls still showed a negativity for related words in the 400–500 ms interval.

As for the later negativity for unrelated compared to related words, inspection of individual data showed that 7
of 9 at-risk children showed this pattern in frontal and central brain regions. In three children the effect was largest in the 600–800 ms time interval, while in four children the effect was most prominent in the 800–900 ms interval. Fifteen of 17 control 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, and two children did not show a negativity for unrelated compared to related targets.

Four-way ANOVAs with semantic relatedness (related and unrelated), electrode site (frontal, central and parietal) and laterality (left, midline and right) and group (at-risk and control) as between-subjects factor yielded a significant interaction between semantic priming and group in the 200–300, 400–500 and 500–600 ms time intervals (Table 2).

For typically developing children related targets were significantly more negative than unrelated targets in the 200–300 ms interval, but there was no effect in this direction in later time windows. In at-risk children there was no trend towards a negativity for related words in the 200–300 ms interval ($F(1,8)=0.118$, $p=.740$). However, from 400 to 600 ms related targets were more negative than unrelated targets in at-risk children, while in the same time intervals unrelated targets elicited the largest negativity in controls at midline frontal and left frontal sites.

Only in the 600–700 ms time window was there a main effect of semantic priming for the whole sample of children where unrelated targets were more negative than related targets. Separate analyses for the two groups showed that this effect was broadly distributed in controls, but only reliable in the left hemisphere for the at-risk group.

3.3. Discussion

3.3.1. Lexical priming effect

Both at-risk children and controls showed an early negativity for related compared to unrelated targets. In controls, this negativity appeared early and was relatively short-lasting, reaching significance only in the 200–300 ms interval. For at-risk children, on the other hand, this negativity did not appear until 300–400 ms and was statistically significant in the whole 400–600 ms time period.

As in experiment 1, the early negativity for related words appeared to reflect a lexical priming effect where lexical–phonological processing was facilitated for words which were semantically related to the prime. The fact that this component was early and short-lasting in controls, and later and longer-lasting in the at-risk group suggests that the onset of the phonological–lexical processing stage may have been delayed, and its duration may have been longer, in the at-risk children than in controls. This finding is in accordance with a study by Friedrich and Friederici (2006) which found that a lexical facilitation effect resulting from cross-modal identity priming was temporally extended in language delayed compared to typically developing 19-month-olds (see Section 2.3.1.).
Both groups of participants displayed an N400-like effect for unrelated compared to related targets. This finding is in line with several similar semantic priming studies of adults which have found an N400 for unrelated compared to related target words in purely auditory as well as visual and cross-modal tasks (Anderson & Holcomb, 1995; Holcomb & Anderson, 1993; Holcomb & Neville, 1990). However, while the N400-like component for unrelated targets already appeared around 400 ms at frontal sites in the

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**3.3.2. Semantic priming effect (N400)**

Table 2

<table>
<thead>
<tr>
<th>Time</th>
<th>Priming effect whole sample $F(1,26)$</th>
<th>Priming effect at-risk children $F(1,8)$</th>
<th>Priming effect typically developing children $F(1,16)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F$-value</td>
<td>Direction of effect</td>
<td>$F$-value and region</td>
</tr>
<tr>
<td>0–100</td>
<td>3.42</td>
<td>$p = .077$</td>
<td>6.56**</td>
</tr>
<tr>
<td>100–200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200–300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300–400</td>
<td>5.89**</td>
<td>Related more negative</td>
<td>Frontal midline: 5.24*</td>
</tr>
<tr>
<td>400–500</td>
<td>8.48***</td>
<td>Related more negative</td>
<td>Frontal midline: 8.40*** left frontal: 5.93**</td>
</tr>
<tr>
<td>500–600</td>
<td>15.51***</td>
<td>Related more negative</td>
<td></td>
</tr>
<tr>
<td>600–700</td>
<td>5.25*</td>
<td>Unrelated more negative</td>
<td>Left hemisphere: 9.40**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significant interactions between semantic priming and group, and effects of semantic priming for the whole sample of children, as well as for the at-risk and the control groups separately. Where an effect was only significant for a specific brain region this is specified above the $F$-value. Time intervals from 700 to 1200 ms are left out as there were no significant effects in this period.

* $p < .05$.
** $p < .03$.
*** $p < .01$. 

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control group, it did not emerge before approximately 600 ms in the at-risk children. The N400-like negativity lasted until about 800 ms in both groups, and thus occupied a shorter time-interval in the at-risk group than in the control group. A possible reason why the N400-like priming effect had a shorter duration in at-risk children is that this component overlapped with the lexical facilitation effect for related words which was later and temporally more extended in at-risks than in controls. Another group difference was that the N400-like effect was significant only in the left hemisphere in children at-risk for dyslexia, but was broadly distributed in controls. Both these findings are compatible with earlier N400-studies of this age-group by Friedrich and Friederici (2004) and Torkildsen et al. (2006), where 19- and 20-month-olds with a low productive vocabulary showed a late N400 restricted to the left hemisphere, while the effect was earlier and broadly distributed, even slightly right-lateralized, in toddlers with a higher vocabulary. Whether the group differences in the N400-like effect in the present study were due to a smaller total vocabulary in the at-risk group or to the risk-status independently of vocabulary, cannot be concluded from the results of experiment 2, as the discrepancy in vocabulary between the two groups was so large that it was impossible to find a subgroup of controls that matched at-risk children on total vocabulary. However, differences between the two groups did not seem to be due to experience with specific words, as test vocabulary was comparable between at-risk children and controls.

4. General discussion

4.1. Comparison of results from experiments 1 and 2

The present study aimed to investigate whether children at-risk for dyslexia display deviant lexical and semantic processing in the second year of life by examining the N400. Two experiments found significant differences between children at-risk for dyslexia and typically developing controls with regard to this component. Additionally, both experiments found differences between the two groups in another component, an early appearing negativity for words which were congruous with or related to a prime. A similar negativity has been interpreted as a lexical priming effect in several studies with the same age group (Friedrich & Friederici, 2004, 2005a, 2005b, 2006).

In experiment 1 the lexical priming effect was found as a separate component only in the at-risk group, while it appeared to overlap with the N400 component in the control group. While there was a significant N400-effect for controls, no such effect, or trend towards an effect, could be seen in the at-risk group in experiment 1. As children in the at-risk group had a smaller productive vocabulary than controls, at-risk children were compared with a sub-group of controls with a similar vocabulary size. However, differences between the two groups still remained in the comparison of at-risks and low vocabulary controls. In experiment 2, both groups of participants displayed the lexical priming effect and the N400 component. However, the onset of both these responses was delayed in the at-risk group compared to the control group.

Experiments 1 and 2 differed with respect to stimulus modality. Experiment 1 was a cross-modal study with picture-word pairs. As no N400 effect could be identified in the at-risk group in this study, a second experiment was designed to test whether the lack of an N400 in at-risk children could be due to cross-modal integration difficulties. In experiment 2, where semantic priming was assessed in a unimodal auditory task, an N400-like effect was found in children at-risk for dyslexia, showing that this component can be elicited also in at-risk children, at least at the age of 24 months. However, differences between at-risk children and controls in lexical-semantic processing were still present in experiment 2. Consequently, it is improbable that group differences in experiment 1 could be explained only in terms of cross-modal integration deficiencies in the at-risk group.

The patterns of group differences found in the two experiments have several similarities. In both studies the lexical priming effect was more prominent in the at-risk group than in controls: In experiment 1 there was a marked lexical priming effect in the at-risk group, while this effect appeared to overlap with the N400 in controls. In experiment 2 the lexical priming effect in at-risk children appeared later than in controls, but had a much longer duration. Conversely, the N400-like effect was less prominent in children at-risk for dyslexia than in controls in both experiments: In experiment 1 this component was not observed in at-risk children, while in experiment 2 it appeared later and had a shorter duration than for controls.

The enhanced lexical priming effect in at-risk than control children may be due to slower or more effortful lexical–phonological processing in the at-risk group. Also, the more marked lexical priming in at-risk children may reflect increased reliance on cues (primes) aiding lexical processing. The reduced N400-like effect may consequently be a result of at-risk children spending more processing resources on lexical–phonological processing and therefore having fewer resources left for evaluation of semantic relationships and integration of words into context.

4.2. Comparisons with earlier ERP studies of dyslexic children and adults

It is not straightforward to compare the early appearing negativity indexing facilitated lexical processing in the present study with ERP components found in earlier studies of dyslexics, as it is unclear whether this response has a counterpart in school-age children and adults. Moreover, ERP data on lexical processing in dyslexia are scarce, as studies have tended to focus on perceptual tasks involving discrimination and categorization of speech sounds (for a review, see Lyytinen et al., 2005). However, a study by Bonte and Blomert (2004) which examined recognition of spoken
words in dyslexic children and controls found that the N200 (mean amplitude in the 250–350ms interval) was larger in dyslexics, and interpreted this as a reflection of increased processing effort in the lexical access stage in dyslexic children. This is interesting, as the enhanced N200 found in dyslexics appears to have a functional similarity to the early negativity observed in the present study in indexing lexical–phonological processing. Deviant N200 responses to tones have also been related to reading disability and language impairment in children: Tonquist-Uhlen (1996) found longer latencies for the N200 in 9- to 15-year-olds with a language impairment, and Byring and Järviletho (1985) observed that a prolonged N200 response was positively correlated with spelling errors. Finally, Bernal et al. (2000) found a larger N200 for a pitch change in dyslexic children than in controls.

As for the N400 component, results of the present experiment are consistent with several earlier studies of dyslexic adults and school age children which have found delayed latencies for the N400 (Brandeis et al., 1994; Helenius et al., 1999 (magnetoencephalography study); Neville et al., 1993). While the N400 was clearly delayed in the at-risk children in experiment 2, it is unclear whether this component was considerably delayed or simply absent in experiment 1. Epochs of 1250ms were used in the experiment, and it is possible that the incongruity response was so late in the at-risk group that it did not appear within this time frame. However, a study by Friedrich and Friederici (2006) showed that the mechanisms underlying the N400 need not necessarily be in place by this age in children with delayed or impaired language development. In an experiment using 1600ms epochs, Friedrich and Friederici found no evidence of an N400 in a group of 19-month-olds who were shown to have poor expressive language skills at 30 months, while a control group with age-appropriate language abilities one year later did exhibit an N400 response. In this regard it should also be noted that reduced amplitudes of the N400 in dyslexics have been observed in an adult study (Stelmack & Miles, 1990). Moreover, in a behavioral experiment with poor reading comprehenders and controls, poor readers showed only associative, not semantic priming effects (Nation & Snowling, 1999).

4.3. A naming deficit in dyslexia?

Experiment 1 served as a kind of spontaneous naming task where the N400-like incongruity effect crucially depended on the child forming a lexical expectation (no matter whether this expectation was consciously or automatically generated) from the picture and then assessing the relation between this expectation and the presented word. Since naming skills for pictured objects have been predicted from vocabulary size, which is also in line with earlier evidence (Nation, 2005).

Experiment 2 also assessed lexical expectations generated by previous stimuli, but this time expectations were generated by a word, not a picture. However, at-risk children differed significantly from controls with regard to the N400-like negativity in this experiment as well. Results from experiment 2 thus suggest that a possible deficit in the generation of lexical expectations in children at-risk for dyslexia is not restricted to pictured objects, but rather appears to be modality independent. Moreover, as opposed to experiment 1, where the absence or presence of components was what distinguished the two groups, group effects in experiment 2 were due to latency differences, indicating that processing speed may be one of the important factors distinguishing at-risk children from controls with regard to generating lexical expectations.

Naming speed is, however, a complex measure which is affected by perceptual, lexical–phonological and motoric processes. It has been suggested that it is important to assess whether the naming deficit in dyslexia may be due to a motor programming deficit (Nation, 2005). In the present study, no behavioral or linguistic response on the part of the participants was required, thus the motoric aspect of naming was removed. Differences between at-risk children and controls in the present study consequently appear to be due to either perceptual or lexical–phonological processes. However, results of the current experiment cannot be used to distinguish between these two latter explanations. In this regard, it should be noted that there are two important ongoing debates about the underlying causes of dyslexia. The principal debate concerns whether the deficit in dyslexia is specific to linguistic processing or whether linguistic problems are secondary to lower-level deficits in sensory processing (for recent contributions to the debate, see Bishop, 2006; Goswami, 2006; Nicolson & Fawcett, 2006; Tallal, 2006; White et al., 2006). A second debate concerns whether deficits in phonological processing and naming speed represent independent causes of dyslexia (Vukovic & Siegel, 2006; Wolf et al., 2002). The present study examined only processing of linguistic stimuli, and thus did not attempt to distinguish between explanations in terms of linguistic and lower-level sensory processing as explanations for group differences between children at-risk for dyslexia and controls. Furthermore, no measures intended to separate naming processes from phonological processes were included, and therefore results cannot be used to illuminate a possible independent contribution of naming speed to the deficits in dyslexia.

However, regardless of the underlying causes of dyslexia, results of the present experiment suggest that early deficits in children at-risk for dyslexia are not restricted to lower
level auditory or phonological processing, but also extend to higher-order language skills such as lexical and semantic processing.

5. Conclusion

While several previous studies have shown deviations in early event-related potential components reflecting auditory and phonological processing in children at familial risk for dyslexia, there is a lack of data about brain responses indexing processing in other linguistic domains such as lexicon, semantics and syntax from this group. The present study investigated whether toddlers at-risk for dyslexia display atypical brain correlates of lexical and semantic priming.

In experiment 1, a cross-modal paradigm with congruous and incongruous picture-word pairs was used, yielding an N400-like incongruity effect for controls, but no such effect, or trend towards an effect, in children at-risk for dyslexia. Moreover, at-risk children showed a prominent early negativity for words which were related to the picture, indicating facilitated lexical–phonological processing of primed words, while this effect appeared to overlap with the N400 effect in controls. Differences between controls and at-risk children still remained when at-risk children were compared to a sub-group of controls with a lower mean vocabulary, suggesting that the deficit in at-risk children was larger than what could be predicted from vocabulary size. As differences between at-risk children and controls could be due to cross-modal integration problems in the at-risk group, a second unimodal auditory experiment was conducted to separate effects of cross-modality and lexical–semantic processing. In experiment 2 both groups of participants displayed the lexical–phonological priming effect and the N400 incongruity response. However, the onset of both these components were significantly delayed in the at-risk group compared to the control group. Thus, it is unlikely that the group differences in Experiment 1 could be explained only in terms of cross-modal integration deficiencies in the at-risk group.

Results of the present study suggest that early deficits in children at-risk for dyslexia are not restricted to lower level auditory or phonological processing, but also involve higher-order language skills such as lexical and semantic processing. In this regard, results are in line with earlier behavioral studies which have found a naming deficit in school-age children with dyslexia.

References


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