

Learning to read shapes the activation of neural lexical representations in the speech recognition pathway

Ulrike Schild*, Brigitte Röder, Claudia K. Friedrich

Biological Psychology and Neuropsychology, University of Hamburg, Germany

ARTICLE INFO

Article history:

Received 31 August 2010

Received in revised form 26 October 2010

Accepted 9 November 2010

Keywords:

Speech recognition

Lexical representation

Literacy acquisition

P350

Word fragment priming

ABSTRACT

It has been demonstrated that written and spoken language processing are tightly linked. Here we focus on the development of this relationship at the time children start reading and writing. We hypothesize that the newly acquired knowledge about graphemes shapes lexical access in neural spoken word recognition. A group of preliterate children (six years old) and two groups of beginning readers (six and eight years old) were tested in a spoken word identification task. Using word onset priming we compared behavioural and neural facilitation for target words in identical prime-target pairs (e.g., *mon-monster*) and in prime target pairs that varied in the first speech sound (e.g., *non-monster*, Variation condition). In both groups of beginning readers priming was less effective in the Variation condition than in the Identity condition. This was indexed by less behavioural facilitation and enhanced P350 amplitudes in the event related potentials (ERPs). In the group of preliterate children, by contrast, both conditions did not differ. Together these results reveal that lexical access in beginning readers is based on more acoustic detail than lexical access in preliterate children. The results are discussed in the light of bidirectional speech and print interactions in readers.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

An intimate relationship between spoken and written language processing has been observed in different tasks. For example, adult participants were slower to decide that two words rhyme when spelling was inconsistent (e.g., *boat* and *note*) than when both words were spelled similarly (e.g., *bank* and *tank*; Seidenberg and Tannenhaus, 1979). Similarly, spoken word recognition was slower for words with final vowel-consonant clusters (rimes) that could have different spellings (e.g., *-ough* in *through*

or *tough*) compared to words with rimes that had only one possible spelling (e.g., *-ust* in *must* or *just*; Chéreau et al., 2007; Jakimik et al., 1985; Slowiaczek et al., 2003; Ziegler and Ferrand, 1998; Ziegler et al., 2004). In line with the enhanced reaction times, neural processing effort as indexed by the event-related potentials (ERPs) was enhanced for inconsistently spelled words compared to consistently spelled words (Pattamadilok et al., 2009; Perre and Ziegler, 2008; Perre et al., 2009a,b).

There are two main hypotheses about the interaction of oral and written language systems. According to the first, learning to read is basically associated with aspects of phonological processing in speech recognition, specifically with the ability to deal with phonetic units of speech (Morais, 1993). This assumption was based on the observation that illiterates have difficulties in adding or subtracting a phone at the beginning of nonsense words (Morais et al., 1979) or in repeating nonsense words (Castro-Caldas et al.,

* Corresponding author. Tel.: +49 040 428 38 5836;

fax: +49 040 42838 6591.

E-mail addresses: Ulrike.schild@uni-hamburg.de (U. Schild),

Brigitte.roeder@uni-hamburg.de (B. Röder),

Claudia.friedrich@uni-hamburg.de (C.K. Friedrich).

1998; Reis and Castro-Caldas, 1997). It was argued that literates have little difficulty in performing such tasks because the phonological route to word recognition is shaped by orthography. The fact that diminished phonological processing in illiterates is restricted to nonsense words was taken to argue that the phonological route works in parallel to a lexical route and to a semantic route to word recognition. Both these routes enable proper responses to words in illiterates.

A second influential model of speech and print interaction (Grainger and Ferrand, 1994, 1996) proposed interactions between the oral and written language system at several levels of representations. This model focuses on a lexical pathway that involves phoneme units which activate lexical word form units. Phoneme representations in spoken language processing are thought to communicate with grapheme representations in written language processing. This was indicated, for example, by longer detection latencies for phonemes with variable orthographic realisation (orthographic consistency; e.g., /f/ in *farm* or *pharmacy*) compared to phonemes with consistent spelling (such as /b/, Dijkstra et al., 1995). Furthermore, printed and written word form representations are thought to be linked at the lexical level. This was indicated, for example, by longer detection latencies for spoken words with many orthographic neighbours (words with an orthography that is similar to many other words in the lexicon) compared to words with few orthographic neighbours (Ziegler et al., 2003).

In sum, two different approaches that need not to be mutually exclusive have been proposed to account for the effects that literacy acquisition has on speech recognition. Learning to read and write might (i) modulate a phonological route that is separate from a lexical route (e.g., Castro-Caldas et al., 1998; Reis and Castro-Caldas, 1997) or (ii) directly modulate the representations that are involved in the activation of lexical representations (e.g., Grainger and Ferrand, 1994, 1996). Both hypotheses were mainly based on results from studies with adults. They need further evaluation from a developmental perspective.

Here we used event-related brain potentials (ERPs) to elucidate the changes that the neural speech recognition system undergoes during the time children start reading and writing. Former research suggested that ERPs recorded in unimodal auditory word fragment priming reflect two parallel processing routes in adult speech recognition (Friedrich et al., 2009; Schild et al., 2010). In this paradigm, spoken word targets are preceded by spoken word onset primes that either match their following words (identical condition: spoken *mon-* followed by the spoken word *monster*), mismatch in the initial phoneme (Variation condition: *non-monster*), or are completely unrelated (Control condition: *dra-monster*). A left-hemispheric ERP deflection elicited between 200 and 300 ms after target word onset, named the P350, reflected fine-grained prime-target matching. It was more positive for unrelated target words than for identical target words. Target words that varied in the first speech sound from their primes elicited intermediate P350 amplitudes. Therefore, the P350 was related to the gradual activation of neural

word form or lexical representations (see also Friedrich, 2005; Friedrich et al., 2004a,b, 2008). In parallel to the left-hemispheric P350 deflection, a central negativity was observed. This ERP deflection was similarly reduced for the Identity condition and the Variation condition compared to the Control condition. That is, in contrast to the P350, the central negativity did not differentiate between the Identity and the Variation condition. It was, therefore, related to a phonological route that enables rough phonological expectancy mechanisms (Friedrich et al., 2009; Schild et al., 2010).

We tested a group of preliterate children (six years old) and two groups of beginning readers (six and eight years old) with the same materials and methods as in our previous unimodal word fragment priming study with adults (Friedrich et al., 2009; Schild et al., 2010). The basic research questions were (i) whether learning to read and write is related to changes in neural spoken word recognition; (ii) whether or not ERP indices of parallel processing (the P350 and the central negativity) are elicited in preschoolers and young pupils; and (iii) whether the P350 and/or the central negativity are differently modulated in beginning readers and in pre-readers. Different patterns of neural priming for the central negativity would be evidence for the assumption that a phonological route is modified by learning to read and write (e.g., Castro-Caldas et al., 1998; Reis and Castro-Caldas, 1997). Different patterns of neural priming reflected in the P350 effect would be evidence for the assumption that a lexical route is restructured by literacy (e.g., Grainger and Ferrand, 1994, 1996).

2. Materials and methods

2.1. Participants

Fifty-one children were tested (19 pre-reading preschoolers, 13 reading preschoolers and 19 beginning readers [2nd grade]). The children were recruited from local schools and preschools or with newspapers advertisements. They were offered a present for participation. Informed consent was obtained from the parents of the children. All children were right-handed as assessed by the Edinburgh Inventory (LQ, Oldfield, 1971). All children were native speakers of German living in monolingual environment and had normal or corrected-to-normal vision. None of the children reported hearing or neurological problems. All children had normal or above normal IQ scores, as measured with the Raven Colored Progressive Matrices (CPM, Bulheller and Häcker, 2002). Pre-reading preschoolers were not yet able to read or write. The BISC test (Bielefelder Screening zur Früherkennung von Lese-Rechtsschreibschwierigkeiten, Jansen et al., 2002) indicated that no child was at risk for developing reading or writing impairments. Pupils and reading preschoolers performed a reading test (ELFE1–6, Lenhard and Schneider, 2006). Participant characteristics and results of all tests are given in Table 1. The study was approved by the ethical committee of the German Psychological Association (“Ethikkommission der Deutschen Gesellschaft für Psychologie”, 10.2006).

Table 1

Demographic and data on mean results for standardized tests assessing IQ-scores (CPM: Raven Colored Progressive Matrices, Bulheller and Häcker, 2002), phonological awareness (BISC: Bielefelder Screening zur Früherkennung von Lese-Rechtsschreibschwierigkeiten, Jansen et al., 2002), reading proficiency (ELFE1-6, Lenhard and Schneider, 2006) and handedness (LQ: Lateralization Quotient, Oldfield, 1971).

	Sex (male/female)	Age (years, month (range))	CPM (percent: mean (SD))	BISC (risk points: mean (SD))	ELFE (percent: mean (SD))	LQ (mean (SD))
Pre-reading preschoolers	13/6	6.4 (5.11–6.11)	73.4 (17.6)	0.5 (0.9)	–	89.3 (12.5)
Reading preschoolers	5/8	6.4 (5.1–7.0)	86.5 (15.6)	–	39.1 ^a (32.4)	89.4 (9.8)
Beginning readers (2nd grade)	10/9	8.1 (7.10–8.8)	72.2 (25.4)	–	68.2 (23.2)	71.6 (25.4)
Significant differences between groups	–	–	n.s.	–	$t(30) = 2.97$ $p < .01$	

^a Note, that normally children were tested in the middle or at the end of the schoolyear except for the first schoolyear, there norms were only available for testing at the end of the year. Thus, for the reading preschoolers we took these norms.

2.2. Stimuli

Sixty monomorphemic disyllabic German nouns stressed on the first syllable served as stimuli (see Appendix A). Care was taken to ensure that words were known by children between 3.5 till 4.7 years of age. We checked production data of four bilingual German-French children in the DuFDE project (Deutsch und Französisch – Doppelter Erstspracherwerb; Köppe, 1997; children: Annika, Francois, Pascale and Ivar), and of nine monolingual German children in the “Childes” database (childes.psy.cmu.edu; children: Anna, Caroline, Carsten, Emely, Falko, Lisa, Rahel, Simone and Soeren) in that age range. Only words that were named at least once by one child within free speech were included in the study.

Sixty meaningless strings were created from the words by changing the initial PLACE feature (*Monster* → **Nonster*). The first syllable of these changed strings were used as fragments in the Variation condition (see below). Sixty pronounceable pseudowords were created by changing the last phoneme/s of each word (e.g. *Monster* – **Monste*). These pseudowords served as distractors for the lexical decision task.

All stimuli were spoken by a female and a male professional native-speaker of German. Speakers were not aware of the specific aims of the study. Digitized primes (first syllable fragments taken from the word and string utterances) and target words were combined according to their overlap (Identity condition: *mon-Monster*, Variation condition: *non-Monster*; Control condition: *dack-Monster*). Each target word was presented once in each condition (Identity, Variation, Control). In 25% of the trials a pseudoword was presented instead of the target word. Pseudowords were combined with fragments in the same way as words. To prevent purely physical-acoustic priming, prime fragments were taken from the male speaker, and targets were taken from the female speaker.

2.3. Design and procedure

Each participant received 240 test trials (180 target words, 60 target pseudowords) with 20 trials in each block. Trials were presented in pseudorandomized order with the following restrictions: Within block 1–4, 5–8 and 9–12 no repetition of a target word or a pseudoword occurred. There

was not any immediate repetition of a condition and there were never more than six target words in a row. We produced four different orders of stimulus presentation.

Participants were comfortably seated in an electrically shielded and sound attenuated chamber. An experimental trial began with the presentation of the ‘fixation picture’ at the center of the screen. Participants were instructed to fixate this figure whenever it appeared. A fragment (mean duration: 347 ms) was presented via loudspeakers 500 ms after the onset of the fixation picture. The fixation picture remained on the screen. The target (word or pseudoword, mean duration time: 714 ms) was delivered 850 ms after the onset of the fragment. Participants were instructed to respond as fast and as accurate as possible to words, but refrain from responding when the target was a pseudoword. Note that there was a silent interval of at least 290 ms between prime and target, ensuring a comparable baseline period of 200 ms for all target ERPs. If an overt response was received, feedback was given for 2 s: a smiley was presented if the participant responded correctly to a word, whereas a ghost was presented if the participant incorrectly responded to a pseudoword. No feedback was delivered when no response occurred. After 3.5 s the fixation picture disappeared. The next trial started after a 1.5 s intertrial interval.

Visual fixation (size: 1 cm × 1 cm) and feedback stimuli (size: 3 cm × 7 cm) were presented on a computer screen (distance: 50 cm) in front of the participants. Loudspeakers were placed at the left and the right side of the screen. For responding, half of the participants pressed a button with the left index finger and half of the participants responded with the right index finger.

2.4. Data analysis

As in Friedrich et al. (2009) and Schild et al. (2010), trials with responses shorter than 200 ms and longer than 2000 ms were removed from both behavioural and ERP analyses. Reaction times calculated from the onset of the words to the participants’ responses were submitted to an ANOVA with repeated measurements with the within three-level factor *Fragment* (Identity vs. Variation vs. Control) and the between three-level factor *Group* (non-reading preschoolers vs. reading preschoolers vs. beginning readers).

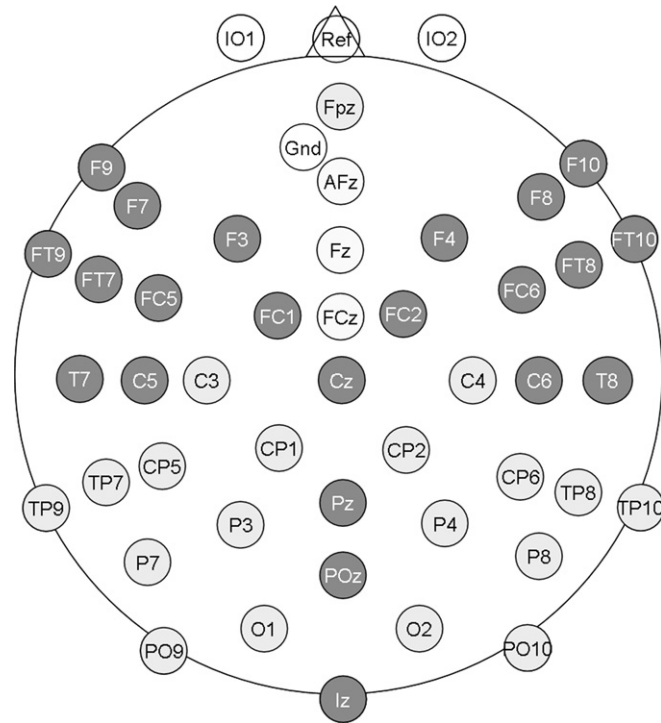


Fig. 1. Regions of interest. Mean amplitudes between 300 and 400 ms were calculated for four lateral and two central regions of interest (ROI). Each lateral ROI consists of nine electrodes (anterior left/right: dark grey, posterior left/right: bright grey). Each central ROI consists of four electrodes (central anterior: bright grey; central posterior: dark grey).

ERP effects were analysed similarly to our previous studies with adults (Friedrich et al., 2004b, 2009; Friedrich, 2005; Schild et al., 2010). For the N100 effect mean amplitudes between 100 and 300 ms were calculated (analysis with laterals ROIs, see below). For the P350 effect and the central negativity mean amplitudes between 300 and 400 ms were calculated for four lateral Regions of Interest (ROIs): left anterior cluster: F9, F7, F3, FT9, FT7, FC5, FC1, T7, C5; right anterior cluster: F10, F8, F4, FT10, FT8, FC6, FC2, T8, C6; left posterior cluster: C3, TP9, TP7, CP5, CP1, P7, P3, PO9, O1; right posterior cluster: C4, TP10, TP8, CP6, CP2, P8, P4, PO10, O2) and two central ROIs (central anterior: FpZ, AFz, Fz, FCz; central posterior: Cz, Pz, POz, Iz), respectively (see Fig. 1). These mean amplitude values were submitted to an ANOVA with repeated measurements with the within three-level factor Fragment (Identity vs. Variation vs. Control), Hemisphere (left vs. right electrode sites, not for the central negativity) and Region (anterior vs. posterior electrode sites) and the between three-level factor Group (pre-reading preschoolers vs. reading preschoolers vs. beginning readers). For group comparisons data was normalized. The Greenhouse-Geisser Epsilon (ϵ) correction was applied to effects including the three-level factor Fragment; corrected p -values were reported. In case of significant interactions, t -tests were computed to evaluate differences among conditions. Only main effects of the factor Fragment, significant interactions with Fragment and significant post hoc comparisons are reported.

3. Results

3.1. Behavioural data

Children made only few errors (3.56% overall). The analysis of errors revealed a main effect of Fragment ($F(2,96)=5.07, p<.01, \epsilon=.98$) and no main effect or interaction with Group. All groups made fewer errors in the Identity condition (Mean: 2.8, SE: 2.6) compared to the Variation condition (Mean: 3.8, SE: 3.3) and the Control condition (Mean: 4.0, SE: 3.5), both $t(21) \geq 2.69$, both $p \leq .01$. Errors for the Variation were in between error rates for the Identity condition and the Control condition, but did not differ significantly from the Control condition.

Mean reaction times of all groups are shown in Fig. 2. The analysis of mean reaction times revealed a main effect of Fragment ($F(2,96)=53.05, p<.001, \epsilon=.94$), but not of group ($F<1.3, n.s.$). Crucially, however a significant interaction of Fragment and Group ($F(4,96)=4.37, p<.01$) was obtained. Post hoc t -tests showed that for beginning readers and reading preschoolers responses in the Identity condition were faster than in the Variation condition ($t(18)=3.60, p<.01$ and $t(12)=5.37, p<.001$, respectively) and in the Control condition ($t(18)=5.56, p<.001$ and $t(12)=8.06, p<.001$, respectively). The pattern of results differed for pre-reading preschoolers. They had similar response times in the Identity and Variation condition ($t(18)<1, n.s.$), which both were faster than in the Control

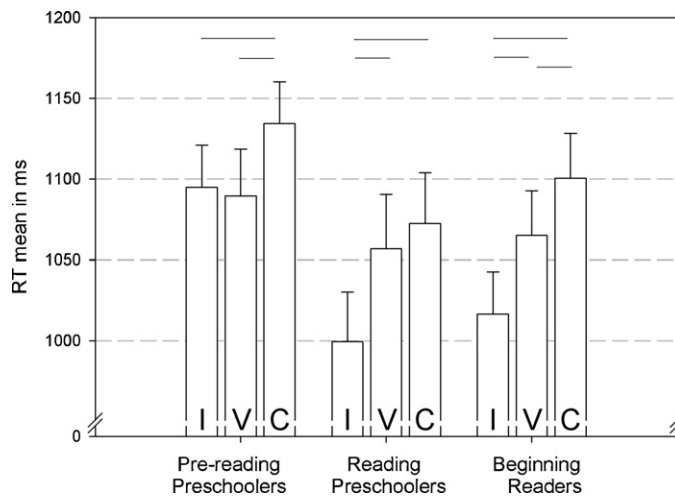


Fig. 2. Mean reaction times. Mean reaction times of Identity (I), Variation (V) and Control (C) condition for all groups. Error bars indicate standard errors. Lines above the bars indicate significant differences in post hoc tests.

condition, $t(18)=4.28$, $p<.001$) and $t(18)=4.18$, $p=.001$, respectively.

We also calculated priming effects (Control minus Identity condition (C–I) and Control minus Variation condition, C–V). An ANOVA with the factors priming and group revealed a significant priming effect ($F(1,48)=37.28$, $p<.001$) and a significant interaction of the factors priming and group ($F(2,48)=10.05$, $p<.001$). Again, post hoc t -tests showed that priming effects differ for beginning readers and reading preschoolers ($t(18)=4.65$, $p<.001$ and $t(12)=5.37$, $p<.001$ respectively), but not for pre-reading preschoolers, $t(18)<1$, n.s. For readers the priming effect of the Identity condition (C–I) was stronger than the priming effect of the Variation condition (C–V); whereas for pre-readers priming effects were not significantly different.

In sum, all groups showed priming effects, i.e. all participants responded faster to fully overlapping prime–target pairs (Identity condition) than to unrelated pairs (Control condition). As was proposed, the pattern of results for the Variation condition was different for beginning readers and preliterate children. Differences between fully overlapping and partially overlapping pairs (Variation condition) were obtained for reading children, but not for pre-reading children.

3.2. Event related potentials

A full list of ANOVA results is displayed in Table 2. Mean ERPs are shown in Figs. 3 and 5. In comparison to adults who showed a marked P1-N1-P2-complex followed by the P350 and the central negativity (Friedrich et al., 2009; Schild et al., 2010), early auditory waveforms elicited in the children were less clear cut. Nonetheless, the P1-N1-P2-N2-complex was followed by the P350 (Fig. 3) and the central negativity (Fig. 5). In Figs. 4 and 6 the corresponding mean amplitudes of the P350 and the central negativity elicited in the three groups are displayed. Table 3 shows a summary of all relevant key-findings for all three groups.

N100 (100–300 ms). By visual sight it seems that amplitudes of conditions differed from each other before 300 ms

(see Fig. 3). However, this was not supported by the results of the ANOVA. Neither the main effect of Fragment nor any interaction with the factors Fragment and Group reached significance (all, $F \leq 1.72$, $p \geq .18$). In sum, ERP differences between the conditions shown for this time window in adults (Friedrich et al., 2009; Schild et al., 2010) were not observed in children.

P350 (300–400 ms). The overall ANOVA revealed a significant interaction of Fragment and Region ($F(2,96)=10.0$, $p<.000$, $\epsilon=.99$), a marginally significant interaction of Fragment and Hemisphere ($F(2,96)=2.8$, $p=.07$, $\epsilon=.99$) and a significant triple interaction of Fragment, Region and Hemisphere ($F(2,96)=4.6$, $p<.05$, $\epsilon=.93$). A significant group effect ($F(2,48)=3.3$, $p<.05$) and marginally significant interactions of Fragment, Region and Group ($F(4,96)=2.2$, $p=.07$); Fragment, Hemisphere and Group ($F(4,96)=2.3$, $p=.06$); and Fragment, Region, Hemisphere and Group ($F(2,96)=2.4$, $p=.06$) allowed to separately analyze the groups.

In Fig. 7 the topography of differences between the ERPs (Control condition minus Identity condition; Control condition minus Variation condition) elicited between 300 and 400 ms after target word onset are illustrated. As can be seen, there were differences in the scalp topography between the groups. The left-lateralized P350 effect that has been repeatedly observed in adults (Friedrich et al., 2004b, 2008, 2009; Friedrich, 2005; Schild et al., 2010) was only seen in the beginning readers (eight years old), whereas the P350 effect in both groups of preschoolers (six years old) was bilaterally distributed. Therefore, post hoc comparisons of the P350 analysis were based on the left hemisphere (left anterior cluster and left posterior cluster) for the beginning readers; and on the frontal region (left anterior cluster and right anterior cluster) for both groups of preschoolers. In Fig. 4 the corresponding mean amplitudes of the P350 elicited in the three groups are displayed.

In beginning readers the analysis of P350 amplitudes elicited over the left hemisphere was confirmed by an interaction of the factors Fragment and Hemisphere ($F(2,36)=7.46$, $p<.01$, $\epsilon=.99$). Post hoc t -test for the left

Table 2

Full list of ANOVA results. Significant effects of fragment or significant interactions with the factor fragment (grey boxes) are highlighted (bold).

Factors ^a	100–300 ms – N100		300–400 ms (lateral) – P350		300–400 ms (central) – N400	
	F-values	p-values	F-values	p-values	F-values	p-values
G	2.66	.08	3.29	.05	0.27	.77
F	1.73	.18	2.26	.11	12.43	<.001
F*G	0.66	.60	0.99	.42	0.99	.42
R	36.06	<.001	37.11	<.001	86.35	<.001
R*G	3.75	.03	1.46	.24	3.94	.03
H	10.92	.002	11.76	.001	–	–
H*G	0.60	.56	0.02	.98	–	–
F*R	0.68	.51	10	<.001	4.53	.01
F*R*G	1.15	.34	2.25	.07	2.74	.04
F*H	0.37	.69	2.78	.07	–	–
F*H*G	1.01	.41	2.32	.06	–	–
R*H	0.13	.72	21.22	<.001	–	–
R*H*G	4.58	.02	1.56	.22	–	–
F*R*H	1.13	.33	4.64	.01	–	–
F*R*H*G	1.07	.37	2.35	.06	–	–

^a G – Group, F – Fragment, R – Region, H – Hemisphere.

hemisphere revealed that P350 amplitudes elicited in the Identity condition were less positive than P350 amplitudes elicited in the Control condition ($t(18) = 3.61, p < .01$). Crucially, P350 amplitudes elicited in the Identity condition and in the Variation condition did also differ. They were

less positive in the Identity condition than in the Variation condition ($t(18) = 2.40, p < .05$).

For reading preschoolers the analysis of P350 amplitudes elicited over the frontal region was confirmed by an interaction of the factors Fragment and Region ($F(2,24) = 9.35$,

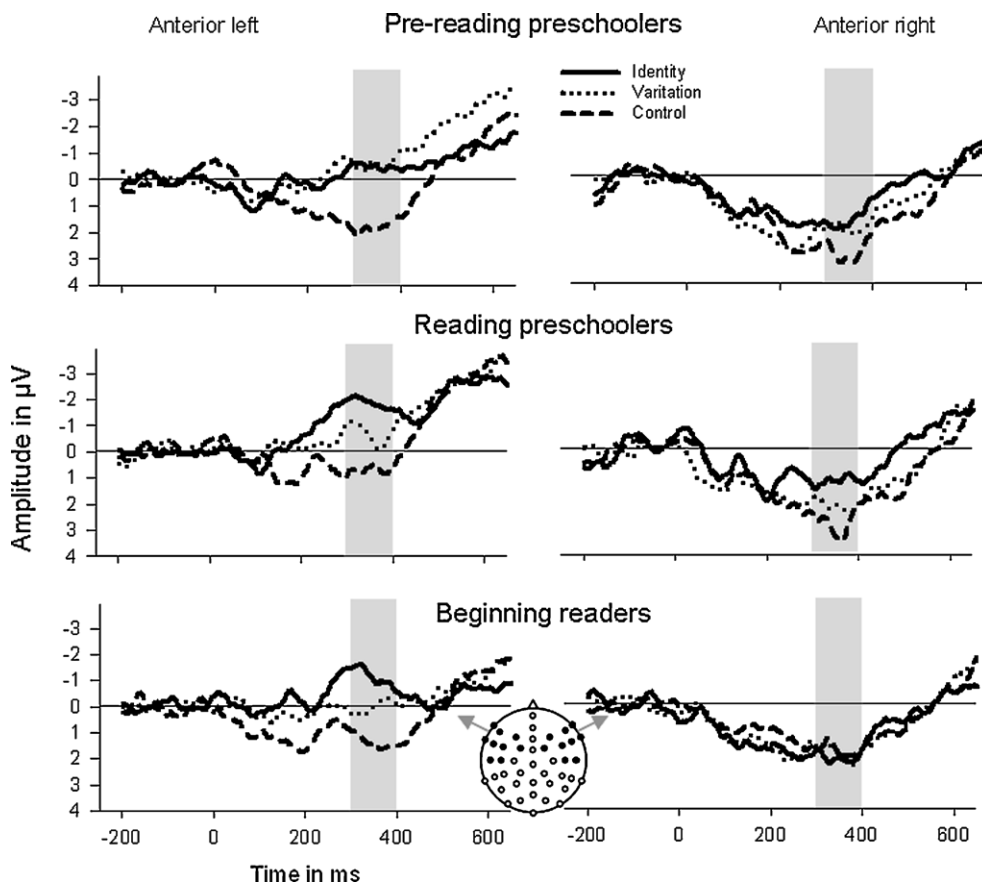


Fig. 3. P350 effects. Mean ERPs over anterior left (left) and anterior right (right) regions for pre-reading preschoolers (top panel), reading preschoolers (middle panel) and beginning readers (bottom panel). Identity (solid line), Variation (dotted line) and Control condition (dashed line). Averaged electrodes that contributed to the mean ERP are displayed by black circles. Grey boxes indicate time window for P350 analysis.

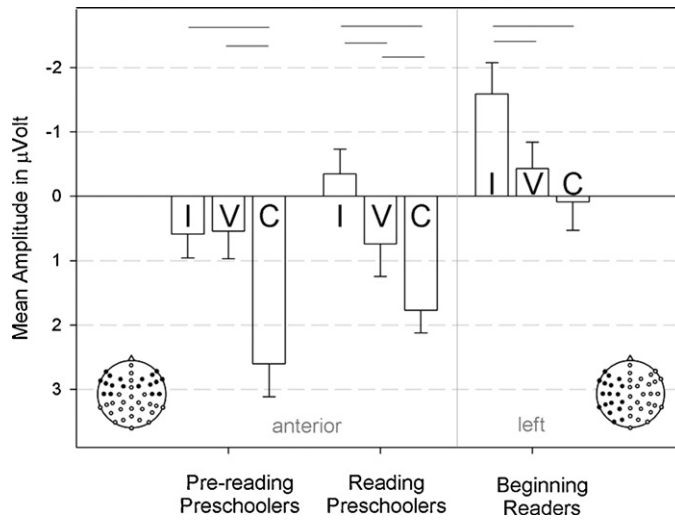


Fig. 4. Quantification of the P350 effects. Mean amplitudes of Identity (I), Variation (V) and Control (C) condition for all groups within 300–400 ms. Please note that for pre-reading preschoolers and reading preschoolers comparison was made in anterior regions; whereas for beginning readers comparison was made for left hemisphere regions (for further explanations, please refer to the text). Electrodes included in the mean amplitudes are displayed by black circles. Lines above bars indicate significant differences revealed by post hoc tests. Error bars indicate standard errors.

$p = .001, \epsilon = .97$). According to post hoc t -tests, the Identity condition elicited less positive P350 amplitudes than the Control condition ($t(12) = 5.00, p < .001$). Most importantly, P350 amplitudes elicited in the Identity condition and in the Variation condition did also differ. In parallel to the beginning readers, P350 amplitudes were less positive in the Identity condition than in the Variation condition ($t(12) = 2.22, p < .05$). Thus, for both groups of reading children the P350 amplitudes differed for the Identity condition and for the Variation condition.

For *pre-reading preschoolers* the analysis of P350 amplitudes elicited over the frontal region was confirmed by an interaction of the factors Fragment and Region ($F(2,36) = 12.43, p < .001, \epsilon = .93$). Again, amplitudes were less positive for the Identity condition compared to the Control condition ($t(18) = 4.26, p < .001$). In contrast to both reading groups, however, the Identity and the Variation condition did not differ for pre-reading preschoolers ($t(18) < 1, n.s.$).

In sum, the pattern of the P350 results for both reading groups was comparable, and replicated the pattern of the P350 results observed for adults (Friedrich et al., 2008; Schild et al., 2010). In both groups P350 amplitudes were more positive in the Variation condition compared to the Identity condition (Fig. 4). In contrast, P350 amplitudes

in pre-reading preschoolers did not differentiate between both conditions.

Central negativity (300–400 ms). Mean ERPs and mean amplitudes of the three groups are displayed in Figs. 5 and 6, respectively. The overall ANOVA revealed a significant main effect of Fragment ($F(2,96) = 12.43, p < .001, \epsilon = .99$), an interaction of Fragment and Region ($F(2,96) = 4.53, p = .01, \epsilon = .94$) and a triple interaction of Fragment, Region and Group ($F(4,96) = 2.74, p < .05$). Therefore, each group was separately analysed. As can be seen in Fig. 7, the central negativity showed a bilateral posterior-central scalp topography for all groups. Therefore, post hoc comparisons were restricted to the posterior ROIs:

For *beginning readers* a marginally significant interaction of the factors Fragment and Region was observed, $F(2,36) = 3.16, p = .07, \epsilon = .82$. Post hoc t -test revealed that amplitudes over posterior regions in the Control condition were more negative than in the Identity and Variation condition, both, $t > 2.72, p < .05$. Crucially, the Identity condition and the Variation did not differ, $t < 1, n.s.$

For *reading preschoolers* a significant interaction of the factors Fragment and Region was observed, $F(2,24) = 3.34, p < .01, \epsilon = .83$. Amplitudes over posterior regions in the Control condition and in the Variation condition were more negative than in the Identity condition, both, $t > 2.70, p < .05$. That is, the central negativity elicited in the Identity

Table 3
Summery of effects for all three groups.

	RTs		P350		Central negativity	
	IV ^a	IC ^a	IV	IC	IV	IC
Pre-reading preschoolers	–	+	–	+	–	+
Reading preschoolers	+	+	+	+	+	+
Beginning readers (2nd grade)	+	+	+	+	–	+

^a IV – differences between Identity and Variation condition, IC – difference between Identity and Control condition, –, no significant difference, +, significant difference.

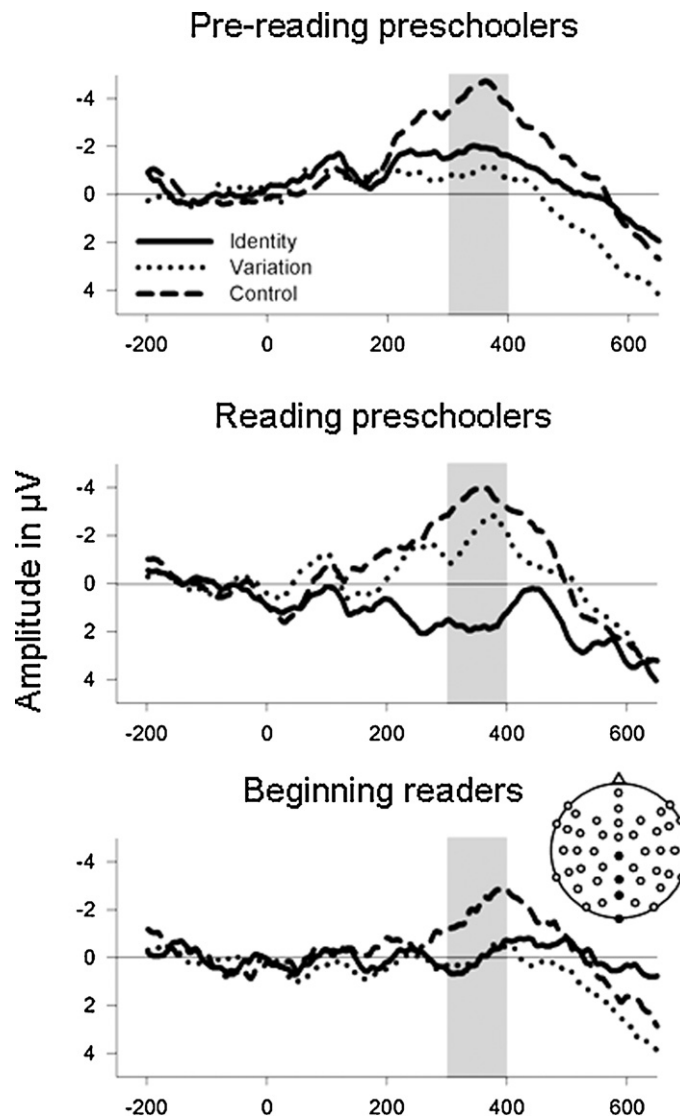


Fig. 5. Central negativity effects. Mean ERPs over posterior central regions for pre-reading preschoolers (top panel), reading preschoolers (middle panel) and beginning readers (bottom panel). Identity (solid line), Variation (dotted line) and Control condition (dashed line). Electrodes that contributed to the mean ERP are displayed by black circles. Grey boxes indicate time window for N400 analysis.

condition and in the Variation condition did differ in this group.

Also, for *pre-reading preschoolers* an interaction of Fragment and Region was observed, $F(2,24)=7.00$, $p<.01$, $\epsilon=.97$. Amplitudes over posterior regions in the Control condition were more negative than in the Identity and Variation condition, both, $t>2.50$, $p<.05$. Comparable to the group of beginning readers, the Identity condition and the Variation did not differ, $t<1.2$, n.s.

In sum, expect of the reading preschoolers, the results for the central negativity were comparable to the pattern of results observed for adults (Friedrich et al., 2008; Schild et al., 2010). In pre-reading preschoolers and beginning readers the central negativity was enhanced for the Control condition, but did not differ for the Identity condition and the Variation condition. Only in reading preschoolers

did the Identity condition and the Variation condition elicit different amplitudes of the central negativity.

4. Discussion

The present results indicate that learning to read and write is associated with functional modulations of speech recognition. Behavioural and ERP data show that preliterate but not beginning readers tolerate variation between the speech signal and a single phoneme. The present ERP data allow relating the behavioural results to sub-processes at the neural level. They are further evidence for the parallel architecture of speech recognition. In line with earlier studies with adults (Friedrich et al., 2008; Schild et al., 2010), the ERPs pointed to two routes of speech processing that operate in parallel even in children. In a time window between

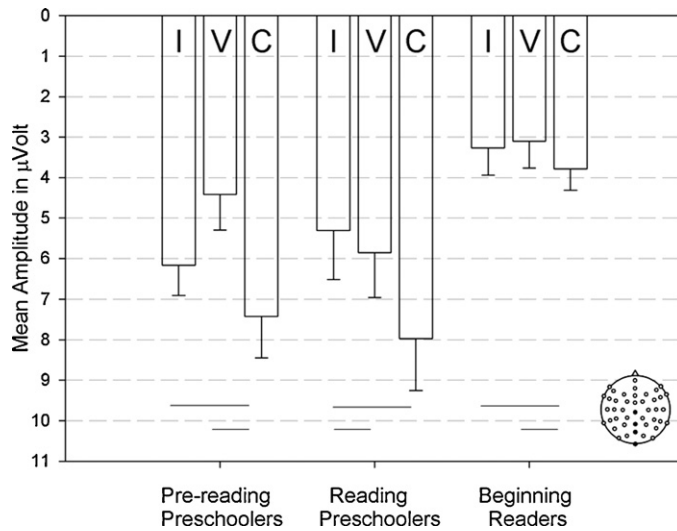


Fig. 6. Quantification of the central negativity effects. Mean amplitudes of Identity (I), Variation (V) and Control (C) condition for all groups within 300–400 ms over posterior sites. Electrodes included in the mean amplitudes are displayed by black circles. Lines above bars indicate significant differences revealed by post hoc tests. Error bars indicate standard errors.

300 and 400 ms after target word onset, a P350 effect and a central negativity were elicited. Both ERP deflections will be discussed in turn.

The P350 results demonstrate that activation patterns through the neural lexical access pathway are more distinct in beginning readers than in preliterate children. Beginning readers (six and eight years old) showed the gradual activation as a function of the goodness of fit between the prime (*mon-*, *non-*, or *dra-*) and the target word (*monster*) that was formerly observed for adults (Friedrich et al., 2009; Schild et al., 2010). Their reaction times were slower and neural activation as indexed by the P350 effect in the ERPs was less effective when the first phoneme diverged from the target word (*non-monster*) than when it was identical to the first phoneme of the target word (*mon-monster*). In contrast, the lexical pathway in preliterate children (six years old) tolerated one-phoneme mismatch between the speech signal and the word. Reaction times and ERPs did not dissociate the Identity condition and the Variation condition in preliterate children. The finding that a neural lexical pathway is modulated by literacy supports the

assumption of the bi-modal interactive-activation model of speech and print interaction (Grainger and Ferrand, 1994, 1996) by indicating that the newly established processing route for written words directly interacts with representations at the lexical access pathway in spoken word recognition.

Here we suggest that the higher sensitivity to phoneme mismatch in reading children is basically triggered by spreading activation from sub-lexical grapheme representations to representations in the speech recognition system. Although the bidirectional interactive model of speech and print interaction (Grainger and Ferrand, 1994, 1996) assumes connections with the sub-lexical level and with the lexical level in adults, previous research with children suggested that the former are established earlier. Orthographic consistency effects in six to seven years old demonstrated that beginning readers immediately use grapheme information for spoken word processing (Goswami, 2005; Ventura et al., 2007, 2008); whereas, orthographic neighbourhood effects at the lexical level were only observed in 11 years old advanced readers, but

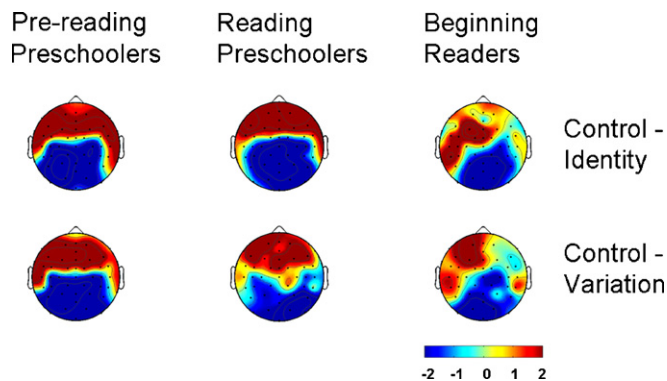


Fig. 7. Topographical voltage maps. Topographical voltage maps of the difference waves for the time window 300–400 ms (P350 effect) displayed for the Control condition minus Identity- condition (upper panel) and for the Control condition minus Variation- condition (lower panel), respectively.

not in 8 years old beginning readers (Ziegler and Muneaux, 2007).

The mechanisms via which graphemes can alter the activation of spoken word forms can be illustrated for an example target from the present experiment. The initial speech sound of the word *monster* activates a sub-lexical representation of the phoneme /m/. However, this speech sound also shares almost all phonetic features with the phoneme /n/. Both consonants are produced in a nasal, voiced manner. They only diverge in the place of articulation. In preliterate children the phoneme level provides the only source of information that can be taken to resolve the competition between both sub-lexical representations. In beginning readers, grapheme representations additionally contribute to the competition process. The phoneme /m/ activates its corresponding grapheme 'M'. The grapheme feeds back activation to the phoneme/m/ and feeds forward activation to spoken word forms beginning with /m/. These additional facilitating connections from grapheme representations to phoneme representations and to word form representations will make the fragment *mon-* (Identity condition) a far more appropriate input than the fragment *non-* (Variation condition) for activating the word *monster*.

One might argue that the different sensitivity to Variation in the speech signal in preliterates and beginning readers is related to their different vocabulary sizes. Beginning readers might command a larger vocabulary than preliterate children, and therefore might use more fine-grained lexical representations to resolve the resulting competition (Jusczyk, 1993; Metsala and Walley, 1998; Walley et al., 2003). Although we took care that the primes presented in the Variation condition could not be completed to existing German words (see also Friedrich et al., 2009; Schild et al., 2010), stronger competition effects due to a larger vocabulary in beginning readers might not be excluded definitely. This enhanced competition might further force the system to rely on any type of information that makes it possible to better distinguish between lexical candidates. Information provided by the graphemes appears to be a valuable source in this respect.

The central negativity elucidated processing at a phonological route of spoken word processing. For pre-reading preschoolers and for beginning readers we replicated the adult pattern of results for the central negativity. Amplitudes were similarly reduced for the Identity condition and for the Variation condition compared to the Control condition. Only in reading preschoolers the central negativity was remarkably enhanced in the Variation condition compared to the Control condition. Given our previous interpretation of the central negativity as reflecting a rough phonological matching mechanism between the prime and the target word (Friedrich et al., 2008; Schild et al., 2010) we might conclude that this phonological route is especially sensitive to subtle variation at the time children start reading and writing. This effect finds a parallel in the reaction time data. In the group of reading preschoolers we did not find any behavioural facilitation for the Variation condition compared to the Control condition. It might appear that at the time when children learn that each grapheme roughly corresponds to a phoneme (phonologi-

cal awareness, see for review Castles and Coltheart, 2004; Goswami, 2008; Ziegler and Goswami, 2006), a phonological route is crucially involved. In more experienced readers (8 years old beginning readers and adults) this phonological route appears to be less important. This finding somehow restricts the assumption that learning to read and write is basically associated with restructuring of a phonological route (e.g., Castro-Caldas et al., 1998; Reis and Castro-Caldas, 1997).

In addition to the experimental modulation of the P350 and the central negativity, the N100 component has been formerly found to be modulated in unimodal spoken word fragment priming in adults (see Friedrich et al., 2009; Schild et al., 2010). Similar to a previous ERP study with phonological priming in preliterate and reading children (Bonte and Blomert, 2004), we also found a remarkable N100 component in all groups tested in the present study (see Fig. 5). However, N100 amplitudes did not differ between conditions in any group. Thus, early auditory ERP effects remain difficult to interpret in children.

Finally, our data suggest developmental plasticity in the lateralization of neuronal lexical representations from preschool to early school years that are not related to literacy acquisition. Although ERPs revealed a relative positivity for unrelated vs. identical targets between 300 and 400 ms (P350 effect) in all groups, the scalp topography was related to children's age. Both groups of six year old preschoolers (preliterate and reading respectively) showed a bilateral P350 effect over the anterior scalp. Only eight-year old beginning readers showed the left-lateralization of the P350 effect that was formerly shown for adults (Friedrich et al., 2004a,b, 2009). These findings integrate into a dynamic pattern of results for language lateralization in infancy. For example, the topography of ERP differences for known vs. unknown words changed from a left-hemispheric dominance in 10-month-olds (Kooijman et al., 2005) to a symmetric effect in 14-month-olds (Mills et al., 1997, 2004), and switched again to a left-lateralized effect in 20 months olds (Mills et al., 1993, 1997, 2004). Our results might reveal that left hemispheric specialization in lexical access becomes more focused between six and eight years of age. However, different numbers of girls and boys in our groups (see Table 1) might limit this conclusion as there appear to be sex differences in the lateralization of cognitive functions (Shaywitz et al., 1995).

5. Conclusions

There are three major outcomes of the present study. (i) ERP deflections that indicate parallel processing in speech recognition in adults can be replicated in six and eight year old children. As in adults, the ERPs show a P350 effect and a central negativity. (ii) A different pattern of results for both ERP deflections across the groups support our interpretation that the P350 and the central negativity are associated with different processes (Friedrich et al., 2008; Schild et al., 2010). (iii) Finally, the present results not only support the assumption that spoken language processing is modulated during the time children start reading and writing. The different P350 amplitude patterns in preliterate children and beginning readers reveal that neural

lexical access is more precise in beginning readers than in pre-readers.

Acknowledgement

The work was supported by a grant of the German Research Foundation (FR 2591/1-1).

Appendix A.

Target words	Variation fragments	Pseudo-words	Target words	Variation fragments	Pseudo-words
Be-sen [broom]	de	Bese	Bo-den [ground]	do	Bode
Bre-zel [pretzel]	dre	Breze	Brüc-ke [bridge]	drüc	Brücker
Dack-el [dachshund]	back	Dacke	Dau-men [thumb]	bau	Daume
Dok-tor [doctor]	bok	Dokte	Do-se [can]	go	Doser
Dra-che [dragon]	gra	Drachel	Dü-se [blast pipe]	bü	Düser
Ga-bel [fork]	da	Gaber	Gra-ben [ditch]	dra	Grabel
Kä-fer [beetle]	tä	Käfe	Kä-fig [cage]	tä	Käfe
Kä-se [cheese]	tä	Käsel	Kar-re [kart]	tar	Karrel
Ket-te [chain]	tet	Kettel	Kir-che [church]	tir	Kircher
Kis-sen [cushion]	tis	Kisse	Kis-te [box]	tis	Kister
Kof-fer [trunk]	tof	Koffe	Kro-ne [crown]	tro	Kroner
Kü-che [kitchen]	tü	Kücher	Kü-ken [chick]	tü	Küke
Kur-ve [curve]	tur	Kurvel	Mat-te [mat]	nat	Matter
Mau-er [wall]	nau	Mauen	Mo-nat [month]	no	Mone
Mon-ster [monster]	non	Monste	Mün-ze [coin]	nün	Münzig
Na-gel [spike]	ma	Nagich	Na-me [name]	ma	Namer
Nu-del [noodle]	mu	Nude	Num-mer [number]	mum	Numme
Pau-se [break]	tau	Pausel	Pei-tsche [whip]	tei	Peitschel
Pin-sel [brush]	tin	Pinse	Po-ny [pony]	to	Pone
Pul-ver [powder]	tul	Pulve	Pup-pe [doll]	tup	Puppel
Ta-ler [thaler]	ka	Tale	Ta-sche [bag]	ka	Tascher
Tas-se [cup]	pas	Tasser	Tau-be [pigeon]	pau	Taubor
Tel-ler [plate]	pel	Telle	Tep-pich [carpet]	kep	Teppe
Teu-fel [demon]	keu	Teufe	Ti-ger [tiger]	pi	Tige
Toch-ter [daughter]	poch	Tochte	Ton-ne [barrel]	kon	Tonnel
Tor-te [cake]	por	Tortat	Trä-ne [tear]	prä	Träni
Trec-ker [tractor]	prec	Trecke	Trep-pe [stairs]	prep	Trepper
Trom-mel [drum]	krom	Tromme	Tun-nel [tunnel]	kun	Tunne
Na-del [needle]	ma	Nade	Tan-te [aunt]	pan	Tanter
Tau-cher [diver]	kau	Tauche	Ta-xi [taxi]	ka	Taxer

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.dcn.2010.11.002.

References

- Bonte, M., Blomert, L., 2004. Developmental changes in ERP correlates of spoken word recognition during early school years: a phonological priming study. *Clin. Neurophysiol.* 115, 409–423.
- Bulheller, S., Häcker, H., 2002. Coloured Progressive Matrices (CPM) (3., neu norm. Aufl.). Frankfurt/M, Harcourt.
- Castles, A., Coltheart, M., 2004. Is there a causal link from phonological awareness to success in learning to read? *Cognition* 91, 77–111.
- Castro-Caldas, A., Petersson, K.M., Reis, A., Stone-Elander, S., Ingvar, M., 1998. The illiterate brain. Learning to read and write during childhood influences the functional organization of the adult brain. *Brain* 121, 1053–1063.
- Chéreau, C., Gareth Gaskell, M., Dumay, N., 2007. Reading spoken words: orthographic effects in auditory priming. *Cognition* 102, 341–360.
- Dijkstra, T., Roelofs, A., Fieuw, S., 1995. Orthographic effects on phoneme monitoring. *Can. J. Exp. Psychol.* 49, 264–271.
- Friedrich, C.K., 2005. Neurophysiological correlates of mismatch in lexical access. *BMC Neuroscience* 6, 64. Retrieved from <http://www.biomedcentral.com/1471-2202/6/64>.
- Friedrich, C.K., Kotz, S.A., Friederici, A.D., Alter, K., 2004a. Pitch modulates lexical identification in spoken word recognition: ERP and behavioral evidence. *Cogn. Brain Res.* 20, 300–308.
- Friedrich, C.K., Kotz, S.A., Friederici, A.D., Gunter, T.C., 2004b. ERPs reflect lexical identification in word fragment priming. *J. Cogn. Neurosci.* 16, 541–552.
- Friedrich, C.K., Lahiri, A., Eulitz, C., 2008. Neurophysiological evidence for underspecified lexical representations: asymmetries with word initial variations. *J. Exp. Psychol. Human* 34, 1545–1559.
- Friedrich, C.K., Schild, U., Röder, B., 2009. Electrophysiological indices of word fragment priming allow characterizing neural stages of speech recognition. *Biol. Psychol.* 80, 105–113.
- Goswami, U., 2005. The effects of spelling consistency on phonological awareness: a comparison of English and German. *J. Exp. Child Psychol.* 92, 345–365.
- Goswami, U., 2008. The development of reading across languages. *Ann. N.Y. Acad. Sci.* 1145, 1–12.
- Grainger, J., Ferrand, L., 1994. Phonology and orthography in visual word recognition: effects of masked homophone primes. *J. Membr. Lang.* 33, 218–233.
- Grainger, J., Ferrand, L., 1996. Masked orthographic and phonological priming in visual word recognition and naming: cross-task comparisons. *J. Membr. Lang.* 35, 623–647.
- Jakimik, J., Cole, R.A., Rudnicki, A.I., 1985. Sound and spelling in spoken word recognition. *J. Membr. Lang.* 24, 165–178.
- Jansen, H., Mannhaupt, G., Marx, H., Skowronek, H., 2002. Bielefelder Screening zur Früherkennung von Lese-Rechtschreibschwierigkeiten (BISC) (2., überarb. Aufl.). Hogrefe, Göttingen.
- Jusczyk, P.W., 1993. From general to language-specific capacities: the WRAPASA model of how speech perception develops. *J. Phon.* 21, 3–28.
- Kooijman, V., Hagoort, P., Cutler, A., 2005. Electrophysiological evidence for prelinguistic infants' word recognition in continuous speech. *Cogn. Brain Res.* 24, 109–116.
- Köppe, R., 1997. Sprachentrennung im frühen bilingualen Erstspracherwerb. *Narr Francke Attempto/BRO, Französisch/Deutsch*.
- Lenhard, W., Schneider, W., 2006. ELFE 1-6: Ein Leseverständnistest für Erst- bis Sechstklässler. Hogrefe, Göttingen.
- Metsala, J.L., Walley, A.C., 1998. Spoken vocabulary growth and the segmental restructuring of lexical representations: precursors to phonemic awareness and early reading ability. In: Metsala, J.L. (Ed.), *Word Recognition in Beginning Literacy*. Lawrence Erlbaum, Mahwah, NJ, pp. 89–120.
- Mills, D.L., Coffey-Corina, S., Neville, H.J., 1993. Language acquisition and cerebral specialization in 20-month-old infants. *J. Cogn. Neurosci.* 5, 326–342.
- Mills, D.L., Coffey-Corina, S., Neville, H.J., 1997. Language comprehension and cerebral specialization from 13 to 20 months. *Dev. Neuropsychol.* 13, 397–445.
- Mills, D.L., Prat, C., Zangl, R., Stager, C.L., Neville, H.J., Werker, J.F., 2004. Language experience and the organization of brain activity to phonetically similar words: ERP evidence from 14- and 20-month-olds. *J. Cogn. Neurosci.* 16, 1452–1464.
- Morais, J., 1993. Phonemic awareness, language and literacy. In: Joshi, R.M., Leong, C.K. (Eds.), *Reading Disabilities: Diagnosis and Component Processes*. Kluwer, New York, pp. 175–184.
- Morais, J., Cary, L., Alegria, J., Bertelson, P., 1979. Does awareness of speech as a sequence of phones arise spontaneously? *Cognition* 7, 323–331.
- Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.
- Pattamadilok, C., Perre, L., Dufau, S., Ziegler, J.C., 2009. On-line orthographic influences on spoken language in a semantic task. *J. Cogn. Neurosci.* 21, 169–179.
- Perre, L., Midgley, K., Ziegler, J.C., 2009a. When beef primes reef more than leaf: orthographic information affects phonological priming in spoken word recognition. *Psychophysiology* 46, 739–746.
- Perre, L., Pattamadilok, C., Montant, M., Ziegler, J.C., 2009b. Orthographic effects in spoken language: on-line activation or phonological restructuring? *Brain Res.* 1275, 73–80.
- Perre, L., Ziegler, J.C., 2008. On-line activation of orthography in spoken word recognition. *Brain Res.* 1188, 132–138.
- Reis, A., Castro-Caldas, A., 1997. Illiteracy: a cause of biased cognitive development. *J. Int. Neuropsychol. Soc.* 3, 444–450.
- Schild, U., Roeder, B., Friedrich, C., 2010. Neuronal spoken word recognition: the time course of processing variation in the speech signal. *Lang. Cogn. Proc.* doi:10.1080/01690965.2010.503532.
- Seidenberg, M.S., Tannenhaus, M.K., 1979. Orthographic effects on rhyme monitoring. *J. Exp. Psychol. Learn.* 5, 546–554.
- Shaywitz, B.A., Shaywitz, S.E., Pugh, K.R., Constable, R.T., Skudlarski, P., Fulbright, R.K., Bronen, R.A., Fletcher, J.M., Shankweiler, D.P., Katz, L., Core, J.C., 1995. Sex differences in the functional organization of the brain for language. *Nature* 373, 607–609.
- Slowiaczek, L.M., Soltano, E.G., Wieting, S.J., Bishop, K.L., 2003. An investigation of phonology and orthography in spoken-word recognition. *Q. J. Exp. Psychol.-A* 56, 233–262.
- Ventura, P., Kolinsky, R., Pattamadilok, C., Morais, J., 2008. The developmental turnpoint of orthographic effects in speech recognition. *J. Exp. Child Psychol.* 100, 135–145.
- Ventura, P., Morais, J., Kolinsky, R., 2007. The development of the orthographic consistency effect in speech recognition: from sublexical to lexical involvement. *Cognition* 105, 547–576.
- Walley, A.C., Metsala, J.L., Garlock, V.M., 2003. Spoken vocabulary growth: its role in the development of phoneme awareness and early reading ability. *Read. Writ.* 16, 5–20.
- Ziegler, J.C., Ferrand, L., 1998. Orthography shapes the perception of speech: The consistency effect in auditory recognition. *Psychon. Bull. Rev.* 5, 683–689.
- Ziegler, J.C., Ferrand, L., Montant, M., 2004. Visual phonology: the effects of orthographic consistency on different auditory word recognition tasks. *Membr. Cogn.* 32, 732–741.
- Ziegler, J.C., Goswami, U., 2006. Becoming literate in different languages: similar problems, different solutions. *Dev. Sci.* 9, 429–453.
- Ziegler, J.C., Muneaux, M., 2007. Orthographic facilitation and phonological inhibition in spoken word recognition: a developmental study. *Psychon. Bull. Rev.* 14, 75–80.
- Ziegler, J.C., Muneaux, M., Grainger, J., 2003. Neighborhood effects in auditory word recognition: phonological competition and orthographic facilitation. *J. Membr. Lang.* 48, 779–793.