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Substantial gains in word learning ability between 20 and 24 months: A longitudinal ERP study ☆

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ABSTRACT

This longitudinal ERP study investigated changes in children's ability to map novel words to novel objects during the dynamic period of vocabulary growth between 20 and 24 months. During this four-month period the children on average tripled their productive vocabulary, an increase which was coupled with changes in the N400 effect to pseudoword-referent associations. Moreover, productive vocabulary size was related to the dynamics of semantic processing during novel word learning. In children with large productive vocabularies, the N400 amplitude was linearly reduced during the five experimental learning trials, consistent with the repetition effect typically seen in adults, while in children with smaller vocabularies the N400 attenuation did not appear until the end of the learning phase. Vocabulary size was related only to modulation of the N400 to pseudowords, not to real words. These findings demonstrate a remarkable development of fast mapping ability between 20 and 24 months.

1. Introduction

As children approach their second birthday, most of them undergo an increase in the rate of vocabulary acquisition (Fenson et al., 1994), often termed the "vocabulary spurt". In this longitudinal ERP study, we sought to capture age-related changes in children's ability to learn new object-word relations during the dynamic period of language development between 20 and 24 months. Moreover, we investigated how differences in word processing during learning related to individual differences in vocabulary size.

It is often assumed that the vocabulary spurt marks a transition between two distinct stages of vocabulary acquisition, a change which has been attributed to qualitative changes such as the emergence of certain word learning constraints (Markman, 1990, 1992), or the shift from associative to referential acquisition (Nazzi & Bertoncini, 2003; Nazzi & Pilardeau, 2007), to mention only a few hypotheses. This account has been challenged by modeling showing that vocabulary growth is often continuous rather than discontinuous (Ganger & Brent, 2004), and it has been proposed that improvements in domain-general learning abilities can account for the observed acceleration in word learning (Mayor & Plunkett, 2010; McMurray, 2007). The fact remains, however, that vocabulary learning typically undergoes a dramatic acceleration in the end of the second year, and without assuming two distinct stages of learning, we will use the term vocabulary spurt to describe this acceleration. Improving our understanding of the mechanisms driving this acceleration remains an important focus of language acquisition research.

A possible contributor to the vocabulary spurt is the emergence of the ability to map a novel word to its referent from only a few exposures, a process called *fast mapping* (Carey & Bartlett, 1978; Friedrich, 2011). Fast mapping abilities are readily apparent at the end of children's second year, and the ability has been shown to emerge already around children's first birthday (Friedrich & Friederici, 2008; Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998; Woodward, Markman, & Fitzsimmons, 1994). Current evidence suggests that the ability to learn words from limited exposure starts to develop around six months, although at this point word retention is very weak (Friedrich & Friederici, 2011). Following this, fast mapping ability continues to grow more efficient and refined, with longer and better retention, up until at least 2½ years of age (Bion, Borovsky, & Fernald, 2013).

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1.1. ERP studies of fast mapping and vocabulary development

Electrophysiological studies have successfully used the N400 component to investigate the fast mapping process. The N400 is a component modulated by lexical priming and/or ease of integration into semantic context, and is elicited by words as well as other meaningful stimuli (for reviews, see Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008). Supporting semantic contexts that create an expectation of an upcoming stimulus attenuate the N400 amplitude, which indicates facilitation of lexical-semantic processing (Kutas & Hillyard, 1980). The component has been observed from 6–9 months of age in picture-word congruity paradigms (Friedrich & Friederici, 2011; Junge, Cutler, & Hagoort, 2012), but continues to mature up until around 19 years of age (Atchley et al., 2006; Holcomb, Coffey, & Neville, 1992; Juottonen, Revonsuo, & Lang, 1996).

The use of the picture-word congruity paradigm is suitable for studying the process of fast mapping. When children are shown pictures of unfamiliar objects which are paired with an unfamiliar pseudoword, it is possible to test the child's ability to map the novel word to the object after a certain number of presentations. After familiarization, an incongruity effect on the N400 component indicates successful fast mapping. Using this paradigm, it has been shown that 20-month-olds with large productive vocabularies produce an N400 incongruity effect to newly learned pseudowords presented with incorrectly paired novel objects (Torkildsen et al., 2008). In this study, each pseudoword was presented with the same novel object five times in a learning phase, and the test phase followed immediately at the end of each learning block. Twenty-month-olds with smaller vocabularies did not show an effect of incongruity on the N400 amplitude for pseudowords, although they did produce such an effect in the control condition using real familiar words and objects. Using a similar task with lower demands (more learning trials and a slower pace), Friedrich and Friederici (2008) demonstrated that even 14-month-olds could successfully map novel pseudowords to constantly paired objects and retain this representation for at least a day. This was seen in a larger N400 response to pseudowords presented with incongruous objects compared to the consistently paired object. A modified setup of this experiment was used with 6-month-olds and found evidence of learning the pairings between novel words and objects during the familiarization phase (Friedrich & Friederici, 2011). However, the 6-month-olds did not produce an N400 incongruity effect one day later as the 14-month-olds did.

Many other picture-word matching experiments have used real word/object stimuli familiar to young children rather than novel objects and pseudowords. Several of these studies have found interesting links between N400 responses and children's vocabulary development. In one experiment, 12-month-olds who had high productive vocabularies for their age displayed N400 effects, while those with lower productive vocabularies did not produce an effect even for words their parents had rated as comprehended by the child (Friedrich & Friederici, 2010). Another study found that the lack of an N400 effect at 19 months predicted poor expressive language skills at 30 months (Friedrich & Friederici, 2006). In a task adapted for younger infants, 9-month-olds' receptive vocabulary was found to correlate with the size of an N400 effect (Junge et al., 2012). The lack of an N400 effect in 20-month-old children with familial risk for dyslexia, compared to a control group, has also been demonstrated (Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007a). A similar paradigm using purely auditory word pairs as stimuli (Rämä, Sirri, & Serres, 2013) found a relation between N400 responses and productive vocabulary size. Together, these findings suggest that the mechanism behind the N400 response is related to efficient word processing. However, the study by Torkildsen et al. (2008) described above is the only one reporting a relation between vocabulary size and the N400 incongruity effect to newly learned pseudowords. The use of pseudowords and fantasy objects is important if one wants to control for individual differences in previous exposure to word and picture stimuli, and the types of representations that children might already have begun to build up based on these experiences.

1.2. Modulation of ERP responses during word familiarization and learning

The most commonly reported ERP component to show effects of repetition during word or pseudoword familiarization is a frontal negative component known as the N200-500, most commonly conceptualized as reflecting processes of word form recognition (Friedrich, 2011). This component is enhanced in response to known words compared to unknown words (Mills, Coffey-Corina, & Neville, 1993, 1997), and has been found to emerge for originally unknown words as these are repeated and become more familiar (Kooijman, Hagoort, & Cutler, 2005). The above findings were from unimodal experiments involving only words, but a few picture-word priming paradigms have seen a similar effect of an increased early negativity during familiarization with novel words paired with pictures (Friedrich & Friederici, 2011; Junge et al., 2012). Additionally, several studies have found an effect of congruity where words presented with congruous pictures elicited a larger N200-500 compared to incongruous words (Friedrich & Friederici, 2004, 2005a, 2005b, 2006). The N200-500 word familiarity effect in infants has been shown to be related to measures of language development, such as vocabulary size (Junge, Kooijman, Hagoort, & Cutler, 2012; Kooijman, Junge, Johnson, Hagoort, & Cutler, 2013).

Another study, based on the same experiment as Torkildsen et al. (2008), also focused on the dynamics of the learning phase, and demonstrated a relation between vocabulary size and the modulation of the ERP response to the novel words during learning (Torkildsen et al., 2009). Children with smaller vocabularies and no evidence of fast mapping in the test phase, showed a different pattern of repetition effects in the training phase than children with larger vocabularies. The familiarization process was reflected in a modulation of a fronto-central negativity, which appeared to increase in amplitude until a certain level of encoding was reached, and then decrease with further repetition. The children with low vocabularies, however, did not reach a stage of attenuation of the negative amplitude due to repetition. This negative component was interpreted as an Nc, a component seen specifically in infants and young children in response to several types of stimuli, but most commonly visual stimuli. It is commonly viewed to reflect attentional processing, where novel and salient events typically result in an increase in amplitude (Courchesne, 1978; Csibra, Kushnerenko, & Grossmann, 2008; Richards, Reynolds, & Courage, 2010), and stimulus familiarization or repetition leads to a decrease in amplitude (e.g. Quinn, Westerlund, & Nelson, 2006). While the N200-500 component is elicited by word stimuli specifically, and is believed to be associated with word form processing, the Nc component seems to reflect more general cognitive mechanisms that are involved in many different types of tasks.

Although the N400 has been studied extensively in infants and young children with regards to semantic incongruity, it is unclear how this component changes during the learning process. Especially in a picture-word matching paradigm where words are given a clear meaning, one would expect to see changes in N400 amplitude as children learn the associations between the picture and the word. In adults, the N400 is attenuated with repetition for both real words and for pseudowords that presumably do not activate a semantic representation (e.g. Deacon, Dynowska, Ritter, & Grose-Fifer, 2004; Doyle, Rugg, & Wells, 1996; Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991). N400 repetition effects for words have been reported in school-aged children as well, and this effect seems to grow stronger with age (De Bruin, Martens, Glimmerveen, & Van Strien, 2008; Van Strien, Glimmerveen, Martens, & De Bruin, 2009). While most of the word learning or word familiarization studies on infants have reported mainly frontal or fronto-central effects, and not any clear N400-effects due to repetition, Friedrich and Friederici's (2011) study with 6-month-olds did find a parietal reduction in negativity in the second part of the training phase for words that had been constantly paired with an object compared to words paired with different objects. They interpreted this as an N400 effect showing that the children learned the semantic relation between the word and the object. Other studies of infants and young children have not reported changes in N400 amplitude with familiarization. The critical difference between the N200-500 component and the N400 is that the former does not necessarily involve processing of the relation between the word form and its referent, which in experimental contexts is the semantic representation. Instead this earlier component is mainly modulated by familiarity of a specific phonological form, regardless of its meaning. The N400 component, on the other hand, is primarily affected by the semantic context, which either facilitates lexical access or makes it more difficult. Therefore, changes in the N400 component during repeated word-object presentations should be more indicative of successful formation of an associative memory representation encompassing the word and the object.

1.3. Purpose and hypotheses

The research results presented above suggests that the N400 incongruity effect is a sensitive measure of fast mapping ability. It also seems that measures of change in ERP responses during familiarization and learning can capture individual differences in the learning process due to either age or vocabulary. The purpose of the present study was to investigate the development of electrophysiological responses during fast mapping with a longitudinal design spanning the period in the second year where most children undergo a rapid acceleration in vocabulary growth. To this end, we employed the same paradigm as Torkildsen et al. (2009) and Torkildsen et al. (2008). In this paradigm pseudowords are linked to novel pictures through repeated co-presentation, and subsequently the picture-word associations are switched, eliciting an N400 incongruity response in children who have learned the mappings. In addition, real familiar words and their referents were presented in the same way. Torkildsen et al. (2008) found that 20-month-olds with high productive vocabularies, but not those with low productive vocabularies, showed evidence of successful fast mapping as measured by an N400 incongruity effect to the pseudowords after five learning trials. Both groups, however, produced an N400 effect in the real word condition. A follow-up test at 24 months would be able to show whether these individual differences persist even after the most dynamic time period of the so-called "vocabulary spurt". There have been no longitudinal studies presenting a pseudoword learning experiment to children at two time points around this age. Our first hypothesis was that the size of the N400 incongruity effect to newly learnt pseudowords would predict vocabulary only at 20 months, when many children would still be in an early, slower period of vocabulary development. By 24 months, however, many children with low vocabularies would likely have undergone an acceleration of vocabulary growth and, although their vocabularies would still be relatively small, may have attained fast mapping abilities like those of the high vocabulary group. This would then be reflected in an N400 incongruity effect which was independent of vocabulary size.

Furthermore, we expected that, when grouping children according to their vocabulary size, we would see group differences in modulation of the N400 component during learning of the pseudowords, which would indicate differences in the process of establishing a link between a novel word and its referent. If such differences were linked to whether or not the child had undergone the vocabulary spurt, then they should be most apparent at 20 months, and group differences should diminish at 24 months when most children would have productive vocabularies above 100 words. By comparing repetition effects on the N400 component with those on the frontal N200-500 component we would be able to determine whether group differences were due to differences in general word processing, such as familiarity with the word form, or semantic processing.

In sum, we had the following hypotheses: (1) that the size of the N400 incongruity effect to newly learned pseudowords would be related to productive vocabulary at 20 months, but not at 24 months, (2) that an N400 incongruity effect to real familiar words would be observed at both 20 and 24 months, (3) that an N200-500 repetition effect would be observed at both ages, independent of vocabulary size or word condition, and (4) that N400 repetition effects during the learning phase would be associated with vocabulary size, primarily at 20 months when a substantial number of children would be at a pre-vocabulary spurt stage.

2. Methods

2.1. Participants

2.1.1. 20 months

A sample of 77 children (36 boys) were recruited and tested at 20 months of age (±3 weeks). The selection criteria were that they were typically developing monolingual Swedish learners born at full term (>36 gestational weeks). Reliable electrophysiological data was obtained from 37 children (17 boys). The remaining participants were excluded from EEG analysis due to fussiness, technical problems, or too few artifact-free trials in one or more of the analyzed conditions. The children were recruited through child health care centers in and around Lund, Sweden, and an information campaign sent by mail to all children in certain areas close to Lund that would fall within the appropriate age range during the study period. The project was granted ethical approval by the Regional Ethical Review Board.

2.1.2. 24 months

The same children that participated at 20 months were invited back at 24 months, and 52 children (24 months ±3 weeks) returned for this second session. In addition, two new children were recruited at 24 months in order to obtain a larger sample size at this age. In total 54 children participated in the 24 month session, and 33 of these were included in the EEG analysis (exclusion from EEG analysis was due to the reasons stated above). Longitudinal ERP data was obtained from 23 participants who fulfilled inclusion criteria at both ages.

2.2. Materials

Different stimulus sets were used in the 20 and 24 months experiments. The auditory stimulus material consisted of 51 common count nouns, 30 used at each time point (15 artifact labels and 15 animal labels) and 60 pseudowords which were phonotactically legal in Swedish (30 at each time point). Thus, there was a slight overlap of nine real words between the two time points, but these words were paired with different picture referents. Parents reported that their children comprehended on average 21 of the

30 stimulus words at 20 months (range = 10–28), and 26 of the words at 24 months (range = 6–30). The auditory material was recorded in an anechoic chamber by a female voice, speaking in an infant-directed manner. The visual stimuli consisted of cartoon images of the objects corresponding to the chosen nouns, and fantasy objects and creatures to be paired with the pseudowords, selected from the web-based collection Clipart (Vital Imagery Ltd.).

Two parent questionnaires were used to assess the children's general level of development: a Swedish adaptation of MacArthur-Bates Communicative Development Inventories (CDI Advisory Board, 2006) – the SECDI (Eriksson & Berglund, 2002) in the "Words and Sentences" version, and the 20 and 24 months versions of a Swedish adaptation of the Norwegian Ages and Stages Questionnaires (ASQ) (Janson & Smith, 2003; Squires, Potter, & Bricker, 1999). The ASQ assesses the infant's level of development in various areas including language and motor development.

2.3. Procedure

Pictures were presented on a 17 inch computer screen (34 × 27 cm) approximately 35 cm from the child, and words were presented from a speaker next to the screen. Children sat on their parent's lap, with a screen placed around them in order to block out distractions. Breaks were taken in between blocks if necessary, with the possibility of showing a short video clip to recapture the child's attention. EEG was recorded with infant versions of the 128 channel Hydrocel Geodesic Sensor Nets (Electrical Geodesics, Inc.) connected to a Net Amps 300, with a sampling rate of 250 samples/s, referenced to the vertex. The child was video recorded throughout the experiment, allowing for exclusion of trials where the child was inattentive.

The stimuli were organized into 10 independent blocks, with each block containing 3 real words and objects and 3 pseudowords and novel objects (see Supplementary Material 1 for a graphical illustration of the experimental design). Each picture-word pair was presented five times in a pseudo-randomized order. The first trial in each block was always a real word, there was at least one interleaved item in between item repetitions, and at most two successive real word trials or pseudoword trials. Each block ended with a test phase, where the picture word pairings were switched. Each word/pseudoword was now presented together with one of the other pictures from the same block, yielding an incongruous pairing. Real objects were always paired with other real words, and fantasy objects with other pseudowords. The test phase also included additional conditions that are not reported in this paper, where modified versions of the original pictures were presented with congruous and incongruous words. These conditions were included to investigate object recognition processes, and results from this study are reported in Borgström, Torkildsen, and Lindgren (2015). Two different trial lists were created, with the same stimuli but in different pairings (for the pseudowords and novel objects) and presentation order. Pictures were presented for 2150 ms, with a word onset of 1000 ms after each picture onset, and an inter-trial interval of 500 ms showing a white screen.

2.4. Analysis

2.4.1. EEG processing

Sections of inattentiveness were rejected from the EEG by viewing the video time-locked to the data. A bandpass finite impulse response filter of 0.3–30 Hz was applied, and 1250 ms epochs time-locked to word onset were created, with a 100 ms pre-stimulus baseline. We used an automatic artifact detection procedure in Net Station 4.5 (Electrical Geodesics Inc.) to mark large artifacts and bad channels (max–min voltage changes 200 μV), and trials with more than 15 bad channels were rejected. All trials were then inspected visually and the artifact identification was adjusted so that artifacts caused by eye blinks and eye movements were left in the data for later correction. Remaining bad channels were replaced using spherical spline interpolation. Data was re-referenced to the average of all electrodes (excluding vertical and horizontal eye electrodes and the nasion electrode). An average reference has been argued to be the best reference choice for high-density recordings since it does not bias the signal relative to a specific reference location (e.g. DeBoer, Scott, & Nelson, 2006; Picton et al., 2000). We used EEGLAB (Delorme & Makeig, 2004) to perform an independent components analysis to identify and remove ocular artifacts, and remaining EEG processing was performed in ERPLAB (Lopez-Calderon & Luck, 2014). Only data from subjects who retained at least ten artifact-free trials per condition were included in the grand average and the statistical analyses. The mean number of accepted trials per condition at 20 months was between 15 and 17 for all analyzed conditions, and between 14 and 16 at 24 months.

To our knowledge, all studies investigating the effects of word familiarization or repetition have used electrode montages with a relatively small number of electrodes referenced to the mastoids (Friedrich & Friederici, 2011; Junge et al., 2012; Kooijman et al., 2005; Mills et al., 1993, 1997; Torkildsen et al., 2009). Since this reference site is relatively close to the brain areas generating the N400 (see Kutas & Federmeier, 2011; Lau et al., 2008 for discussion on possible sources of the N400), it is possible that this procedure limits the potential to detect more subtle modulations of the N400. It has been shown that components that have a posterior-temporal distribution (as the N400) are enhanced in amplitude when applying an average reference compared to a linked mastoids reference, while frontal components are larger in amplitude using a linked mastoids reference (Abrams, Westerlund, Hersey, Gustafson, & Nelson, 2004, in DeBoer et al., 2006). The use of an average reference is generally argued to be advantageous, given a large enough number of electrodes, since it "unconfounds estimates of the amplitude and topography of components with the location of the reference electrode" (DeBoer et al., 2006, p. 15). By using a high-density montage and applying an average reference, we hope to be able to better separate the frontal N200-500 component reported in many previous studies and the N400, and investigate whether word and pseudoword repetition affects the N400 in infants in a similar way as in adults.

2.4.2. Statistical analysis

Children were divided into two productive vocabulary groups according to a median split, and this was used as a between-subject factor in all statistical analyses. Nine regions of interest (ROI), each including six electrodes, were selected that covered left, midline, and right sections of frontal, central, and parietal regions. The mean amplitude for the six electrodes in each ROI was used in the statistical analyses (channel layout and ROIs can be seen in Supplementary Material 2). Our hypotheses concerned ERP components that generally emerge between 200 and 800 ms, so statistical analyses focused on this segment of the ERP. This segment was divided into 200 ms consecutive time windows for initial omnibus repeated measures analyses of variance (ANOVAs): 200–400, 400–600 and 600–800 ms. The mean amplitude within each time window was used as a statistical measure. Due to the considerably larger sample sizes that contributed reliable data at each age compared to the sample that contributed data at both time points, our analyses were primarily conducted on each age group separately. However, when results seemed to differ between the age groups, analyses were followed up with an analysis of the longitudinal sample in order to confirm an effect of age. Results from omnibus level ANOVAs on the longitudinal sample are provided in Supplementary Material 3.

For the effect of repetition during the learning phase, repeated measures ANOVAs were performed with Word Type (2 levels: real word, pseudoword), Repetition (5 levels), Region (3 levels) and Laterality (3 levels) as within-subject factors, and Vocabulary group (2 levels) as a between-subject factor, for all three time windows and both age groups separately. For the effect of congruity, the same procedure was performed, replacing the Repetition factor with a Congruity factor (2 levels). The incongruous trial in the test phase was compared to the final (5th) congruous trial, at which point the picture-word associations would be best established.

Follow-up analyses were directed to best capture the two components of interest. The earliest 200–400 ms time window was used to test the frontal N200-500 word familiarity effect, and the two later time windows were collapsed to 400–800 ms to test for the N400 component of semantic processing. This division was chosen based on previous findings in this age group (e.g. Friedrich, 2011; Friedrich & Friederici, 2004, 2010; Torkildsen et al., 2008), as well as visual inspections of the waveforms. The results section includes ERP waveforms from selected channels in the ROIs, but detailed topographies in all conditions can be viewed in Supplementary Materials 4–9. The follow-up analyses were performed on the two word types separately, at specific electrode regions. In general, only significant effects and certain effects approaching significance ($p < .100$) that include the repetition or congruity factors are reported. An alpha-level of .05 was used for all statistical tests. The Huyn–Feldt correction was used when the assumption of sphericity was violated, and in these cases unadjusted degrees of freedom and adjusted p-values are reported

3. Results

3.1. Developmental data

Data from the parent questionnaires are presented in Table 1. The productive vocabulary groups were formed according to a median split at each age. At 20 months, the median in the ERP sample corresponded well with the population median (Eriksson & Berglund, 2002). The low vocabulary group had a maximum score of 58 words, which is around the common 50- to 75-word threshold often associated with a marked acceleration of productive vocabulary growth. At 24 months, the sample median was higher (around the 65th percentile) than the estimated population median. Development of ASQ scores followed the same general pattern, where the sample scores were placed below population medians at 20 months, and above at 24 months (Janson & Smith, 2003). Since this data comes from two different samples, we compared these results with those from the longitudinal sample. The longitudinal sample showed a similar pattern, with slightly higher results compared to the reference groups at 24 months than at 20 months, although the longitudinal sample had a median productive vocabulary of just over the 50th percentile (81 words), which was slightly higher than the entire 20 month sample. At 24 months, the longitudinal sample scored a median in the 70th percentile. Overall, the data suggest that the present sample had a steeper growth curve than the reference groups.

3.2. Results from overall ERP ANOVAs

The overall effects of repetition and congruity were tested in three 200-ms time windows, for each age group separately.

3.2.1. Effects of repetition

As shown in Table 2, effects of repetition were similar at both ages, a main effect of repetition in all three time windows, and consistent interactions with region. In general, amplitudes over frontal and central regions became more negative with repetition, while over parietal regions they were not consistently affected in the earliest time window, but became less negative from 400 ms onward. Real words and pseudowords did not elicit different repetition effects in either time window.

3.2.2. Effects of congruity

Congruity effects differed at 20 and 24 months. At 20 months, the first effects of congruity appeared in the 600–800 ms time window, and there was no main effect of congruity, but an interaction with word type that indicated an incongruity effect only for real words. There was also an interaction with region such that parietal regions showed the largest difference in amplitude between congruous and incongruous presentations. At 24 months, however, there was a significant interaction between congruity and region already in the 200–400 ms time window. Moreover, there was a main effect of congruity from 400 to 800 ms, as well as several interactions with region and word type. These interactions indicated that for pseudowords there was a larger negativity to

Table 1
Developmental data.

Scale	Measure	Full sample				ERP sample			
		n	Median	Mean (SD)	Range	*n*	Median	Mean (SD)	Range
20 months									
ASQ	Communication	74	45 (39)	41.89 (13.96)	5–60	37	45	40.95 (14.66)	5–60
ASQ	Gross Motor	74	60 (100)	54.32 (7.95)	25–60	37	55	53.24 (8.18)	30–60
ASQ	Fine Motor	74	50 (39)	49.93 (9.12)	30–60	37	55	44.05 (9.37)	30–60
ASQ	Problem Solving	74	45 (35)	43.45 (7.76)	25–60	37	45	44.05 (7.06)	35–60
ASQ	Personal/Social	74	50 (46)	49.46 (7.66)	30–60	37	50	49.46 (7.80)	35–60
SECDI	Prod. Vocabulary	74	66 (45)	110 (112)	0–514	37	79	95 (88)	7–299
LV group	Prod. Vocabulary					18	27	30 (17)	7–58
HV group	Prod. Vocabulary					19	188	219 (129)	79–514
24 months									
ASQ	Communication	54	55 (48)	52.13 (11.06)	20–60	33	60	53.64 (10.18)	20–60
ASQ	Gross Motor	54	60 (100)	55.65 (5.99)	35–60	33	60	55.76 (6.75)	35–60
ASQ	Fine Motor	53	55 (58)	53.02 (6.23)	35–60	32	55	53.28 (6.17)	35–60
ASQ	Problem Solving	53	50 (56)	48.40 (9.29)	25–60	32	50	50.00 (8.03)	30–60
ASQ	Personal/Social	54	50 (52)	50.37 (6.86)	35–60	33	50	50.00 (7.40)	35–60
SECDI	Prod. Vocabulary	54	315 (65)	291 (166)	6–605	33	318	293 (154)	15–548
LV group	Prod. Vocabulary					17	204	173 (108)	15–318
HV group	Prod. Vocabulary					16	391	421 (68)	342–548

Note. Maximum score on each ASQ subscale = 60. The percentage of children in the Norwegian reference group (for the ASQ), and the Swedish reference group (the SECDI) that scored the same or less than the sample median score for each scale is reported in parentheses next to the full sample median scores.

Table 2
Results from 5-way ANOVAs including all conditions and regions.

20 months	Repetition $F(4,140)$	Repetition × Region $F(8,280)$	Congruity $F(1,35)$	Congruity × Word Type $F(1,35)$	Congruity × Region $F(2,70)$	Congruity × Word Type × Region $F(2,70)$	Congruity × Word Type × Laterality $F(2,70)$
200–400 ms	7.01***(.167)	7.12***(.169)					
400–600 ms	9.57***(.215)	20.68***(.371)					
600–800 ms	7.91***(.184)	23.13***(.398)	.208	7.20*(.171)	6.27**(.152)	3.77*(.097)	7.02**(.167)
24 months	**Repetition $F(4,124)$**	**Repetition × Region $F(8,248)$**	**Congruity $F(1,31)$**	**Congruity × Word Type $F(1,31)$**	**Congruity × Region $F(2,62)$**	**Congruity × Word Type × Region $F(2,62)$**	**Congruity × Word Type × Laterality $F(2,62)$**
200–400 ms	3.47**(.101)	4.47***(.126)	.391	.028	4.06*(.116)		
400–600 ms	4.92**(.137)	9.96***(.243)	4.51*(.127)	.032	3.96*(.113)	9.65**(.237)	
600–800 ms	2.44(p = .054)	12.11***(.281)	9.55**(.236)	.138	4.08*(.116)	8.19**(.209)	

Note. Effect sizes (η_p^2) are reported for significant effects in parentheses next to the *F*-value. We report only non-significant results in cases where interactions with other factors were significant. Only up to 3-way interactions are reported.
* $p < .05$.
** $p \leqslant .01$.
*** $p \leqslant .001$.

incongruous presentations across all regions, while for real words only parietal regions had a larger negativity, while frontal regions had a smaller negativity.

Further analyses, including ERP plots and follow-up statistical tests on specific regions, are presented for each word type separately. This is motivated both by our theoretical hypotheses and the omnibus ANOVAs showing both effects of region and word type.

3.3. ERP responses to pseudowords

3.3.1. Learning phase – effect of repetition

3.3.1.1. 20 months. Over frontal regions there was a positive deflection starting around 200 ms. As the pseudowords were repeated, this deflection was reduced to baseline and then became more negative, as is characteristic for the N200-500 component (see Fig. 1). In the 200–400 ms time window, only frontal regions had a significant effect of repetition, $F(4,140) = 4.82$, $p = .002$, $\eta_p^2 = .121$, with a significant linear contrast $F(1,35) = 16.30$, $p < .001$, $\eta_p^2 = .318$, where the mean amplitude became more negative with repetition. There was no interaction with vocabulary group.

Responses to pseudowords were dominated by a large posterior negativity peaking around 600 ms, typical of the N400 component. There was a significant main effect of repetition at parietal regions between 400 and 800 ms, $F(4,140) = 8.90$, $p < .001$, $\eta_p^2 = .203$, and a significant linear contrast where the mean amplitude became less negative with each presentation, $F(1,35) = 27.41$, $p < .001$, $\eta_p^2 = .439$. Visual inspection suggested that there were differences between the two vocabulary groups in how the parietal negative amplitude was modulated by repetition (see Fig. 1). The most apparent difference was over right parietal channels, where the high vocabulary group (HV) displayed a clear attenuation of the N400 amplitude between the first and the third presentation, while in the low vocabulary group (LV) the amplitude increased between

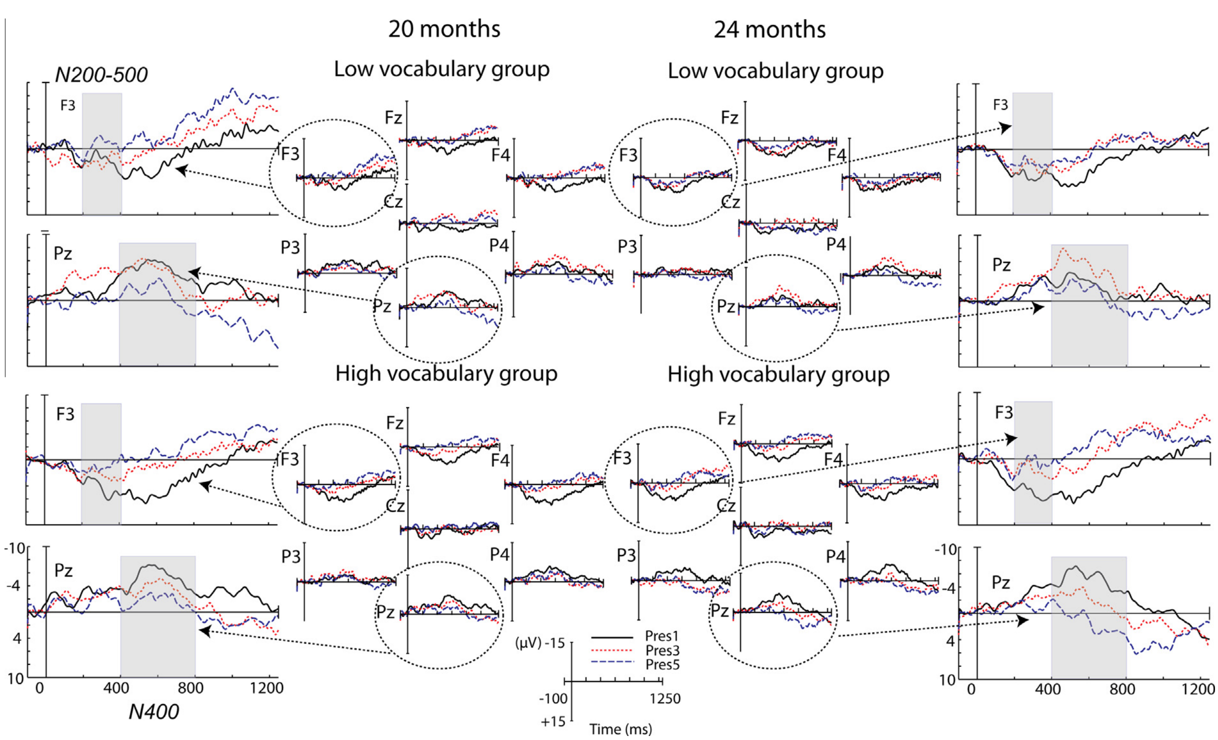

Fig. 1. Pseudowords learning phase. ERPs to the 1st, 3rd and 5th presentations of pseudowords during the learning phase, at both ages and for the two vocabulary groups separately. Grey bars indicate the time window selected to test effects for each component.

these conditions, before starting to decrease after the third presentation. Pairwise comparisons (with a Bonferroni correction) of the first presentation with all subsequent presentations, showed that the HV group had a significant difference already between the first and second presentation ($p = .037$), while the LV group only had significant differences between the first and fourth ($p = .023$) and first and fifth presentations ($p = .001$). In order to investigate the relation between vocabulary size and the change in N400 during the first part of the learning phase, we calculated a difference score for the mean N400 amplitude between the third and the first presentations over right parietal electrodes. This change score correlated with vocabulary size, such that a larger attenuation of N400 amplitude due to repetition was related to a larger vocabulary size, ($r = .347$, $p = .036$).

In order to explore the relation between the two components modulated by repetition, we calculated difference scores between the first and the fifth presentations, capturing the total change in amplitude for each individual participant. The change in amplitude of the N200-500 component (frontal regions between 200–400 ms) correlated significantly with the change in amplitude of the N400 component (parietal regions between 400–800 ms), $r = -.484$, $p = .002$. A larger increase in the N200-500 component was associated with a larger attenuation of the N400 component.

3.3.1.2. 24 months. In the 200–400 ms time window, there were effects of repetition only over frontal regions, $F(4,124) = 3.21$, $p = .017$, $\eta_p^2 = .093$, with a linear contrast, $F(1,31) = 14.33$, $p = .001$, $\eta_p^2 = .316$. The largest effect was between the first and the second presentation, where the mean amplitude became more negative, and then there was a smaller increase in negativity between the third and the fourth presentation (see Fig. 1). There was no interaction with vocabulary group in either time window.

There was a significant effect of repetition across all five presentations over parietal regions between 400 and 800 ms, $F(4,124) = 5.49$, $p < .001$, $\eta_p^2 = .150$, following a linear contrast, $F(1,31) = 10.68$, $p = .003$, $\eta_p^2 = .256$. There was also a near significant interaction between repetition and vocabulary group, $F(4,124) = 2.32$, $p = .061$, $\eta_p^2 = .069$. When inspecting separate grand averages for each vocabulary group, the HV group had a clear reduction in N400 amplitude from the first to the third and to the fifth presentation, while the LV group had an increase in negativity between the first and the third presentation across all parietal regions. The negative amplitude started to decrease after the third presentation (see Fig. 1). Pairwise comparisons (with a Bonferroni correction) of the first presentation with all subsequent presentations, showed that there was a significant difference already between the first and second presentation in the HV group ($p = .006$), while in the LV group the first presentation did not differ significantly from any of the subsequent presentations (difference between 1st and 5th: $p = .884$). The change in amplitude between the first and the third presentations correlated significantly with productive vocabulary ($r = .394$, $p = .023$), as was the case at 20 months.

As at 20 months, a larger increase in the N200-500 component was associated with a larger N400 decrease due to repetition across the five pseudoword presentations, ($r = -.464$, $p = .006$).

3.3.2. Switch phase – effect of incongruity

Pseudowords presented with mismatching pictures, were compared to the fifth congruous presentation. At 20 months, responses did not differ between congruous and incongruous conditions (see Fig. 2). There were no significant effects of congruity at any electrode site, and no interaction with vocabulary size. At 24 months, however, there was a greater negativity to incongruous pseudowords across centro-parietal regions starting from approximately 400 ms. At central sites there was a significant main effect of congruity in the 400–800 ms time window, $F(1,31) = 14.53$, $p = .001$, $\eta_p^2 = .319$, and no interaction with vocabulary group. At parietal regions, there was no significant effect of congruity in the 400–800 ms time window, but since the negativity was long-lasting, we also tested a later time window, 600–1000 ms. Here there was a significant interaction between congruity and laterality, $F(2,62) = 3.66$, $p = .032$, $\eta_p^2 = .106$, and a follow-up analysis showed that the right parietal region had a significant effect of congruity, $F(1,31) = 7.08$, $p = .012$, $\eta_p^2 = .186$. Although the omnibus ANOVA showed a significant interaction between congruity and region already between 200 and 400 ms at 24 months, no region had a significant effect of congruity for pseudowords this early.

Because of the differences between the two age groups, we performed a longitudinal analysis in both time windows on the group of children that contributed data at both time points ($n = 23$), including age as a within-subject factor (2 levels). In the 200–400 ms time window, however, there was no significant interaction between age and congruity, The analysis in the 400–800 ms time window confirmed a significant interaction between congruity and age over central regions, $F(1,22) = 5.524$, $p = .028$,

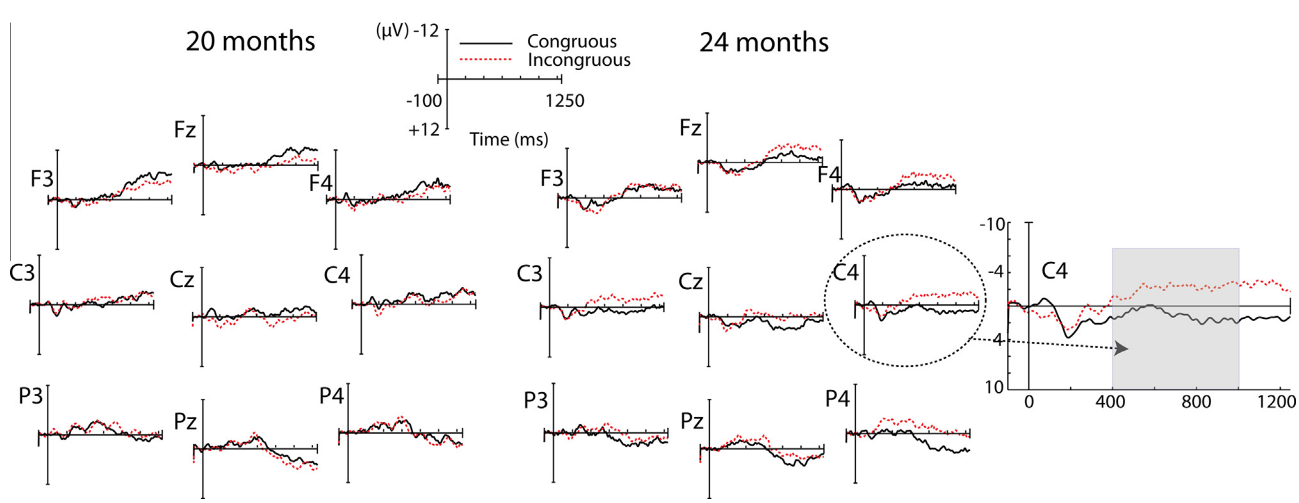

Fig. 2. Switched pseudowords. ERPs to pseudowords presented with incongruous pictures, compared with the final congruous presentation in the learning phase. Grey bars indicate the time window selected to test effects for each component.

$\eta_p^2 = .201$, while there was no main effect of congruity. Follow-up analyses on each age group showed that, as in the whole sample, these longitudinal participants showed no effect of congruity at 20 months, while at 24 months there was a main effect of congruity over central regions, $F(1,22) = 6.90$, $p = .015$, $\eta_p^2 = .259$.

3.4. ERP responses to real words

3.4.1. Learning phase – effect of repetition

3.4.1.1. 20 months. The N200-500 component was seen over frontal channels, as there was a positive wave starting around 200 ms in response to the first presentation, which during successive presentations of the words was reduced to baseline and then became more negative (see Fig. 3). In the 200–400 ms time window, where there was an effect of repetition in the frontal region, $F(4,140) = 5.79$, $p < .001$, $\eta_p^2 = .142$, with no interaction with vocabulary group, and a significant linear contrast, $F(1,35) = 17.24$, $p < .001$, $\eta_p^2 = .330$, as well as a quadratic contrast, $F(1,35) = 7.22$, $p = .011$, $\eta_p^2 = .171$. The quadratic effect was due to a slightly decreased negativity between the third and fifth presentation after an initial larger increase in negativity during the first three presentations.

Over posterior channels words elicited a large negativity peaking around 600 ms, characteristic of the N400 component (see Fig. 3). In the whole sample, there was a significant effect of repetition over parietal regions, where the amplitude between 400 and 800 ms was reduced as words were presented repeatedly, $F(4,140) = 8.82$, $p < .001$, $\eta_p^2 = 0.201$. This effect followed a linear contrast pattern, $F(1,35) = 24.34$, $p < .001$, $\eta_p^2 = .410$. There was also a significant three-way interaction between repetition, laterality and vocabulary group, $F(8,280) = 2.50$, $p = .012$, $\eta_p^2 = .067$. Follow-up tests showed that this interaction concerned the left parietal region, where only the high vocabulary group had a significant effect of repetition, $F(4,72) = 6.55$, $p < .001$, $\eta_p^2 = .267$ (LV group: $F(4,68) = 1.95$, $p = .112$, $\eta_p^2 = .103$). In separate group ANOVAs including all parietal regions, both vocabulary groups had a significant main effect of repetition, LV: $F(4,68) = 3.99$, $p = .006$, $\eta_p^2 = .190$; HV: $F(4,72) = 5.37$, $p = .001$, $\eta_p^2 = .230$. There was no correlation between the early N200-500 effect and the later N400 repetition effect, as was the case for pseudowords at both ages.

3.4.1.2. 24 months. In the 200–400 ms time window, there was no main effect of repetition at any region, but a near significant interaction with laterality over frontal regions, $F(8,248) = 2.07$, $p = .057$, $\eta_p^2 = .063$. The effect of repetition was only significant at right frontal electrodes, $F(8,248) = 2.69$, $p = .036$, $\eta_p^2 = .080$. There was a significant effect of repetition over parietal regions between 400 and 800 ms, $F(4,124) = 3.68$, $p = .007$, $\eta_p^2 = 0.106$, where the mean amplitude became less negative with repetition, confirmed by the linear contrast, $F(1,31) = 12.06$, $p < .002$, $\eta_p^2 = .280$. There was no interaction with vocabulary group. In contrast to the measures at 20 months, the early frontal repetition effect was correlated with the N400 attenuation, in the same way as for pseudowords ($r = -0.436$, $p = 0.011$).

3.4.2. Switch phase – effect of incongruity

Words presented with mismatching pictures were compared to the fifth congruous presentation in the learning phase. At both ages incongruous words elicited a large negativity over posterior sites peaking around 600 ms (see Fig. 4). The effect of congruity between 400 and 800 ms was significant over parietal regions at both ages (20 months: $F(1,35) = 7.92$, $p = .008$, $\eta_p^2 = .185$; 24 months: $F(1,31) = 17.60$, $p < .001$, $\eta_p^2 = .362$). There was no interaction with vocabulary group at either age. A longitudinal analysis including age as a within-subject factor confirmed that

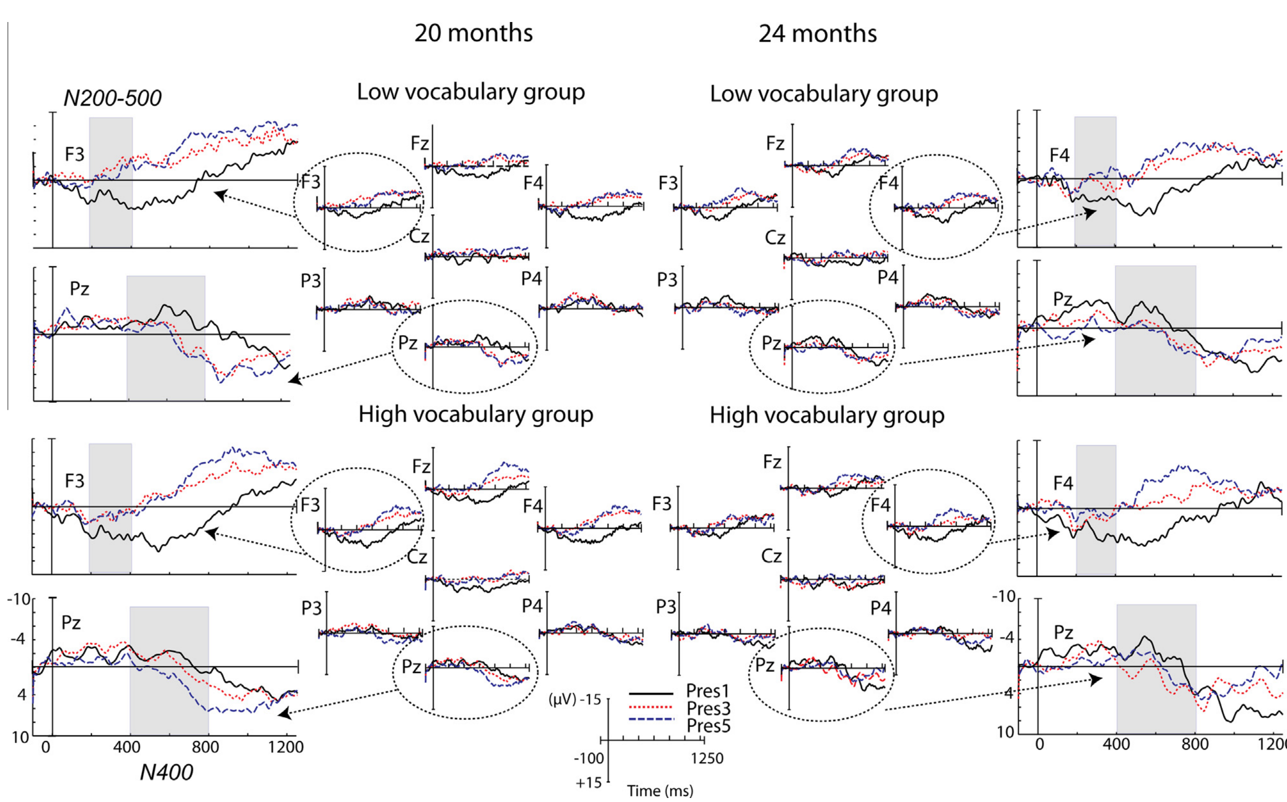

Fig. 3. Real words learning phase. ERP responses during the learning phase to presentation 1, 3 and 5 of real words. Grey bars indicate the time window selected to test effects for each component.

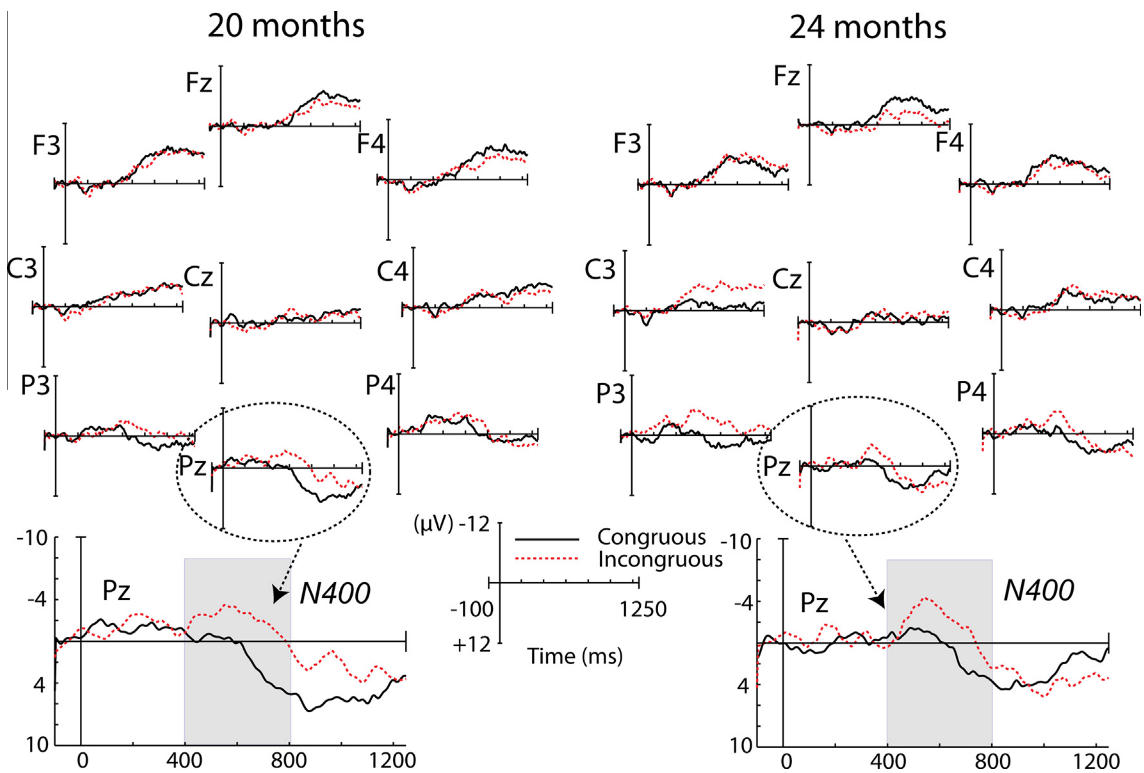

Fig. 4. Switched words. ERPs to real words presented with incongruous pictures, compared with the final congruous presentation in the learning phase. Grey bars indicate the time window selected to test effects for each component.

there was no interaction between age and congruity, but instead a strong main effect of congruity over parietal regions in the 400–800 ms time window, $F(1,22) = 16.53$, $p = .001$, $\eta_p^2 = .429$. As for pseudowords, there was no effect of congruity at any region in the 200–400 ms time window, despite an interaction between congruity and region at 24 months in the omnibus ANOVA. There was also no interaction between age and congruity between 200–400 ms, when performing a longitudinal analysis.

4. Discussion

4.1. Development of novel word-object mapping from 20 to 24 months

The 24-month-olds in this study differentiated between congruous and incongruous pairings of the pseudowords, indicating that they had successfully mapped the novel pseudowords to the novel objects after five exposures. However, there was no such effect at 20 months, suggesting that at this age the children did not fully learn the associations between the novel pseudowords and their referents. Thus, in only four months the children clearly improved in fast mapping ability. This effect of age was not due to sample differences, since the pure longitudinal sample showed the same pattern of development as the full sample. Surprisingly, the response to incongruity was not related to vocabulary size as in Torkildsen et al. (2008), where children with large vocabularies at 20 months did show an N400 incongruity effect when associations between novel pseudowords and referents were broken. However, an N400 effect was seen in response to familiar real word-object pairs at both ages, demonstrating that the N400 mechanism with regards to word stimuli was in place, as many other studies have previously established (e.g. Friedrich & Friederici, 2008; Junge et al., 2012; Torkildsen et al., 2008). This incongruity effect for real words was also independent of vocabulary size. The vocabulary groups in Torkildsen et al.'s (2008) study followed a 75-word cutoff, which corresponded to the median-split in the present study. Thus, the present study's lack of effect of productive vocabulary on the N400 response in 20-month-olds cannot be due to differences in vocabulary size compared to the previous study (Torkildsen et al., 2008).

It seems reasonable to interpret the incongruity effect to the pseudowords, with its parietal peak around 600 ms, as an N400 response. However, the topography also showed a more temporally sustained negativity over central regions to the incongruous pseudowords compared to the real word condition. The central incongruity effect was statistically significant in an earlier time window than the effect over parietal regions, which was not significant until after 600 ms. That pseudowords elicited a later parietal incongruity effect than real words seems reasonable considering that the pseudowords were newly learnt, and would be expected to be processed more slowly. The central distribution may indicate involvement of additional processes in response to the newly learned pseudowords, perhaps associated with enhanced attention. The negative central (Nc) component is a commonly observed response modulated by attention, novelty detection and saliency in young children (see de Haan, 2006 for a review), and might be present in the 24 month sample's response to the incongruous pseudowords. Although the children established a mapping between the pseudowords and the novel objects, these associations are likely to be weak compared to the previously familiar real words and objects. If the children were not confident about the pseudowords' referents, they might have responded with increased attention to incongruous presentations because they continued to process these stimuli in an attempt to integrate them into the context. This would explain that the central negativity to incongruous pseudowords was sustained throughout the epoch, without a return to baseline. In comparison, when a dog is labeled "car" it might be so obviously incorrect that the children dismiss it more rapidly. This interpretation is reasonable even without assuming the involvement of an additional component, the Nc. Instead, it is possible that the extra resources required to process the novel pseudowords simply generate an N400 component with a more widespread topography.

A question that arises is why the 20-month-olds in this experiment did not respond to the incongruity in the pseudoword condition when a sample of the same age in Torkildsen et al. (2008) did, as well as even younger children in a similar paradigm (Friedrich & Friederici, 2008). In Friedrich and Friederici's (2008) study, where 14-month-olds produced an N400 to newly learned pseudowords, a larger number of learning trials were used and there were also fewer words to be learned (8 trials, and only 8 consistent word-object association) which reduces the demands compared to the present study. Although five learning trials were used in the current experiment just as in Torkildsen et al. (2008), the presentation rate was faster, with a 500 ms inter-trial interval (ITI) compared to 1000 ms ITI used in both Torkildsen et al. (2008) and Friedrich and Friederici (2008). Speed of word processing is a measure of linguistic maturity, and thus a faster presentation rate may have presented too much of a challenge to the younger children's processing capacities (see Fernald & Marchman, 2012; Fernald, Perfors, & Marchman, 2006). We also only presented one incongruous trial per item in the test phase, while the previous experiment included two trials per item. This, along with the additional trials presenting modified pictures in the test phase (see the methods section) may have increased the demands in this experiment and made it too difficult for the 20-month-olds to build up specific expectations about which words would follow each picture.

Vocabulary size was not related to the magnitude of the N400 incongruity effect in any of the conditions in this experiment. Previous research have reported mixed results, with some studies showing that better language skills in young children were related to a larger N400 semantic priming effect to real words (Friedrich & Friederici, 2004, 2006, 2010; Junge et al., 2012; Rämä et al., 2013; Torkildsen et al., 2007a), while others report no such relation (Friedrich & Friederici, 2005a; Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007b; Torkildsen et al., 2008). Similarly, studies using eye tracking measures of word comprehension have shown that differences in the efficiency of online processing of real words are associated with differences in vocabulary size (e.g. Fernald & Marchman, 2012; Fernald et al., 2006). Torkildsen et al. (2008) is the only study to report a correlation between productive vocabulary and an N400 effect to newly learned pseudowords specifically. The difference in demands of the task is the most likely explanation that this result was not replicated. At 20 months, the task was probably too difficult for most of the children, regardless of vocabulary size, while at 24 months, it is possible that most children had attained a similar ability of fast mapping, such that vocabulary size was no longer a relevant dimension of differentiation. Even the low vocabulary group at 24 months had a quite substantial productive vocabulary, with a mean of 173 words. Only four subjects at 24 months had vocabularies under 75 words, which is considered a common milestone of the vocabulary spurt. According to our hypothesis that receptive fast mapping ability is a relevant factor underlying the acceleration of productive vocabulary growth that takes place around 75 words, we had not expected a relation between vocabulary size and an N400 effect to newly learned pseudowords at 24 months. Moreover, individual differences in productive vocabulary size are caused by many factors other than fast mapping ability, such as language exposure, and even if receptive fast mapping ability is one contributing factor, it may be outweighed by others.

The data on vocabulary size, as well as general development measured by the ASQ, indicated that the children participating in this study had a slightly steeper growth curve than the reference groups for the instruments. Particularly, they advanced from vocabularies around the 50th percentile at 20 months to the 70th percentile at 24 months. This may be associated with the relatively high educational level of the parents that chose to participate. It is possible that this accelerated growth curve influenced the results in the sense that the neural changes we see in four months in the present sample may be somewhat more protracted in a sample with an average vocabulary growth.

4.2. Dynamics of word familiarization

During familiarization of both real words and pseudowords, repetition affected the same two components. The first was an early frontal response starting around 200 ms, which can reasonably be interpreted as an N200-500 component. There was an initial positivity in response to the first presentations of both words and pseudowords which changed to an increased negativity as the stimuli were repeated. This effect is in line with results from previous studies (Friedrich & Friederici, 2011; Kooijman et al., 2005; Mills et al., 1993, 1997) and is commonly interpreted as an effect of word form recognition and facilitated lexical-phonological processing following familiarization (see Friedrich, 2011 for a review). However, in addition to word form processing, the N200–500 component has been linked to semantic processing, as it in some cases has been sensitive to word-object incongruity (Friedrich & Friederici, 2004, 2005a, 2005b, 2006). This was not the case in the present study, however. At 20 months, there was a strong linear repetition effect for both real words and pseudowords. At 24 months, on the other hand, most of the increase in negativity happened between the first and the third presentation, with a weaker effect of subsequent repetitions. This could mean that, with age, the children reached a certain level of familiarity or recognition of the stimuli in fewer presentations. A recent study demonstrated that a faster emerging word familiarization effect in infants is associated with better word processing skills 6 months later, which supports the idea that this is a measure of word processing maturity (Junge & Cutler, 2014). However, in the present study there was no effect of vocabulary group on any of the N200–500 effects, which indicates that children with small and large productive vocabularies were similarly able to recognize the words and pseudowords after a first presentation. Previous studies have shown a link between a stronger word familiarization effect and language skills, but these studies have involved younger infants, below 12 months (e.g. Junge et al., 2012; Kooijman et al., 2013). It is possible that individual differences in this component decrease with age, resulting in the word familiarity effect in older infants being less associated with vocabulary skills.

A parietal negativity with a peak around 600 ms, characteristic of the N400 component, was also modulated by repetition. For real words, the negative amplitude of this component was attenuated with repetition independent of vocabulary size, and the linear repetition effect was stronger (had considerably larger effect size) at 20 months than at 24 months. At 24 months, the difference between the first and subsequent word presentations was smaller, suggesting that the words were comprehended and processed fairly easily already at the first presentation. This is reasonable given the picture-word priming paradigm, where pictures of known objects functioned as primes for the upcoming words. Presumably, the older children had stronger semantic representations of the real words used in the experiment, and therefore even the first presentation of the object functioned well as a prime for the word. This also indicates that the real word condition involved a greater amount of learning at 20 months, where each presentation served to further strengthen the association between the object and the word.

At both ages, the modulation of the N400 component in response to repetition of pseudowords differed depending on the children's vocabulary size, shown by a direct correlation between N400 attenuation and vocabulary size. While children with larger vocabularies displayed a clear linear reduction in N400 amplitude to pseudowords (the same pattern as for real words), children with smaller vocabularies displayed an initial increase in negativity over primarily right parietal electrodes up to the third presentation, and then a subsequent decrease in negativity. Statistically, in the high vocabulary group already the second presentation of the pseudowords elicited a lower N400 amplitude than the first presentation, while in children with low vocabularies the effect of repetition on the N400 did not appear until the fourth presentation at the earliest. This suggests that children with large vocabularies reached a certain level of encoding of the pseudowords, or mapping between the novel object and pseudoword, in fewer trials than those with smaller vocabularies. Assuming the standard interpretation of the N400 amplitude where larger amplitude reflects greater effort in semantic processing/access (e.g. Kutas & Federmeier, 2011; Lau et al., 2008), then children with larger vocabularies reached a level of less effortful processing in fewer trials than children with smaller vocabularies. This parallels recent findings on the N200–500 component in 10-month-olds showing that infants displaying more mature word familiarity effects reached a level of word recognition in fewer trials than infants with less mature responses (Junge & Cutler, 2014). The present study's results indicate that in this sample of older children, similar differences in modulation of the N400 component are related to language skills. Despite this association between vocabulary size and N400 modulation, we cannot draw any conclusions regarding the causal relationship. As with all correlational results, it may be that a quicker N400 attenuation facilitates word learning and therefore leads to larger vocabularies, or a larger vocabulary could itself lead to improved word processing skills, including semantic processing, which would be expressed by the N400 attenuation. Moreover, the N400 attenuation may be an indication of general brain maturation which could also facilitate vocabulary growth.

This effect of vocabulary size on ERP modulation during novel object-pseudoword learning is in line with the results from Torkildsen et al.'s (2009) study. However, in that study the patterns and topographies of the repetition effects were different. Children with low vocabularies showed a pattern of continuously increasing negativity due to repetition starting from 200 ms after word presentation, while the high vocabulary group showed an initial increase in negativity followed by a decreased negativity after the third presentation. This pattern was mainly seen over frontal and central electrodes and was interpreted as an Nc component indicating a decrease in attention in the high vocabulary group following a certain level of encoding. What these two data sets have in common is that children with smaller vocabularies did not display an attenuation of negative amplitude to the same extent as those with larger vocabularies. The differences in topography between the two studies can likely be found in the different choices of reference. In the present study, it was possible to choose an average reference due to the large number of electrodes. This may have enabled the clear effects over parietal regions, a region where Torkildsen et al. (2009) did not find significant effects of repetition. Whether the N400-like effect in the present study is analogous to the component interpreted as an Nc in Torkildsen et al. (2009), or whether these studies have captured functionally different processes, is difficult to determine. However, since the effect of repetition began around 400 ms over parietal channels (but earlier on frontal channels), and the negative component that peaked around 600 ms resembled the component elicited by incongruity in the switch phase, it seems reasonable to interpret our results as a modulation of the N400 component during learning.

The correlation between the N200-500 component and the N400 component during familiarization of novel words indicates that the two components are present within the same individuals. Children who had a larger word familiarization effect were more likely to show a larger attenuation of the N400 due to repetition. Such a relation between these two components has not been reported previously, and suggests that a more efficient processing of the word form is associated with facilitated semantic processing. In the younger age group, this association was only relevant for pseudowords, while in the older group the two components were related during both novel and familiar word processing.

An interesting aspect of our results is that vocabulary size was related only to modulation of the N400 to pseudowords, not to real words, and not to modulations of the frontal N200-500 component. Thus, the link between the two components is only partial. This suggests that toddlers with different vocabulary sizes processed and recognized the actual lexical item similarly, but differed more in semantic processing (pseudoword-object pairing). In this paradigm the effect of mere repetition of the words and pseudowords cannot be separated from the priming effect of the picture on the word/pseudoword. Thus, the modulation of ERPs during familiarization will likely depend both on stimulus repetition, i.e. decreased novelty of the stimuli, and on a build-up of the association between the picture and word/pseudoword which enables the picture to function as a prime. However, our knowledge about the N400 component as an index of semantic processing supports the interpretation that the children with larger vocabularies were more efficient at encoding a novel word as a label for a novel object, although the children in this sample with smaller vocabularies were equally efficient at encoding the actual word form (as indexed by the N200-500 effect). A retrospective study of 19-month-olds who would later show poor expressive language and a study of 20-month-olds at-risk for dyslexia both found temporally extended N200-500 effects in these risk-groups (Friedrich & Friederici, 2006; Torkildsen et al., 2007a). However, our low vocabulary group did not show such a pattern. This is probably because the children in our study were only classified according to their current vocabulary, and most of the children in the low vocabulary group were not at-risk in terms of their current vocabulary. They were not late talkers, but rather at the lower end of the normal range. The fact that the N400 modulation to real words was independent of vocabulary size also underscores that it is the formation of rapid associations between words and referents that differs between high and low producers, and not the processing of items that have a more consolidated status in long-term memory.

4.3. General discussion and conclusions

The longitudinal design of this study have allowed us to demonstrate a remarkable development of fast mapping ability between 20 and 24 months, measured electrophysiologically in a fairly large sample of children. During this four-month period the children on average tripled their productive vocabulary size, an increase which was coupled with changes in the N400 effect to pseudoword-referent associations. Moreover, we have shown that differences in productive vocabulary size are related to differences in the dynamics of semantic processing during novel word learning, where children with larger vocabularies seem to reach a level of less effortful semantic processing of novel words after fewer exposures. Our data also demonstrates that, in toddlers with large vocabularies, the N400 component responds to word and pseudoword repetition in a similar way as in adults, with a linear attenuation of negativity.

The clear N400 repetition effect found in this study is quite new in the infant word learning literature. The general pattern of decreasing parietal negativity with repetition, with the exception of the response to pseudowords in the low vocabulary group, is in line with adult research on the N400 component showing attenuation of amplitude due to repetition of both real words and pseudowords. Although children with larger vocabularies showed evidence of more efficient semantic processing of the pseudowords during learning, at both 20 and 24 months, this difference was not directly predictive of successful fast mapping between words and pictures in terms of an N400 incongruity effect. This most likely has to do with the specific learning load in the experiment which may have been too heavy even for the high producers, and thus the task did not differentiate well between the two groups. Perhaps if the experiment had included more learning trials, or had a slower pace, the high producers at 20 months would have responded to the switched pairings of the pseudowords.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2015.07.002.

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