Phonological representations at the onset of reading acquisition: steady use of phonological detail from preschool to 2nd grade

Anne Bauch
Claudia K. Friedrich
Ulrike Schild
University of Tuebingen, Germany

Abstract: We tracked the developmental path of aspects of spoken word recognition in the beginning years of reading acquisition in German L1 speaking children. Speech processing of phonological feature variation in voicing was tested in preschool, 1st and 2nd grade. During the word onset priming test, spoken words (targets; “Kino”, Engl. cinema) followed spoken syllables (primes) that were either identical to target word onsets (“Ki“), deviated in the onset speech sound in voicing (“Gi”) or were unrelated (“Ba”). Event-related potentials (ERP) and lexical decision latencies were recorded. Results showed a comparable pattern from preschool to 2nd grade. ERP effects emerged around 100 – 300 ms, replicating previous findings for voicing variations. Children’s faster lexical decisions with increasing age were not paralleled in ERP timing differences between age groups. Thus, from a developmental perspective, emerging and increasing reading skills might not relate to increasing sensitivity for phonological feature variation in the tested aspects of spoken word recognition.

Keywords: spoken word processing; lexical access; event-related potentials, literacy acquisition; preschoolers.

Corresponding author(s): Anne Bauch, Department of Psychology, University of Tuebingen, Schleichstrasse 4, 72076 Tuebingen, Germany. Email: anne.bauch@uni-tuebingen.de.

ORCID ID(s): https://orcid.org/0000-0003-4661-2523 (AB); https://orcid.org/0000-0002-2877-349X (CKF); https://orcid.org/0000-0001-9683-8446 (US)

Citation: Bauch, A., Friedrich, C.K., & Schild, U. (2025). Phonological representations at the onset of reading acquisition: steady use of phonological detail from preschool to 2nd grade. *Language Development Research, 5*(3), 1–32. http://doi.org/10.34842/ldr2025

Introduction

Speech unfolds over time and so word beginnings diverge when more identifying information becomes available for that word. Adult listeners habitually predict words before all the information is available in the speech stream. They appear to face this sequential nature of speech by parallel processing of multiple words. They consider several word candidates that match the input at a given point in time. This parallel processing is a basic feature of psycholinguistic models of spoken word recognition (e.g., Marslen-Wilson, 1987; McClelland & Elman, 1986; Norris & McQueen, 2008; for review see Weber & Scharenborg, 2012). The strength of activation reflects overlap as well as mismatches between the input and stored words (e.g., Allopenna et al., 1998; Soto-Faraco et al., 2001). The mismatch is detected at the level of phonological features (as an example for a phonological feature, namely voicing, consider the different onset of the English words “bin” and “pin”). A single feature mismatch is enough to delay spoken word recognition (e.g., Friedrich et al., 2009), while more feature mismatches add further delay (e.g., Connine et al., 1993; Slowiaczek et al., 1987). In the present study, we aim to track the developmental trajectory of sensitivity to such phonological feature variation in voicing variations in children during the onset of reading acquisition in middle childhood. This developmental period has been associated with the plasticity of phonological processing (e.g., Goswami, 2000).

Initially, enhanced phonological processing in readers was demonstrated by performance in tasks that measure explicit understanding and processing of speech units (*phonological awareness* in general, or *phonemic awareness* for single speech sounds in particular; Anthony & Lonigan, 2004; Goswami, 2000; see also Caravolas & Bruck, 1993; Hulme et al., 2005). For example, reading children outperformed prereaders on phoneme segmentation(Ehri & Wilce, 1980; Treiman & Cassar, 1997; Tunmer & Nesdale, 1985), and literate adults outperformed illiterate adults on phoneme addition and deletion (Morais et al., 1979). Whether reading experience only affects metalinguistic, post-lexical levels (skills associated with phonemic awareness; see Cutler & Davis, 2012; Mitterer & Reinisch, 2015) or also earlier stages of speech processing (like pre-lexical and lexical stages before word access, henceforth automatic stages) itself is disputed. Some authors have argued that reading experience updates aspects of spoken word recognition (e.g., Dehaene et al., 2015; Harm & Seidenberg, 2004; Muneaux & Ziegler, 2004; Pattamadilok et al., 2010; Taft, 2006; Ziegler & Ferrand, 1998). They assume that phonological representations along the speech recognition pathway are restructured by reading and its precursor functions such as phonological and phonemic awareness and grapheme knowledge (Dehaene et al., 2015; Harm & Seidenberg, 2004; Taft, 2006). So called “orthographic consistency effects” seem to back up the assumption that orthographic information is involved in auditory word activation in metalinguistic tasks. For example, listeners tended to identify rhyming word pairs faster, when the pairs shared similar phonology and orthography (e.g., “house – mouse”) as when the spelling differed between the words (e.g., “flow –

though”; Pattamadilok et al., 2007, 2014; Perre et al., 201; Ventura et al., 2004; Ziegler & Ferrand, 1998). Furthermore, brain imaging revealed that when listening to speech, adult readers showed higher activity in brain regions which are associated with processing phonological information (compared to illiterate adults; Chang et al., 2010; Dehaene et al., 2010; Mesgarani et al., 2014; see Monzalvo & Dehaene-Lambertz, 2013 for a replication with 6-year-old reading vs. non-reading children). However, other studies have questioned the existence of an intimate relationship between online speech processing and literacy. For instance, by comparing brain activity to speech perception tasks in adults with varying degrees of literacy skills (from illiterate to proficient readers), Hervais-Adelman et al. (2021) did not find evidence that direct brain responses to speech differed between groups with different literacy levels. Instead, the authors suggested that literacy instead might rather promote connectivity between different brain regions that are involved in speech processing, like graphomotor areas and the left posterior superior temporal gyrus, which is associated with the categorical representation of speech sounds.

The analysis of event-related potentials (ERPs) provides detailed insight in temporal processes of word recognition and is suited to investigate word activation processes during an unfolding speech signal. In relation to potential orthographic effects that might occur while listening to spoken language, ERPs have, for example, been used to investigate word-level based auditory orthographic consistency effects through various tasks, such as lexical decision tasks (Perre & Ziegler, 2008), rhyme judgement tasks (Pattamadilok et al., 2011) or non-linguistic Go-NoGo tasks (Perre et al., 2011). Those studies found considerable evidence of an activation of orthographic cues as early as 100 – 300ms after word onset.

Using the ERP analysis, we previously tried to take a closer look at which factors of reading acquisition might potentially modulate word activation at automatic and post-lexical stages of speech processing and sensitivity to phonological feature variation (Bauch et al., 2021). For 10 weeks, pre-literate 6-year-old German native speaking preschoolers participated daily in short games that were either targeting skills in phonemic awareness (solely or in combination with grapheme knowledge, e.g., onset phoneme identification tasks among others) or took part in a control intervention that trained arithmetic skills (for detailed information about the control training, see Schild et al., 2020). In the phonemic trainings, children were especially sensitized for a set of phonemes that differed in the German language only in one phonological feature, namely voicing feature (/g/ and /k/). After the training had taken place, we were interested in whether the specific training in precursor functions of reading might modulate the processing of subtle phonemic mismatch in comparison to the control group. All children participated in a word onset fragment priming paradigm with a lexical decision task. We tested sensitivity to phonemic mismatch by means of ERP amplitude differences and reaction times. Children listened to target words that were preceded by prime syllables that either matched in their initial phoneme (Identity condition, e.g., “Ki – Kino”, Engl. cinema), differed in the voicing feature (Variation condition, e.g., “Gi – Kino”) or were unrelated (Control condition, e.g., “Ba – Kino”). In previous studies using the same paradigm, adults (e.g., Friedrich et al., 2009) as well as reading preschoolers and 2nd grade children but not preliterate preschoolers (Schild et al., 2011), depicted a graded activation pattern of response times and ERPs that depended on the goodness-of-fit between the onset phoneme of syllable prime and target word. In those studies, prime-target pairs varied in place of articulation (e.g., “Non – Monster”) and revealed differentiating ERP amplitudes emerging between 300 – 400ms (referred to as P350 effect) after stimulus onset, indicating that participants used phonological feature variation for multiple word activation during lexical access. While the effect manifested bilaterally in preschool children, 2nd graders showed a left-lateralization that was comparable to the pattern found in adults (e.g., Friedrich et al., 2009), indicating developmental plasticity in hemispheric lateralization that might be independent of literacy acquisition. From these results, we concluded that multiple activation of phonological matching word forms in pre-reading preschoolers appeared to be more tolerant to variation in place of articulation than in reading children and adults. Reading children potentially might use more phonological detail than pre-readers for activating word candidates that match the input (as reflected in graded P350 effects in their ERPs).

Results from the training study (Bauch et al., 2021) partially backed up those previous findings: While reaction time latencies indicated similar post-lexical processing of the phonemic mismatch in all training groups and an adult control group, we found evidence for enhanced phonological processing at early stages of phonological perception (around 100 – 300 ms after stimulus onset) bilaterally over anterior regions for children in the phonemic trainings only. ERP amplitudes to matching prime-target pairs and partially mismatching prime-target pairs revealed that preliterate preschoolers who participated in a phonemic awareness training processed phonemic variation with more sensitivity than preliterate preschoolers who had received the control training. Specifically, mismatching word onset feature started to impact speech processing around 100 ms after word onset, which is a time window that was previously associated with the N100/T-complex and enhanced early auditory and phonological analysis of speech input, as well as auditory attention mechanisms (Connolly, 1993; Diesch & Luce, 2000; Näätänen & Picton, 1987; O'Rourke & Holcomb, 2002; Poeppel et al., 1997; Sanders, Newport, & Neville, 2002; Wolpaw & Penry, 1975). Altogether, we concluded from our previous studies (Bauch et al., 2021; Schild et al., 2011) that like adults (Friedrich et al., 2009; Schild et al. 2012), children use phonological detail for processing spoken language and that processing of phonological detail might be enhanced in children who either have explicit reading expertise (Schild et al., 2011) or have been trained in precursor functions of reading (Bauch et al., 2021), compared to same aged children without reading-related training. The results also indicated that different phonological features might be processed at different processing stages, although direct comparisons between the studies could not be drawn due to methodological differences and different levels of literacy experience between the participants.

To further investigate the role of reading expertise on phonological processing of spoken language especially in a longitudinal approach, in the current study we followed up the children of our training groups in a longitudinal approach. We aimed to gain more insight in the development of phonological representations beyond a cross-sectional comparison as done in Schild et al. (2011). Furthermore, we were interested in how phonological processing of voicing alterations might develop during the first years of formal reading instruction. Specifically, we sought to investigate whether the found enhanced phonological processing of voicing alterations in the trained children might be a short-term product of the training or might undergo further development after the children started learning to read. Children from our training study (Bauch et al., 2021) were re-invited to our laboratory at the end of their first and their second grade. The subjects participated in the same word onset priming paradigm with identical stimulus material as during preschool assessments (see Bauch et al., 2021). If enhanced sensitivity to voicing mismatch during phonological encoding was a temporal by-product of our explicit phonemic awareness training tailored to this phonological feature, this effect in the children might have vanished after a year of attending 1st grade. However, if increasing levels of phonological awareness and reading skills through formal teaching directly relate to increasing sensitivity for phonological feature variation in early automatic speech processing, we expected a stronger priming effect for ERPs as well as for reaction times in 2nd graders, compared to 1st graders, compared to preschoolers.

Methods

Procedure

All participants were part of a training study that was conducted during their final year of kindergarten in their respective kindergarten institutions (approximately 6 months prior to entering elementary school, a transition that is accomplished in Germany within the 6th year of life). The children received a training of precursor functions of reading (phonemic awareness training only or in combination with letter knowledge) or an arithmetic control training (details see Schild et al., 2020). In total, $N = 102$ monolingual children participated in the training study. Ten additional bilingual children also attended the training to maintain the integrity of the pre-school groups, but they did not participate in the study and data collection. After the ten-week-training period, the preschoolers took part in an individual testing session lasting about 30-40 minutes, in which we obtained explicit measurements of language and general cognitive abilities. Furthermore, the children attended one session at our laboratory. Here, they conducted a reaction time experiment with EEG recording that took about 30-40 min to complete.

All children and parents were invited to participate in two follow-up sessions at the end of 1st and 2nd grade. We obtained measures of reading skill as well as explicit measurements of language (about 60 min) for 1st and 2nd graders. We repeated the reaction time experiment with EEG recording with the pupils in each grade in an additional session at our laboratory (about 30-40 min, more details below).

Participants

The trainings were carried out at local kindergartens in the city of Tuebingen, Germany. Before the training started, parents and children received written information about the project and gave their written consent to participate in the whole study (including all three measurements). The ethical committee of the German Psychological Association (Ethikkommission der Deutschen Gesellschaft für Psychologie, 08.2014) advised us regarding the procedures we adopted in this study. There were no ethical concerns raised by the committee.

Originally, we invited all children from the former training study (Bauch et al., 2021) to again participate in the longitudinal study. Because the ERP analysis results differed for preschoolers from the phonemic training groups and the control training group, we did not plan a collapse of all data for the present study. Instead, we aimed for separate analysis for the different training groups. Unfortunately, only 9 children from the original control training group (N = 21) contributed complete data for all three points of measurements (preschool, 1st and 2nd grade), which led to inconclusive analysis results for this particular group of participants. Hence, for the present study we only considered data from children who had previously received one of the two phonemic interventions[1]. This sample included N = 46 children (n = 24 from the phonemic awareness only group, n = 22 from the combined phonemic awareness and letter knowledge group).

A detailed description of training results is presented in Bauch et al. (2021). As pre-post-intervention comparisons in the intervention study revealed, both groups with a phonemic training showed an increased performance on phonological awareness test compared to the control group. Furthermore, ERP analysis revealed sensitivity for phonological mismatch in both groups with a phonemic awareness training, but tolerance for phonological mismatch in the control group. In neither the phonological

---

[1] In the original analysis reported in Bauch et al. (2021) we found that children from both phonemic trainings showed similar ERP processing in the time window of interest (100-300ms), but not the control group. For the present longitudinal analysis, we therefore planned separate analyses for the phonemic groups and the control group. As only 9 children of the control group contributed complete data sets over the two follow up years, we decided to drop the control group from further analyses. We decided to refrain from merging the 9 valid data sets from the control group with the 28 data sets from the phonemic training groups because of the previously found differences in the baseline neurophysiological processing of the phonemic groups and the control group.

awareness test nor in ERPs, did we find group differences between children that received a pure phonemic awareness training and children with a combined phonemic-orthographic training. Additionally, we compared preschooler's letter knowledge before and after the training. However, there was no significant difference between the growth of letter knowledge between these children and children of a group that exercised on precursor functions of mathematical abilities. This indicated that there was no advantage of letter knowledge in any of the training group that exceeded maturation effects. Consequently, we decided to collapse data sets from both phonemic awareness training groups for the present analysis.

From the 46 preschoolers who had received phonemic awareness training, 28 fulfilled the following inclusion criteria: (1) Parents of the child were native speakers of German and German was the only language spoken at home. (2) The child was not identified as an early reader in preschool via the "Ein Leseverständnistest für Erst- bis Sechstklässler" reading test (ELFE 1-6, Lenhard & Schneider, 2006). A child was considered to be an early reader in this test when they were able to read aloud single unknown words at the subtest "Word Comprehension". (3) The child was not able to read words (except for their own name) in preschool. (4) The child participated and completed all standardized tests in all three points of measurement (preschool, 1st grade, 2nd grade). (5) We were able to obtain EEG recordings from the child at each point of measurement that provided enough segments for analysis (i.e., EEG recordings contained only a minimal amount of noise and provided a minimum of 15 segments per condition (40% of segments per condition) for ERP analysis). (6) The child's error rate in the lexical decision task was below the cut-off rate (for missing words > 20%; for incorrect responses to pseudo-words > 80%). (7) In 1st as well as in 2nd grade, the child's scores in the reading test "Würzburger Leise Leseprobe - Revision" (WLLP-R, Schneider et al., 2011) and in all subtests of the phonological awareness test "Test zur Erfassung der phonologischen Bewusstheit und Benennungsgeschwindigkeit" (TEPHOBE, Mayer, 2011) were at least at average or above average. The final sample size of $N = 28$ aligned with sample sizes of previous studies with the same paradigm and analysis design in children and in adults, which yielded robust findings of the effects in question (e.g., for children: $n = 21\text{-}24$ in Bauch et al., 2021; $n = 13\text{-}19$ in Schild et al., 2011; for adults: $n = 20\text{-}25$ in Friedrich et al., 2009; Schild et al., 2012). Thus, we considered the sample size sufficient for analysis. Out of the 28 datasets we considered for the present analysis, $n = 13$ had received a combined phonemic-orthographic training in preschool.

Table 1 summarizes demographic information and sample characteristics. Preschool children did not have advanced reading skills, but rudimentary knowledge of letters (e.g., knowledge of the letters in their given names). At preschool, all children scored at least average in the phonological awareness test TEPHOBE. For none of the children, parents reported neurological or hearing problems. All children had normal or corrected to normal eyesight. Handedness for all participants was obtained via the "Edinburgh Handedness Inventory" (EHI, Oldfield, 1971).

Training of phonemic awareness

Children received a daily training of phonemic awareness over a period of ten consecutive weeks. Each session ran for approximately 10 to 15 minutes and was conducted by instructed collegiate and doctoral members of the Department of Psychology, Eberhard-Karls-University Tuebingen, Germany. Each session consisted of two to three short games that focused on the training of phoneme onset detection (e.g., identifying the first sound in a given object) and on the training of phoneme synthesis and analysis (e.g., segmenting words to their single phonemes and vice versa, e.g., segmenting the word "gold" in its respective phonemes). The training program was adapted from Küspert and Schneider (2008) and Plume and Schneider (2004). For more details on the training study materials, see Bauch et al., (2021).

Table 1. ***Demographic data and mean results of the standardized tests***

Variable	Preschool	1st Grade	2nd Grade
Sex (male/female)	16/12	16/12	16/12
Mean age (*SD*)[a]	73.78 (4.71)	85.92 (5.03)	96.60 (5.13)
Mean LQ (*SD*)	54.86 (57.31)	-	-
Mean TEPHOBE (*SD*) Total Score	21.64 (3.90)	24.25 (3.70)	26.28 (1.18)
Mean Letter Knowledge (*SD*); capital/small letters	11.00/7.64 (4.09/3.92)	-	-
Mean WLLP-R (*SD*)	-	43.28 (13.68)	73.32 (19.55)

Note. Presented results include standardized tests on handedness (LQ; Oldfield, 1971), phonological awareness (max = 28, TEPHOBE Total Score; Mayer, 2011), letter knowledge (max = 15 for capital and small letters) and reading speed (max = 140, WLLP-R; Schneider et al., 2011). By the end of the 1st and 2nd grade children knew all capital and small letters from the letter knowledge test. Reading speed was only assessed at 1st and 2nd grade, handedness LQ was once measured at preschool. [a] In months, at post-test. Laterality index (LQ) between -100 to -29 indicates left handedness, LQ between -28 to 48 indicates no preference in handedness, LQ between 49 to 100 indicates right handedness.

Test materials

Phonological awareness was tested during preschool, 1st grade and 2nd grade. Reading skills were obtained in the two follow-up sessions in school. Handedness was tested once in preschool.

Phonological awareness. Phonological awareness was measured with the TEPHOBE (Mayer, 2011). This test is available in a version for preschoolers and 1st graders combined and a version for 2nd graders. The TEPHOBE version for preschool children and 1st graders contains the four subtests *Synthesis of Onset and Rhyme, Phoneme Synthesis, Rhyming,* and *Categorization of Initial Sounds*. Due to ceiling effects in the preschoolers, we decided to test 1st graders with the TEPHOBE version for 2nd graders. This version contains five subtests, *Rhyming, Categorization of Onset Phonemes, Categorization of Offset Phonemes, Phoneme Elision* and *Phoneme Reversal*. The latter was excluded as it did not assess a skill relevant for our research question.

Letter knowledge and reading skills. The children were asked to name 15 capital and their corresponding small letters to measure their rudimentary letter knowledge in preschool (G, K, B, P, A, E, I, U, O, D, T, S, W, H, R). We tested 1st and 2nd graders once with one version of the WLLP-R (Schneider et al., 2011). This reading test assesses reading speed in elementary school children. The WLLP-R is available in two versions, which contain the same items but in changed sequence. 1st graders were tested with the A version, 2nd graders with the B version. In preschool, we used the ELFE 1-6 (Lenhard & Schneider, 2006) to identify early readers who were later excluded from the study. The ELFE 1-6 measures reading comprehension of 1st to 6th graders in three subtests (*Comprehension of Words, Comprehension of Sentences, Comprehension of Texts*). Children were excluded when they were able to read and understand words that were given in the subtest *Comprehension of Words,* ergo when they were able to read single given words.

Experimental stimuli and procedure

The experimental material was identical to the material we used in Bauch et al. (2021). We used 74 monomorphemic disyllabic German nouns as targets (see Table A1 in the appendix). All of the nouns were stressed on the first syllable. Half of the nouns started with the phonemes /g/ or /k/, the other half started with /b/ or /p/. The latter phonemes had not been a set of sounds that we trained in the interventions and served as a set of control phonemes that also differed in the voicing feature, in order to track potential generalization effects across different set of phonemes. 74 pseudo-words were added as distractors for the lexical decision task. We generated them by extracting the second syllable of each target word and substituting them with the second syllable of another target word. For example, the second syllable of “Ki*no*” (Engl. cinema) was inserted as the second syllable in “Buers*te*” (Engl. brush) and vice versa, resulting in the two pseudo-words “Ki*te*” and “Buer*no*” (both words do not exist in the German language). Primes were created from the first syllable of each target word.

The prime-target combination varied across three conditions. In the Identity condition, prime and target completely matched (e.g., "Ki - Kino"). In the Variation condition, the prime varied from its assigned target in the voicing of its initial sound (e.g., "Gi - Kino"). In the Control condition, the prime and the target were unrelated insofar as their first syllables contained different phonemes and, additionally, the first phoneme differed in place of articulation as well as in voicing to maximize differences between prime and target (e.g., "Ba - Kino"). Furthermore, prime-target pairs in the control condition never matched in the respective vowels following the initial consonants. A pseudo-word appeared instead of a target in 33% of the trials. Primes and pseudo-words were combined according to the different conditions in the same way as the primes and targets. Targets appeared once in each condition, pseudo-words only once in total.

A male and a female native German speaking actor and actress produced the spoken material. The primes were taken from words spoken by the male speaker while the targets and pseudo-words were taken from the female speaker to prevent mere acoustical priming effects. None of the speakers was aware of the purpose of the study.

Children completed a unimodal auditory word fragment priming experiment with EEG recording. In total, 296 trials (222 targets and 74 pseudo-words) were presented, which appeared in twelve blocks. In eight blocks, the children listened to 25 trials and in four blocks to 24 trials. Targets were not repeated within a block. Trials were randomized within each block. The sequence of the blocks was balanced across participants. We introduced the experiment as a "Word-Catching-Game". Children were instructed to press the space bar as fast and as correctly as possible whenever they heard a real word and refrain from responding whenever they heard a pseudo-word. Each trial started with the presentation of a fixation picture (1x1 cm, a smiley) in the middle of the screen. After 500 ms the auditory prime was presented. The auditory target or a pseudo-word followed 200 ms after offset of the prime to create a comparable and adequate baseline period for the ERPs. Visual feedback (3x7 cm) was provided for about two seconds in every case the child responded correctly to a target (a smiley flying into a basket) or incorrectly pressed the space bar for a pseudo-word (a little ghost appeared in the middle of the screen). The next trial started 1.5 seconds after feedback offset. No feedback was given whenever the child missed a target. In this case, the next trial started 3.5 seconds after the onset of the target. After each block, a short break was provided. Half of the children used the index finger of their right hand, while the other children used the index finger of their left hand to press the space bar.

Electrophysiological recording

We used 46 active Ag/AgCl electrodes (Brain Products) attached into an elastic cap (Electro Cap International, Inc.) for the continuous EEG recording according to the international 10-20 system (bandpass filter 0.01-100 Hz, BrainAmp Standard, Brain Products, Gilching, Germany). The reference and the ground electrodes were placed on the tip of the nose and in the electrode cap at position AF3, respectively. Two additional electrodes were placed below each eye. Two eye-calibration blocks were presented before and after the experiment. EEG data was processed with the Brain Electrical Source Analysis Software (BESA, MEGIS Software GmbH, Version 5.3). We applied the surrogate Multiple Source Eye Correction (Berg & Scherg, 1994) implemented in BESA for eye-movement artifact correction. For offline analysis, the signal was re-referenced to an average reference. All artifact rejection was computed manually and by visual inspection. Individual noisy channels were linearly interpolated for all trials ($M = 3.40$, $SD = 1.72$, *Range* = 0-9). Results reported in the main text were based on recordings filtered offline with a 0.3 Hz high-pass filter. As pointed out by a reviewer, strong high-pass filter might carry the risk of EEG distortion (e.g., Tanner et al., 2015). Therefore, and as suggested by the reviewer, we also considered a re-analysis of the ERP recordings filtered at 0.1 Hz. Those results are reported in Table A2 in the appendix. The re-analysis with 0.1 Hz filter obtained the same significant interaction effects as we found with our original 0.3 Hz filter analysis, therefore we opted for reporting our original analysis with 0.3 Hz filter in the following results section. ERPs were computed only for targets with correct responses, starting from the beginning of the speech signal until 700 ms post-stimulus onset, with a 200 ms pre-stimulus baseline.

Data analysis

Explicit tests. We applied a repeated measures ANOVA with the within-factor *Age* (Preschool vs. 1st grade vs. 2nd grade).

Reaction times and errors. Reaction times (RT) shorter than 200 ms and longer than 2000 ms were removed from analysis. A repeated measures ANOVA with the within-factors *Condition* (Identity vs. Variation vs. Control) and the within-factor *Age* (Preschool vs. 1st grade vs. 2nd grade) was applied. The same procedure was used for the analysis of errors in word trials (omissions).

Event-related potentials. In order to analyze N100 as well as P350 effects, and to keep the analysis closer to the analysis we carried out in our previous studies, four lateral regions of interest (ROI, anterior-left: F9, F7, F3, FT9, FT7, FC5, FC1, T7, C5; posterior-left: C3, TP9, TP7, CP5, CP1, O9, P3, PO9, O1; anterior-right: F10, F8, F4, FT10, FT8, FC6, FC2, T8, C6; posterior-right: C4, TP10, TP8, CP6, CP2, P8, P4, PO10, O2) were identified prior to analyses. Averaged ERPs across each participant and each condition entered analysis. ERP amplitudes were computed with the same ANOVA as the reaction times, with the additional factors *Region* (anterior vs. posterior) and *Hemisphere* (left vs. right). To make the present analysis comparable to the results of Schild et al. (2011) and Bauch et al. (2021), we adapted the same time windows in the present study. This resulted in a first-time window ranging from 100 to 300 ms and a second time window from 300 to 400 ms. Both time windows preceded the behavioral responses. The following result section will only report the highest-ranking significant interactions of *Condition* with significant post hoc comparisons. In case of significant interactions, further follow-up ANOVAs and *t*-tests were computed. All *t*-test results reported below were subject to a Holm-Bonferroni correction.

Results

Explicit tests

In the test for phonological awareness, the ANOVA revealed a main effect of *Age* ($F(2, 54) = 17.80$, $p < .001$, $p^2 = .40$). Children scored best on this when they were at the end of 2nd grade, medium when they were at the end of 1st grade and lowest when they were in preschool. All time points differed significantly from each other, all $t(27) \geq 2.65$, $p \leq .01$, $d \geq .36$. Also in the speed reading test, the ANOVA revealed a main effect of *Age* ($F(1, 27) = 140.83$, $p < .001$, $p^2 = .84$). Children scored higher in the reading test in the 2nd grade, compared to the 1st grade, $t(27) = 11.86$, $p \leq .001$, $d = 15.52$.

Reaction time and error analysis

The ANOVA for reaction times revealed a main effect of *Condition* ($F(2, 54) = 87.49$, $p < .001$, $p^2 = .76$). Response times differed significantly from each other in each condition, all $t(27) \geq 5.69$, $p \leq .0001$, $d \geq$ .1.01. Across all points of measurement, children responded fastest to the Identity condition ($M = 956.78$ ms, $SD = 99.78$ ms), followed by medium response times in the Variation condition ($M = 988.79$ ms, $SD = 98.65$ ms), and slowest response times in the Control condition ($M = 1061.30$ ms, $SD = 109.57$ ms). Furthermore, a main effect of *Age* ($F(2, 54) = 10.03$, $p < .001$, $p^2 = .27$) revealed that across all trials, children responded faster as pupils (1st grade: $M = 987.79$ ms, $SD = 114.52$ ms; 2nd grade: $M = 954.70$ ms, $SD = 135.78$ ms) than they responded as preschoolers ($M = 1064.38$ ms, $SD = 126.40$ ms), both $t(27) \geq 3.30$, $p \leq .002$, $d \geq .59$. There was no difference between the overall response times obtained at the end of the 1st and 2nd year of schooling, $t(27) = 1.24$, n.s. We did not find an interaction effect of *Age* x *Condition* ($F(4, 108) = 1.71$, n.s.). Figure 1 illustrates the mean response times as a function of age and condition.

The overall error rate across children and conditions was 2.84% ($SD = 1.65$, Range 1.05% - 7.50%). The ANOVA revealed a main effect of *Age* ($F(2, 54) = 21.75$, $p < .001$, $p^2 = .45$). At the end of their 1st and 2nd grade, children made less mistakes than they made in preschool, both $t(27) \geq 4.90$, $p \leq .0001$, $d \geq .70$. While in preschool, children missed on average 4.76% ($SD = 3.23\%$) “yes” responses to words, the error rate dropped to 1.88% ($SD = 1.45\%$) and 1.44% ($SD = 1.48\%$) at the end of 1st and 2nd grade, respectively. Overall error rates at the end of 1st and 2nd grade, did not differ significantly, *t*(27) = 1.31, n.s. There was no significant main effect of Condition (*F*(2, 54) = 1.95, n.s.), and no interaction between *Age* x *Condition*, *F*(4, 108) = 0.85, n.s.

Event-related potentials

Figure 2 presents the ERP effects for anterior and posterior regions for each age group. Figure 3 presents averaged priming effects between the three age groups, suggesting that there were no timing differences of ERP deflections paralleling the reaction time differences obtained at the three ages.

100 – 300 ms, N100. The ANOVA revealed significant interactions of *Condition* x *Region* (*F*(2, 54) = 26.51, $p < .001$, $p^2 = .50$) and *Condition* x *Hemisphere* (*F*(2, 54) = 7.84, $p = .001$, $p^2 = .23$). A graded ERP priming pattern emerged when anterior and posterior regions were considered separately (as guided by the significant interaction of the factors *Condition* and *Region*). Amplitudes from the Identity condition and from the Variation condition were both more negative over anterior and more positive over posterior regions than amplitudes from the Control condition, all $t(83) \geq 2.93$, $p \leq .004$, $d \geq .34$. Crucially, amplitudes from the Identity condition were also more negative (resp. positive) than amplitudes from the Variation condition, $t(83) \geq 2.13$, $p \leq .03$, $d \geq .23$.

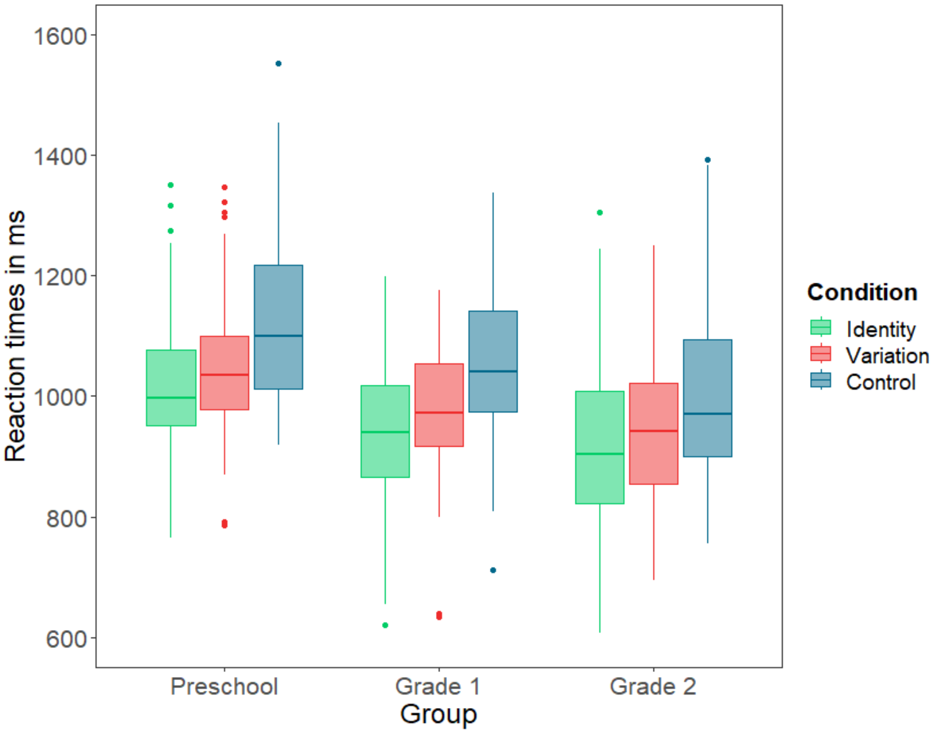

Figure 1. ***Mean reaction times and quantiles of the three conditions (Identity,***

Variation and Control) for each age group (Preschool, Grade 1, Grade 2).

At the same time, there were indices of rough priming, not differentiating the Identity and the Variation condition, for the left hemisphere (the significant interaction of the factors *Condition* and *Hemisphere* guided separate consideration of both hemispheres). Over the left hemisphere, amplitudes in the Identity and Variation condition were both more negative than in the Control condition, both $t(83) \geq 4.01$, $p \leq .0001$, $d \geq .46$. There was no difference between amplitudes from the Identity and Variation condition, $t(83) = 0.07$, n.s. Over the right hemisphere, amplitudes in the Variation condition were more negative than amplitudes from the Control condition, $t(83) = 3.22$, $p = .001$, $d = 0.34$. There were no significant differences between the Identity and Variation condition, nor between the Identity and Control condition, all $t(83) \leq 1.63$, n.s.

Additionally, and as suggested by a reviewer as post-hoc analysis, we included a latency analysis of peaks to consider for timing differences in neurophysiological processing between the three age groups. There were no significant differences in the latencies between the age groups, $F(2, 81) = 0.46$, $p = .631$, $p^2 = .01$. Figure 3 presents averaged priming

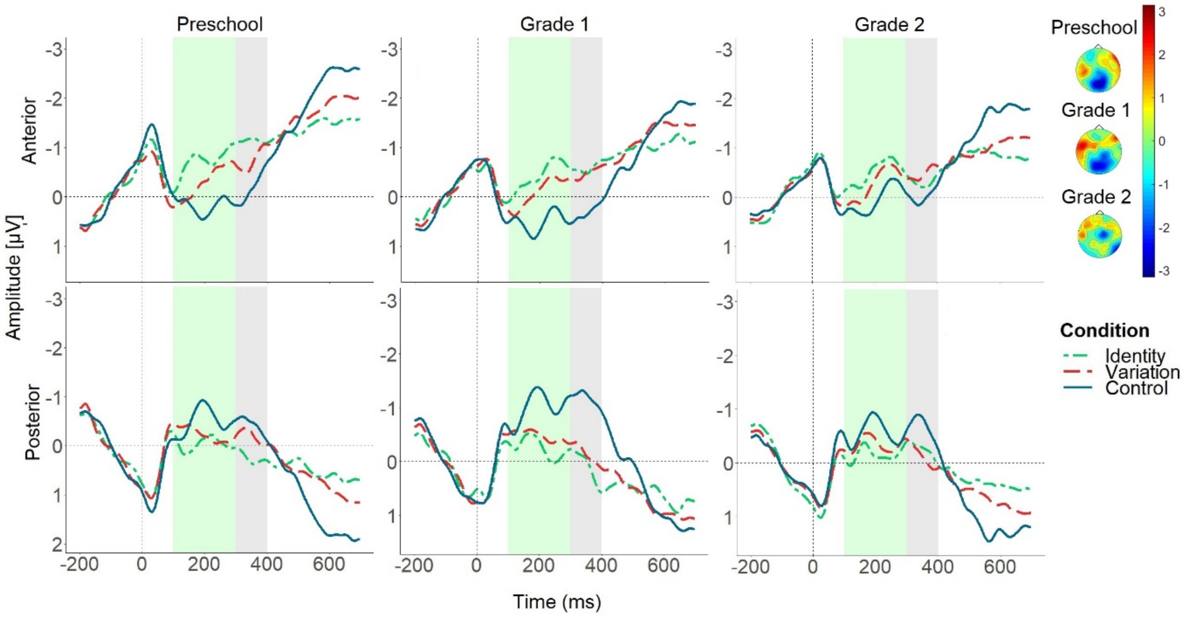

Figure 2. ***Mean ERP effects over anterior and posterior regions for all groups. Identity condition (green, short-dashed line), Variation condition (red, long-dashed line) and Control condition (blue, solid line). The light green bar marks the analysis area for the time window ranging from 100 to 300 ms. The grey bar marks the analysis area for the time window ranging from 300 to 400 ms. Topographical voltage maps***

indicate difference waves for the Variation condition minus the Identity condition for each age group. Topographical voltage maps represent averaged amplitude differences for all age groups for the time window ranging from 100 to 300 ms, during which significant differences between the Identity condition and the Variation condition occurred.

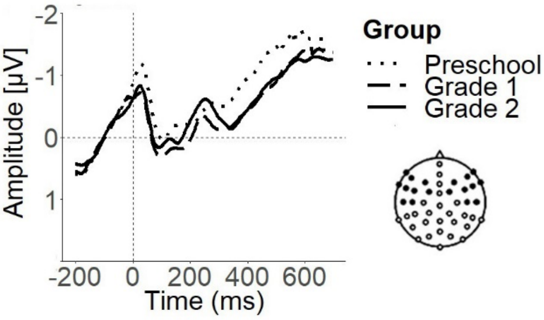

Figure 3. ***Averaged amplitudes for all conditions for each age group. Preschoolers (dotted line), 1st graders (dashed line), 2nd graders (solid line). Electrode position map with marked electrodes for anterior regions.***

effects between the three age groups, suggesting that there were no timing differences of ERP deflections paralleling the reaction time differences obtained at the three ages.

300 – 400 ms, P350. Again, the ANOVA revealed two significant interactions, one of the factors *Condition* x *Region* (*F*(2, 54) = 23.74, $p < .001$, $p^2 = .47$), and another one of the factors *Condition* x *Hemisphere* (*F*(2, 54) = 6.18, $p = .004$, $p^2 = .19$).

Both interactions pointed to rough priming, not differentiating the Identity and the Variation condition in the second time window. Guided by the significant interaction of the factors *Condition* and *Region*, we analyzed anterior and posterior regions separately. There were no differences between amplitudes from the Identity and Variation condition (both $t(83) \leq 1.26$, n.s.), but amplitudes from both conditions were more negative over anterior and more positive over posterior regions than amplitudes rising from the Control condition, all $t(83) \geq 4.02$, $p \leq .0001$, $d \geq .44$. Guided by the significant interaction of the factors *Condition* and *Hemisphere*, we also analyzed left and right regions separately. Over the left and right hemisphere, only amplitudes from the Variation condition were more negative than amplitudes from the Control condition, $t(83) \geq 2.72$, $p \leq .007$, $d \geq .28$. We found no differences in the comparisons between the amplitudes from both Identity and Variation condition and Identity and Control condition, all $t(83) \leq 1.88$, n.s.

To sum up, we found graded response times and early graded ERP priming patterns differentiating all three conditions across all three tested ages. There were no timing differences in the ERPs paralleling speeded lexical decisions when children were able to read.

Discussion

In a longitudinal study, we tested how children process spoken words after a training of phonemic awareness in preschool, and as a function of formal reading and writing instruction in elementary school. The training comprised ten weeks with daily ten-minute training sessions (see Bauch et al., 2021). For the second and third measurement, we tested the children who had participated in the training at the end of their first and second year of elementary school. We were interested in the degree of speech detail that children considered for different aspects of spoken word recognition, and in the timing of those aspects as a function of reading acquisition. To this end, we recorded lexical decision latencies and ERPs to targets presented in spoken word onset priming at all three measurements. We considered different responses to targets overlapping with preceding primes (e.g., "Ki - Kino") compared to partially mismatching targets (e.g., "<u>G</u>i - <u>K</u>ino") as informative regarding the amount of speech detail that children exploit. ERPs indicated that children were able to exploit phonological feature variation at all points of measurements. In the ERPs, matching and partially mismatching targets elicited differences substantiating 100 to 300 ms after target word onset across all ages, replicating previous results for phonemic variations in voicing for preschoolers sensitized to voicing mismatches (Bauch et al., 2011). Reduced amplitudes within this time window have been interpreted to be related to facilitated auditory processing and phonological encoding (Friedrich et al., 2009; Lange & Röder, 2006; O'Rourke & Holcomb, 2002; Praamstra & Stegeman, 1993; Sanders & Astheimer, 2008; Sanders & Neville, 2003; Schild et al., 2014; Schild et al., 2012).

Steady priming effects in the ERPs across the three age groups indicated that the processing of phonological detail did not change with emerging reading experience (1st grade) and prolonged reading experience (2nd grade). After preschool, children's phonemic awareness training continued during this longitudinal study when they entered elementary school, where they received formal instruction on the phonological principle. Indeed, children constantly improved in phonological awareness measures in offline explicit phonological awareness tasks. Children scored lowest on these measures of phonological awareness when they were in kindergarten and highest when they were in 1st and 2nd grade. This is in line with various studies showing that specific aspects of phonological awareness profit from reading acquisition (Ehri & Wilce, 1980; Morais et al., 1979; Treiman & Cassar, 1997; Tunmer & Nesdale, 1985). Additionally, other factors such as general maturation processes and/or linguistic exposure might underlie development of phonological awareness related skills in children aged 6 to 8 years (Bentin et al., 1991; Cunningham & Carroll, 2011). Yet, this growth in metalinguistic speech processing was not reflected in the amount of detail children used during spoken word processing at pre-lexical level. These results might imply that sensitivity for phonemic mismatch was sufficiently adapted at the the end of the preschool training. Thus, and contrary to our expectation, children do not appear to specify their phonological representations as a function of developing phonological awareness, phonemic awareness or more broadly emerging reading skills. Rather, they appear to reach a threshold level of which might be sufficient to facilitate phonetically mediated access and strategic mechanisms across middle childhood.

Still, we interpret the current results in favor of the assumption that, in middle childhood, automatic stages of speech processing are modulated by facilitated phonological processing via precursors of literacy such as phonological and phonemic awareness (Dehaene et al., 2015; Harm & Seidenberg, 2004; Pattamadilok et al., 2010; Taft, 2006). Former research pointed to the mutual relationship between learning to read and phonemic awareness (Deacon et al., 2013; Perfetti et al., 1987). At an initial stage of reading, decoding letters to corresponding sounds is crucial for understanding the alphabetic script (Anthony & Francis, 2005). Thus, learning to read emphasizes and triggers the refinement of explicit phonological representations which feeds back on their implicit counterparts stored in the mental lexicon. Taking into consideration that adult participants in the training study showed no specific sensitivity to voicing mismatches in the ERPs (Bauch et al., 2021), one might speculate that phonemic information regarding voicing is heightened when readers initially become sensitive to small differences between phonemes. Later on, at least for voicing, such differences might become less important for pre-lexical processing.

Again, in the present study, ERP differences obtained for matching and partially mismatching targets for voicing feature emerged somewhat earlier than the formerly obtained ERP differences for place variation in adults (e.g., Friedrich et al., 2009; Schild et al., 2012) and reading children (Schild et al., 2011). In the present study, ERP differences were evident between 100 and 300 ms after target word onset across all age groups. As the timing of ERP differences in the present study was consistent for all age groups (and hence was not restricted to the training), these results further suggest that timing differences across the various studies using word fragment priming relates to the different features varied in the studies. While initial place varied in partially mismatching prime-target pairs in the former studies (e.g. Friedrich et al., 2009 for adults; Schild et al., 2011 for reading children), initial voicing varied in the present study. We speculate that due to the used stimuli, voicing information in this study might be earlier available in the signal (vibration of voiced speech sounds starts with their onset) than place information (formant information indicating place develops across the speech sound). While voiced plosives in German lack pre-voicing and are therefore available relatively late in the signal (Geiss et al., 2022), our stimuli also consisted of unvoiced plosives with longer VOT times. This might relate to an on average earlier timing of respective ERP differences elicited by voicing feature compared to the place feature. Especially the timing of word form activation might depend on the availability of phonological information and might not always need 300 ms after target word onset. However, as the current study does not allow for direct timing comparisons between the features, future studies will be needed to investigate this question in further detail.

Similarly to the ERP results, children showed delayed responses for partially mismatching targets compared to matching targets in their lexical decisions across all three measurements. While ERPs exclusively reflect prime-target overlap in phonological information, additional factors are associated with lexical decision latencies. For example, participants made delayed responses (compared to an unrelated condition) for target words that partially matched the preceding primes (e.g., "Ana - Anorak") when a better matching completion of the prime existed (e.g., "Ananas", Engl. pineapple; Friedrich et al., 2013). This contrasted with reduced ERP amplitudes for partially overlapping targets compared to an unrelated condition (e.g., "Idi - Anorak"). It was concluded that overlapping words receive bottom-up activation from the primes (as reflected in ERP amplitude reduction), but that better matching words either hinder selection of partially overlapping words or interfere with the lexical decision response (as reflected in delayed lexical decisions). Speeded speech processing is another aspect that reaction times, but not ERPs, capture. Congenitally blind adults made faster lexical decisions in unimodal auditory word onset priming, but their ERPs did not reflect timing differences compared to hearing controls (Schild & Friedrich, 2018). This result suggested that the adult system realizes speeded speech processing via facilitated post-lexical, strategic aspects of processing rather than via facilitated phonological encoding and lexical mapping (which appear optimally adjusted to the input in both hearing and congenitally blind adults).

In the present study, age-related differences only emerged for mean response latencies. Overall, children responded fastest as 2nd graders, with medium speed as 1st graders and slowest as preschoolers. Age-related speeding of responses and the overall decreasing error rates with increasing age might have several triggers, including general and motoric maturation that – among other aspects like repeated testing – might affect speeded motor reactions or enhanced attention and concentration spans. Yet, it is important to note that these factors do not contribute to respective speeding of ERP deflections. This dissociation finds a parallel in a former word onset priming study with congenitally blind and sighted adults (Schild & Friedrich, 2018). In combination with the present results, both studies imply modifications of lexical decision responses between groups that might reflect different adjustments and proficiency in processing auditory input. While lexical decision responses might be sensitive to late strategic mechanisms that interfere with the yes-responses to the targets, ERPs might more closely relate to rapid phonologically mediated lexical access and phonological processes that are less prone to strategic, post-lexical modulations. We might conclude that, comparable to adults, children realize speeded speech processing via relatively late aspects of processing rather than via facilitated phonological encoding and lexical mapping. That is, already in childhood, the timing of input-related implicit aspects of phonologically mediated lexical access appear optimally adjusted to the input.

If one speculates that (besides maturation effects) literacy experience could also affect the performance on a metalinguistic task such as the lexical decision, faster lexical decision latencies with increasing age seem to be in accord with the assumption that reading experience fosters prediction in language processing (Huettig & Pickering, 2019). Eye tracking studies already suggest that proficient readers predict spoken language faster than less proficient readers and illiterate adults (Mishra et al., 2012), and children who are good readers are more efficient in predicting than those who are less-proficient readers (Mani & Huettig, 2014). The present data suggest that enhanced reading proficiency from preschool to 2nd grade might foster priming of lexical decision responses in spoken word recognition. Predictions within a priming paradigm can aid responses for related prime-target pairs. As only the timing of lexical decisions, but not the timing of ERPs, varied with increasing reading proficiency, we might conclude that predictions modulate selection of word candidates in the speech recognition process rather than bottom-up activation of potential word candidates.

Conclusion

With this study, we took a developmental approach on how phonological sensitivity of different aspects of spoken word processing evolves during the very beginning of learning to read. The importance of this work lies in the longitudinal approach in the investigation of neuronal plasticity of phonological representations in middle childhood. The findings suggest a complex relationship between phonemic awareness, reading acquisition, and spoken word processing. Preschool children trained in phonemic awareness showed detailed implicit and explicit spoken word processing. The findings stress the importance of phonological awareness for phonological word processing in early stages of literacy. While meta-linguistic processing continued to develop after children started learning to read, processing of voicing variations did not become more detailed once children gained reading experience and stable knowledge of letters after 1st and 2nd grade. In that, the findings implicate that while the development of metalinguistic phonological skills and underlying neuronal phonological processing might be closely related (e.g., Bauch et al., 2021; Dehaene et al., 2015; Harm & Seidenberg, 2004), diverging pathways of both aspects of phonological processing might emerge. However, unlike adults (Bauch et al., 2021), primary school children still appear to use voicing variation for gradually modulating access to stored phonological representations during spoken word recognition. Thus, beginning readers' pre-lexical processing of phonological feature variation might still profit from training of conscious understanding of the language's structure during formal schooling. It remains to be determined when sensitivity to this feature begins decreasing in implicit spoken word recognition. Furthermore, the findings implicate diverging neuronal processes for different phonological features. We acknowledge the need for more research to understand when sensitivity to certain phonological features decreases in implicit spoken word recognition, emphasizing the ongoing evolution of children's language processing abilities.

References

Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language, 38*(4), 419-439. https://doi.org/10.1006/jmla.1997.2558

Anthony, J. L., & Francis, D. J. (2005). Development of Phonological Awareness. *Current Directions in Psychological Science, 14*(5), 255-259. https://doi.org/10.1111/j.0963-7214.2005.00376.x

Anthony, J. L., & Lonigan, C. J. (2004). The Nature of Phonological Awareness: Converging Evidence From Four Studies of Preschool and Early Grade School Children. *Journal of Educational Psychology, 96*(1), 43–55. https://doi.org/10.1037/0022-0663.96.1.43

Bauch, A., Friedrich, C. K., & Schild, U. (2021). Phonemic training modulates early speech processing in pre-reading children. *Frontiers in Psychology, 12*(1959). https://doi.org/10.3389/fpsyg.2021.643147

Becker, A., Schild, U., & Friedrich, C. K. (2018). Tracking independence and merging of prosodic and phonemic processing across infancy. *Developmental Science, 21*(2). https://doi.org/10.1111/desc.12525

Bentin, S., Hammer, R., & Cahan, S. (1991). The Effects of Aging and First Grade Schooling on the Development of Phonological Awareness. *Psychological Science, 2*(4), 271-275. https://doi.org/10.1111/j.1467-9280.1991.tb00148.x

Berg, P., & Scherg, M. (1994). A multiple source approach to the correction of eye artifacts. *Electroencephalography and Clinical Neurophysiology, 90*(3), 229-241. https://doi.org/10.1016/0013-4694(94)90094-9

Caravolas, M., & Bruck, M. (1993). The effect of oral and written language input on children's phonological awareness: A cross-linguistic study. *Journal of Experimental Child Psychology, 55*(1), 1–30. https://doi.org/10.1006/jecp.1993.1001

Chang, E. F., Rieger, J. W., Johnson, K., Berger, M. S., Barbaro, N. M., & Knight, R.T. (2010). Categorical speech representation in human superior temporal gyrus. *Nature Neuroscience, 13*(11), 1428-1432. https://doi.org/10.1038/nn.2641

Connine, C. M., Blasko, D. G., & Titone, D. (1993). Do the Beginnings of Spoken Words Have a Special Status in Auditory Word Recognition? *Journal of Memory and Language, 32*(2), 193-210. https://doi.org/10.1006/jmla.1993.1011161

Connolly, J. F. (1993). The influence of stimulus intensity, contralateral masking and handedness on the temporal N1 and the T complex components of the auditory N1 wave. *Electroencephalography and Clinical Neurophysiology, 86*(1), 58-68. https://doi.org/10.1016/0013-4694(93)90067-6

Cunningham, A. J., & Carroll, J. M. (2011). Reading-related skills in earlier- and later-schooled children. *Scientific Studies of Reading, 15*(3), 244–266. https://doi.org/10.1080/10888431003706309

Cutler, A., & Davis, C. (2012). An Orthographic Effect in Phoneme Processing, and Its Limitations. *Frontiers in Psychology, 3*(18). https://doi.org/10.3389/fpsyg.2012.00018

Deacon, H., Benere, J., & Pasquarella, A. (2013). Reciprocal Relationship: Children's Morphological Awareness and Their Reading Accuracy Across Grades 2 to 3. *Developmental Psychology, 49*(6), 1113-1126. https://doi.org/10.1037/a0029474

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience, 16*(4), 234-244. https://doi.org/10.1038/nrn3924

Dehaene, S., Pegado, F., Braga, L.W., Ventura, P., Nunes Filho, G., Jobert, A., Dehaene-Lambertz, G., Kolinsky, R., Morais, J., Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*(6009), 1359-1364. https://doi.org/ 10.1126/science.1194140

Diesch, E., & Luce, T. (2000). Topographic and Temporal Indices of Vowel Spectral Envelope Extraction in the Human Auditory Cortex. *Journal of Cognitive Neuroscience, 12*(5), 878-893. https://doi.org/10.1162/089892900562480

Ehri, L. C., & Wilce, L. S. (1980). The influence of orthography on readers' conceptualization of the phonemic structure of words. *Applied Psycholinguistics, 1*(4), 371-385. https://doi.org/10.1017/S0142716400009802

Friedrich, C. K. (2005). Neurophysiological correlates of mismatch in lexical access. *BMC Neuroscience, 6*(64), 64. https://doi.org/10.1186/1471-2202-6-64

Friedrich, C. K., Kotz, S. A., Friederici, A. D., & Gunter, T. (2004). ERPs Reflect Lexical Identification in Word Fragment Priming. *Journal of Cognitive Neuroscience, 16,* 541-552. https://doi.org/10.1162/089892904323057281

Friedrich, C. K., Felder, V., Lahiri, A., & Eulitz, C. (2013). Activation of words with phonological overlap. *Frontiers in Psychology, 4,* 556. https://doi.org/10.3389/fpsyg.2013.00556

Friedrich, C. K., Lahiri, A., & Eulitz, C. (2008). Neurophysiological Evidence for Underspecified Lexical Representations: Asymmetries With Word Initial Variations. *Journal of Experimental Psychology Human Perception & Performance, 34,* 1545-1559. https://doi.org/10.1037/a0012481

Friedrich, C. K., Schild, U., & Röder, B. (2009). Electrophysiological indices of word fragment priming allow characterizing neural stages of speech recognition. *Biological Psychology, 80*(1), 105-113. https://doi.org/10.1016/j.biopsycho.2008.04.012

Geiss, M., Gumbsheimer, S., Lloyd-Smith, A., Schmid, S., & Kupisch, T. (2022). VOICE ONSET TIME IN MULTILINGUAL SPEAKERS: ITALIAN HERITAGE SPEAKERS IN GERMANY WITH L3 ENGLISH. *Studies in Second Language Acquisition, 44*(2), 435-459. doi:10.1017/S0272263121000280

Goswami, U. (2000). Phonological representations, reading development and dyslexia: towards a cross-linguistic theoretical framework. *Dyslexia, 6*(2), 133-165151. https://doi.org/10.1002/(SICI)1099-0909(200004/06)

Harm, M. W., & Seidenberg, M. S. (2004). Computing the meanings of words in reading: cooperative division of labor between visual and phonological processes. *Psychological Review, 111*(3), 662-720. https://doi.org/10.1037/0033-295x.111.3.662

Hervais-Adelman, A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., & Huettig, F. (2021). How does literacy affect speech processing? Not by enhancing cortical responses to speech, but by promoting connectivity of acoustic-phonetic and graphomotor cortices. *Journal of Neuroscience, 42* (47), 8826-8841. 10.1523/JNEUROSCI.1125-21.2022

Huettig, F., & Pickering, M. J. (2019). Literacy Advantages Beyond Reading: Prediction of Spoken Language. *Trends in Cognitive Sciences, 23*(6), 464-475. https://doi.org/10.1016/j.tics.2019.03.008

Hulme, C., Caravolas, M., Málková, G., & Brigstocke, S. (2005). Phoneme isolation ability is not simply a consequence of letter-sound knowledge. *Cognition, 97*(1), B1–B11. https://doi.org/10.1016/j.cognition.2005.01.002

Küspert, P., & Schneider, W. (2008). *Hören, lauschen, lernen - Sprachspiele für Kinder im Vorschulalter* (6. Aufl.). Vandenhoeck & Ruprecht.

Lange, K., & Röder, B. (2006). Orienting attention to points in time improves stimulus processing both within and across modalities. *Journal of Cognitive Neuroscience, 18*(5), 715-729. https://doi.org/10.1162/jocn.2006.18.5.715

Lenhard, W., & Schneider, W. (2006). *ELFE 1-6 - Leseverständnistest für Erst- bis Sechstklässler*. Hogrefe.

Mani, N., & Huettig, F. (2014). Word reading skill predicts anticipation of upcoming spoken language input: a study of children developing proficiency in reading. *Journal of Experimental Child Psychology, 126*, 264-279. https://doi.org/10.1016/j.jecp.2014.05.004

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition, 25*(1), 71-102. https://doi.org/10.1016/0010-0277(87)90005-9

Mayer, A. (2011). *TEPHOBE. Test zur Überprüfung der phonologischen Bewusstheit und der Benennungsgeschwindigkeit*. Reinhardt Verlag.

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology, 18*(1), 1-86. https://doi.org/10.1016/0010-0285(86)90015-0

Mesgarani, N., Cheung, C., Johnson, K., & Chang, E. F. (2014). Phonetic Feature Encoding in Human Superior Temporal Gyrus. *Science, 343*(6174), 1006-1010. https://doi.org/10.1126/science.1245994

Mishra, R., Singh, N., Pandey, A., & Huettig, F. (2012). Spoken language-mediated anticipatory eyemovements are modulated by reading ability - Evidence from Indian low and high literates. *Journal of Eye Movement Research, 5*. https://doi.org/10.16910/jemr.5.1.3

Mitterer, H., & Reinisch, E. (2015). Letters don't matter: No effect of orthography on the perception of conversational speech. *Journal of Memory and Language, 85*, 116-134. https://doi.org/10.1016/j.jml.2015.08.005

Monzalvo, K., & Dehaene-Lambertz, G. (2013). How reading acquisition changes children's spoken language network. *Brain and Language, 127*(3), 356-365. https://doi.org/10.1016/j.bandl.2013.10.009

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition, 7*(4), 323-331. https://doi.org/10.1016/0010-0277(79)90020-9

Muneaux, M., & Ziegler, J. C. (2004). Locus of orthographic effects in spoken word recognition: Novel insights from the neighbour generation task. *Language and Cognitive Processes, 19*(5), 641-660. https://doi.org/10.1080/01690960444000052

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology, 24*(4), 375-425. https://doi.org/10.1111/j.1469-8986.1987.tb00311.x

Norris, D., & McQueen, J. M. (2008). Shortlist B: A Bayesian model of continuous speech recognition. *Psychological Review, 115*(2), 357-395. https://doi.org/10.1037/0033-295X.115.2.357

O'Rourke, T. B., & Holcomb, P. J. (2002). Electrophysiological evidence for the efficiency of spoken word processing. *Biological Psychology, 60*(2-3), 121-150. https://doi.org/10.1016/S0301-0511(02)00045-5

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113. https://doi.org/10.1016/0028-3932(71)90067-4

Pattamadilok, C., Knierim, I. N., Kawabata Duncan, K. J., & Devlin, J. T. (2010). How does learning to read affect speech perception? *Journal of Neuroscience, 30*(25), 8435-8444. https://doi.org/10.1523/JNEUROSCI.5791-09.2010

Pattamadilok, C., Morais, J., Colin, C., & Kolinsky, R. (2014). Unattentive speech processing is influenced by orthographic knowledge: evidence from mismatch negativity. *Brain and Language, 137*, 103-111. doi:10.1016/j.bandl.2014.08.005

Pattamadilok, C., Morais, J., Ventura, P., & Kolinsky, R. (2007). The locus of the orthographic consistency effect in auditory word recognition: Further evidence from French. *Language and Cognitive Processes, 22*(5), 700-726. doi:10.1080/01690960601049628

Pattamadilok, C., Perre, L., & Ziegler, J. C. (2011). Beyond rhyme or reason: ERPs reveal task-specific activation of orthography on spoken language. *Brain and Language, 116*(3), 116-124. https://doi.org/10.1016/j.bandl.2010.12.002

Perfetti, C. A., Beck, I., Bell, L. C., & Hughes, C. (1987). Phonemic Knowledge and Learning to Read are Reciprocal: A Longitudinal Study of First Grade Children. *Merrill-Palmer Quarterly, 33*(3), 283-319. Retrieved from http://www.jstor.org/stable/23086537

Perre, L., Bertrand, D., & Ziegler, J. C. (2011). Literacy affects spoken language in a non- linguistic task: An ERP study. *Frontiers in Psychology, 2,* 1-8. https://doi.org/10.3389/fpsyg.2011.00274

Perre, L., & Ziegler, J. C. (2008). On-line activation of orthography in spoken word recognition. *Brain research, 1188,* 132–138. https://doi.org/10.1016/j.brainres.2007.10.084

Plume, E., & Schneider, W. (2004). *Hören, lauschen, lernen 2. Spiele mit Buchstaben und Lauten für Kinder im Vorschulalter*. Vandenhoeck & Ruprecht.

Poeppel, D., Phillips, C., Yellin, E., Rowley, H. A., Roberts, T. P. L., & Marantz, A. (1997). Processing of vowels in supratemporal auditory cortex. *Neuroscience Letters, 221*(2), 145-148. https://doi.org/10.1016/S0304-3940(97)13325-0

Praamstra, P., & Stegeman, D. F. (1993). Phonological effects on the auditory N400 event-related brain potential. *Cognitive Brain Research, 1*(2), 73-86. https://doi.org/10.1016/0926-6410(93)90013-U

Sanders, L. D., & Astheimer, L. B. (2008). Temporally selective attention modulates early perceptual processing: event-related potential evidence. *Perception & Psychophysics, 70*(4), 732-742. https://doi.org/10.3758/PP.70.4.732

Sanders, L. D., & Neville, H. J. (2003). An ERP study of continuous speech processing. I. Segmentation, semantics, and syntax in native speakers. *Cognitive Brain Research, 15*(3), 228-240. https://doi.org/10.1016/S0926-6410(02)00195-7

Sanders, L. D., Newport, E. L., & Neville, H. J. (2002). Segmenting nonsense: an event-related potential index of perceived onsets in continuous speech. *Nature Neuroscience, 5*(7), 700–703. https://doi.org/10.1038/nn873

Schild, U., Bauch, A., & Nuerk, H.-C. (2020). A Finger-based Numerical Training Failed to Improve Arithmetic Skills in Kindergarten Children beyond Effects of an Active Non-Numerical Control Training. *Frontiers in Psychology, 11*(529). https://doi.org/10.3389/fpsyg.2020.00529

Schild, U., Becker, A., & Friedrich, C. K. (2014). Processing of syllable stress is functionally different from phoneme processing and does not profit from literacy acquisition. *Frontiers in Psychology, 5*(530). https://doi.org/10.3389/fpsyg.2014.00530

Schild, U., & Friedrich, C. K. (2018). What determines the speed of speech recognition? Evidence from congenitally blind adults. *Neuropsychologia, 112,* 116-124. https://doi.org/10.1016/j.neuropsychologia.2018.03.002

Schild, U., Röder, B., & Friedrich, C. K. (2011). Learning to read shapes the activation of neural lexical representations in the speech recognition pathway. *Developmental Cognitive Neuroscience, 1*(2), 163-174. https://doi.org/10.1016/j.dcn.2010.11.002

Schild, U., Röder, B., & Friedrich, C. K. (2012). Neuronal spoken word recognition: The time course of processing variation in the speech signal. *Language and Cognitive Processes, 27,* 159-183. https://doi.org/10.1080/01690965.2010.503532

Schneider, W., Blanke, I., Faust, V., & Küspert, P. (2011). *Würzburger Leise Leseprobe - Revision. Ein Gruppentest für die Grundschule*. Hogrefe.

Slowiaczek, L. M., Nusbaum, H. C., & Pisoni, D. B. (1987). Phonological priming in auditory word recognition. *Journal of experimental psychology. Learning, memory, and cognition, 13*(1), 64–75. https://doi.org/10.1037//0278-7393.13.1.64

Soto-Faraco, S., Sebastián-Gallés, N., & Cutler, A. (2001). Segmental and Suprasegmental Mismatch in Lexical Access. *Journal of Memory and Language, 45*(3), 412-432. https://doi.org/10.1006/jmla.2000.2783

Taft, M. (2006). Orthographically Influenced Abstract Phonological Representation: Evidence from Non-rhotic Speakers. *Journal of Psycholinguistic Research, 35*(1), 67-78. https://doi.org/10.1007/s10936-005-9004-5

Tanner, D., Morgan-Short, K., & Luck, S. J. (2015). How inappropriate high-pass filters can produce artifactual effects and incorrect conclusions in ERP studies of language and cognition. *Psychophysiology, 52*(8), 997–1009. https://doi.org/10.1111/psyp.12437

Treiman, R., & Cassar, M. (1997). Can children and adults focus on sound as opposed to spelling in a phoneme counting task? *Developmental Psychology, 33*(5), 771-780.

Tunmer, W. E., & Nesdale, A. R. (1985). Phonemic segmentation skill and beginning reading. *Journal of Educational Psychology, 77*(4), 417-427. https://doi.org/10.1037/0022-0663.77.4.417

Ventura, P., Morais, J., Pattamadilok, C., & Kolinsky, R. (2004). The locus of the orthographic consistency effect in auditory word recognition. *Language and Cognitive Processes, 19*(1), 57-95. doi:10.1080/01690960344000134

Weber, A., & Scharenborg, O. (2012). Models of spoken-word recognition. *WIREs Cognitive Science, 3*(3), 387-401. https://doi.org/10.1002/wcs.1178

Wolpaw, J. R., & Penry, J. K. (1975). A temporal component of the auditory evoked response. *Electroencephalography and Clinical Neurophysiology, 39*(6), 609-620. https://doi.org/10.1016/0013-4694(75)90073-5

Ziegler, J. C., & Ferrand, L. (1998). Orthography shapes the perception of speech: The consistency effect in auditory word recognition. *Psychonomic Bulletin & Review, 5*(4), 683-689. https://doi.org/10.3758/BF03208845

Data, code and materials availability statement

The Editor, Ben Ambridge, granted an exemption (13th September 2023) to materials sharing for (a) the SPY GAME, which includes copyright pictures (though the protocol for the test is shared), (b) the Edinburgh Handedness Inventory (used in German translation), whose copyright status is unclear, and the following tests which are subject to copyright: (c) TEPHOBE (Mayer, A. (2011). TEPHOBE. Test zur Überprüfung der phonologischen Bewusstheit und der Benennungsgeschwindigkeit. Reinhardt Verlag; (d) WLLP-R (Schneider, W., Blanke, I., Faust, V., & Küspert, P. (2011). Würzburger Leise Leseprobe - Revision. Ein Gruppentest für die Grundschule. Hogrefe/); (e) ELFE 1-6 (Lenhard, W., & Schneider, W. (2006). ELFE 1-6 - Leseverständnistest für Erst- bis Sechstklässler. Hogrefe.). All other data, questionnaires, test sheets and codes are accessible at OSF storage and provide anonymous access under the following link: https://osf.io/sr4wv/?view_only=9fc86cb0875e4b81bd8d3ec1a9b23b50

Ethics statement

The study involving human participants was reviewed and approved by Ethikkommission der Deutschen Gesellschaft für Psychologie. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Authorship and Contributorship Statement

US conceived the study. AB took primary responsibility for drafting the manuscript and conducted the study and analyzed the data. AB, CF, and US contributed to design of the training and the tasks. CF and US commented on drafts. All authors read and approved the submitted version.

Declaration of conflict of interests

The authors declare that there are no conflicts of interests for this report.

Acknowledgements

We are especially grateful to Dr. Anne Rau for scheduling trainings and measurements in close and kind interaction with kindergartens and parents, as well as for carefully reading a former version of this manuscript. We would further like to thank Janina Althaus, Nina Bee, Sabine Braasch, Clemens Bromann, Jana Denkinger, Lena Flik, Eva Franz, Stella Gellner, Birte Herter, Isolde Kolb, Ruth Keßler, Janina Krempel, Johanna Lechner, Larissa Lorch, Monika Peterová Jarošová, Angelika Schmitt, Anna-Lena Schultz, Daniel-Niels Tönsing, Gülsan Usta, Charlotte Veil, Marlene Weller and Miriam Wild for assistance in the training and in collecting the data. We also warmly thank all kindergartens, parents and especially children who participated in this study. The study was part of the dissertation written by Anne Bauch.

Appendix A

Table A1. ***List of stimuli.***

Target words	Pseudo-words	Target words	Pseudo-words
Gei-er (vulture)	Geine	Pap-pe (cardboard)	Papke
Gei-ge (violin)	Geise	Pul-ver (powder)	Pulbel
Git-ter (grid)	Gitsche	Pum-pe (pump)	Pumle
Gloc-ke (bell)	Glocpe	Pud-ding (pudding)	Pudhe
Gra-ben (trench)	Grany	Pup-pe (doll)	Pupte
Gren-ze (border)	Grenhe	Pic-kel (pimple)	Picsche
Gru-be (pit)	Gruza	Po-ny (pony)	Poben
Grup-pe (group)	Grupzle	Piz-za (pizza)	Pizbe
Guer-tel (belt)	Guerbe	Pan-ne (breakdown)	Panze
Gum-mi (rubber)	Gumse	Peit-sche (whip)	Peitter
Gur-ke (cucumber)	Gurbon	Pom-mes (fries)	Pombel
Kaff-ee (coffee)	Kaffnen	Bri-lle (glasses)	Brissen
Ka-ter (male cat)	Kaffel	Bie-ne (bee)	Bieer
Kat-ze (cat)	Katne	Brun-nen (fountain)	Brunnee
Ker-ze (candle)	Kertel	Bon-bon (candy)	Bonke
Ket-te (chain)	Ketzel	Bru-der (brother)	Bruchen
Keu-le (mace)	Keusen	Bam-bus (bamboo)	Bamsche
Ki-no (cinema)	Kite	Ba-by (baby)	Bave
Kir-che (church)	Kirber	But-ter (butter)	Butche
Kir-sche (cherry)	Kirbus	Bue-gel (stirrup)	Buede
Kis-sen (pillow)	Kisle	Bruec-ke (bridge)	Bruecfer
Kis-te (box)	Kiskel	Brem-se (break)	Bremken
Kno-chen (bone)	Knoder	Buer-ste (brush)	Buerno
Kno-ten (knot)	Knore	Brau-se (shower)	Braunig
Koe-nig (king)	Koese	Bom-be (bomb)	Bomtel
Kof-fer (trunk)	Kofke	Bir-ne (pear)	Birgel
Krae-he (crow)	Kraeding	Bue-hne (stage)	Buehmel
Kraeu-ter (herbage)	Kraeude	Blu-me (flower)	Bluchen
Kral-le (claw)	Kralpe	Blue-te (blossom)	Bluene
Krei-de (chalk)	Kreigel	Buef-fel (buffalo)	Buefter
Kroe-te (toad)	Kroepe	Be-sen (broom)	Bele
Kro-ne (crown)	Krote	Blu-se (blouse)	Bluge
Krue-mel (crumbs)	Kruehne	Bla-se (bubble)	Blami
Kue-che (kitchen)	Kueter	Bi-ber (beaver)	Biche
Kue-ken (chicken)	Kuekse	Bee-re (berry)	Beerten
Kur-ve (curve)	Kurby	Beu-tel (bag)	Beuze
Kut-sche (carriage)	Kutkel	Bre-zel (pretzel)	Brete

Table A2. ***EEG analysis ANOVA effects for both time windows of interest (100-300ms and 300-400ms) with EEG signal being preprocessed with 0.1hz high pass filter.***

Effect	df	*F*	*p*	p^2
100 - 300 ms				
Condition	2	1.57	.174	.05
Region	1	3.48	.073	.11
Hemisphere	1	0.00	.973	<.01
Group	2	0.67	.514	.02
Condition x Region	2	31.48	<.001**	.54
Condition x Hemisphere	2	7.07	.002**	.21
Condition x Group	4	0.53	.716	.02
Region x Hemisphere	1	0.13	.716	<0.1
Region x Group	2	1.08	.347	.04
Hemisphere x Group	2	0.16	.813	.01
Condition x Region x Hemisphere	2	0.37	.695	.01
Condition x Region x Group	4	0.80	.494	.03
Condition x Hemisphere x Group	4	1.07	.373	.04
Region x Hemisphere x Group	2	0.06	.899	<.01

Table A2 (continued)

Effect	df	*F*	*p*	p^2
300 - 400 ms				
Condition	2	1.52	.228	.05
Region	1	2.57	.120	.09
Hemisphere	1	0.18	.678	.01
Group	2	0.59	.559	.02
Condition x Region	2	23.61	<.001***	.47
Condition x Hemisphere	2	8.45	.001**	.24
Condition x Group	4	1.94	.108	.07
Region x Hemisphere	1	2.98	.096	.10
Region x Group	2	1.26	.292	.04
Hemisphere x Group	2	0.85	.410	.03
Condition x Region x Hemisphere	2	0.12	.886	<.01
Condition x Region x Group	4	1.50	.219	.05
Condition x Hemisphere x Group	4	1.62	.174	.06
Region x Hemisphere x Group	2	0.93	.399	.03
Condition x Region x Hemisphere x Group	4	1.10	.361	.04

License