Phoneme Categorisation in 20-Month-Old Infants with a Familial Risk of Dyslexia

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Abstract

One of the leading hypotheses in the research towards developmental dyslexia – a learning disability that is mostly visible in problems with reading and writing, despite normal intelligence – is the allophonic representation hypothesis. It states that the underlying cause of dyslexia is a phonological one: the phoneme categories that develop during early childhood are less categorical in dyslexic individuals than in normal readers, which results in impaired phoneme categorisation abilities. This study looks at the difference in phoneme categorisation abilities between 20-month-old infants with a familial risk of dyslexia and typically developing age-matched controls. EEG recordings were made while the infants listened to two pseudowords with a CVC-structure that differed only in the vowel, using an oddball paradigm in which a standard (80%) was alternated with a deviant (20%). The results show that the at-risk children differ from the typically developing children in their response towards the deviant stimulus. However, the results are not yet conclusive enough to say they support or contradict the allophonic representation hypothesis. Further research is necessary.

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Introduction

“I wonder whether dyslexia actually exists,” a professor told the media recently (NOS, 2017). The reading deficit was discredited because of the exceptionally high rate of children diagnosed with developmental dyslexia. The deficit was subscribed to bad education and the diagnosed students just had to try harder. However, it is well established that dyslexia is a neurological disorder and has a genetic origin (Ramus et al., 2003). Although it is quite probable that a large part of the population that is diagnosed with developmental dyslexia is in fact not really dyslexic and indeed does suffer from bad education or laziness, there are also a lot of people that do suffer from dyslexia.

Developmental dyslexia is a language deficit that is expressed in difficulties in reading and writing, despite normal intelligence, cognitive and sensory abilities, motivation and adequate reading instructions (Ferrer et al., 2010; Shaywitz & Shaywitz, 2005). There are several theories going round trying to explain developmental dyslexia, among others the allophonic representation hypothesis (Serniclaes et al., 2004). This hypothesis states that dyslexics suffer from impaired phoneme category representations, which means they have trouble classifying speech sounds. Because of this it is difficult to establish relations between graphemes and phonemes, which impedes establishing proficient reading and writing skills.

For children, learning which speech sounds are part of their native language is an important skill. It is one of the first steps in the direction of learning to understand and speak their mother tongue. Without having correct representations of the phonemes of a language, it might for instance be more difficult to learn words. As sufficient reading and writing skills are becoming more and more important in the current society in which people from all over the world are communicating on a very fast pace with each other, it is important to grasp the mechanisms behind the impairments that dyslexics are facing every day. To contribute to the knowledge about dyslexia, this study looks into the differences in phoneme categorisation abilities between infants with a familial risk of dyslexia and typically developing infants. To what extent do infants of 20 months old of these groups differ in their abilities to categorise phonemes of their native language? To investigate this, EEG signals were recorded while the infants performed a task in a non-attentive oddball paradigm (Näätänen et al., 2004). The results might tell us more about how exactly the two groups differ from each other in their phoneme categorisation abilities. Grasping how these mechanisms work might help to create methods that assist dyslexics develop better reading and writing skills.

Developmental dyslexia

As mentioned above, developmental dyslexia is a reading and writing deficit that occurs without the presence of other deficits on cognitive abilities. The most common accepted underlying reason for the deficit is a phonological impairment (Ramus et al., 2003). It is postulated that people with dyslexia have a problem with the representation, storage and/or retrieval of phonemes. To be able to read or write a text, one needs to make connections between speech sounds and graphemes. These connections are difficult to establish when phonemes are not well represented, stored or retrieved. As a result, reading and writing is more difficult for people with dyslexia than for normal readers.

One of the major theories focusing on the representation of phonemes is the allophonic representation hypothesis. In 1957 (Liberman et al.), it was already established that in general, differentiating between sounds of different phoneme categories (for example between /b/ and /p/) is easier than differentiating between sounds of the same phoneme category (two different occurrences of /b/). However, this is not the case for people with developmental dyslexia. Where typically developed people have separate phoneme categories with a clear boundary in between, the phoneme representation of dyslexics is found to be less categorical which makes it more difficult to discriminate /b/ and /p/, but easier to discriminate between two different occurrences of /b/. Typically developing people have trouble discriminating between two different occurrences of /b/, whereas within-category discrimination is less suppressed for dyslexics (Dufor et al., 2009; Noordenbos et al., 2012a, 2013; Serniclaes et al., 2004; Zoubrinetzky et al., 2016). To make clear how dyslexics differ in their development of speech perception, the acquisition of speech perception abilities of typically developing children will be discussed first, followed by an overview of studies on the allophonic representation hypothesis.

Learning the speech sounds of your native language

Learning a language seems a very easy task for children: in general, everyone learns to speak their native language without formal instruction. Although this process seems not so difficult, there are a lot of complicated steps to follow before someone is able to speak in full sentences. The first steps towards learning a language is figuring out which sounds in your surroundings are speech sounds and which of these speech sounds are part of your native language. These speech sounds have to be categorized, and rules need to be learnt about how these sounds can be combined, as not every two phonemes can be combined with each other. Furthermore, words have to be associated with objects and actions, and more rules need to be learnt about how these words can be put together into grammatical sentences.

These steps towards learning their mother-tongue begin when the infants are still very young. When they are but a few days old, they already have a preference for speech stimuli over non-speech stimuli that match speech in features such as frequency (Vouloumanos & Werker, 2007). In these first few days, they also learn how to discriminate different languages from each other, based on prosodic and rhythmic information (Nazzi et al., 1998). Using this information, infants are able to distinguish their native language from other languages.

From the streams of speech of their target language, infants need to filter the right information to learn which distinctions between speech sounds are meaningful and which are not. Although they are born with the ability to discriminate between all speech stimuli (Kuhl et al., 2006), they reorganize their perceptual system into a system that only discriminates the phonemes that appear in their native language. They change their universal perceptual system into a language-specific one. To do this, they need to classify speech sounds into phoneme categories and determine where the boundaries are on speech continua such as /b/-/d/ (place of articulation) and /p/-/b/ (voicing). This is done during the first year of life. The ability to discriminate native contrasts strengthens, while the ability to discriminate between two variants of the same phoneme declines (Kuhl et al., 2006). For instance, in Japan, where they do not distinguish the /r/ and the /l/, infants can distinguish these two phonemes until the age of approximately 6-8 months, but around the age of 10-12 months they cannot hear the difference any more (Nishi et al., 1994). English infants however are still able to tell the /r/ and the /l/ apart when they reach the age of 12 months and onwards.

Categorising speech sounds is quite a difficult task bearing in mind that, during the processing of ongoing speech, infants are challenged by the large variety that exists in speech sounds. Every utterance that an infant hears is acoustically different, even the utterances of the same phoneme by the same person. They have to deal with talker variability (different speakers produce different sounds), rate variability (slow speech differs in characteristics from fast speech) and context variability (two consecutive phonemes influence each other's pronunciation) (Kuhl, 2004). From all information that is presented, infants need to extract which speech sound belongs to which phoneme category.

It turns out that infants use computational strategies to calculate which sounds belong together in a group and thus are occurrences of the same phoneme, and which sounds should be separated from each other. The statistical distribution of speech sounds tells the languagelearners where the boundaries between categories are. Maye and her colleagues (2002) exposed infants between 6 and 8 months old to speech stimuli on the continuum from voiced /da/ to voiceless /ta/. During the familiarization phase, half of these infants listened to a frequency distribution with two distributional peaks, namely one towards the voiced end and one towards the voiceless end. The other half listened to a unimodal distribution, with only a peak in the middle of the continuum. During the test phase half of the trials were non-alternating (a single stimulus is repeated) and half were alternating (two different stimuli are repeated). Results show that the infants in the bimodal condition looked longer to the speaker when listening during the non-alternating test phase than during the alternating test phase. The infants from the unimodal condition did not show any difference in looking times. This indicates that infants are sensitive to the frequency distribution of speech sounds, showing a preference for a novel distribution.

In general, the change from a universal to a language-specific speech perception system happens in the second half of the first year of life (Kuhl et al., 2006; Werker & Tees, 1984). During this period, infants show a significant increased sensitivity in the perception of native contrasts, and simultaneously show a decrease in perception of non-native contrasts. Not all category boundaries emerge at the same time. The language-specific speech sound categories for vowels evolve somewhat earlier than those for consonants: the first emerge around 6 months (Bosch & Sebastián-Gallés, 2003; Polka & Werker, 1994), while the latter emerge some two to six months later, namely between 8 and 12 months (Werker & Tees, 1984). Also within the group of vowels and the group of consonants, perception for one contrast emerges at a different point in time than for another contrast. Factors that play a role in this development are the salience of the contrast (Yeung et al., 2013) and how often the contrast is perceptible for the infant (Anderson et al., 2003). The more salient a contrast is and the more often it is presented to the infant, the easier it is to perceive. Exceptionally distinct contrasts are even still perceptible after changing to a language-specific perceptual system (Best et al., 1988).

Although infants recognize sounds patterns when they are only a few months old, they are not yet able to hear the differences between all minimal pairs (patterns differing in only one sound). They gradually become more sensitive to differences between phonemes at different word positions. For instance, when they are 10 months old, infants are able to discriminate consonants that differ in voicing and place of articulation at a word-initial position, but not at a word-final position (Zamuner, 2006). The latter ability is acquired some six months later: Zamuner (2006) showed that 16-month-old infants are able to discriminate between consonants at the end of a word. Around the age of 14 months, infants show sensitivity to mispronunciations of consonants at the word-onset of familiar words (Bailey & Plunkett, 2002) and also to mispronunciations of word-medial vowels in novel words (Mani & Plunkett, 2008).

In summary, infants run through a series of steps while learning to discriminate and classify the speech sounds of their native language. They learn to recognise certain sounds as speech sounds and which of these sounds belong to their native language. Furthermore, through distributional learning they overcome the challenge of different kinds of speech variability and learn how to categorise speech sounds. Their universal speech perception systems are changed into language-specific systems during the second half of their first year: while the ability to perceive non-native phonemic contrasts declines, the ability to perceive native phonemic contrasts increases.

Language acquisition in children with a familial risk of dyslexia

As explained above, dyslexics may have an allophonic representation system. The native phoneme categories that usually emerge between the age of 6 and 12 months are less present in people with dyslexia and the sensitivity to non-phonemic contrasts remains. It is as if their speech perception system does not change into a language-specific one, but remains universal. This can be observed in their abilities to tell certain speech sound contrasts apart. To investigate the differences between dyslexics and typically developing people, both behavioural and neurological studies have been carried out. To give an overview of the research that has already been done on this subject, both behavioural and neurological studies on the allophonic representation hypothesis are discussed below.

Behavioural studies on the allophonic representation hypothesis

In behavioural studies investigating this hypothesis, participants are usually asked to do a phoneme identification and a phoneme discrimination task for pairs of stimuli. While the first task mostly informs us about the distinction between two or more categories, the second task gives information about the discrimination abilities within and between categories. Most of the time the pairs of stimuli exist of two stimuli which only differ in one aspect – such as place of articulation or manner of articulation – and are similar in all other ways. For example, the phonemes /b/ and /p/ are both bilabial plosives, but they differ in voicing. The /b/ is voiced, which means it starts with a period of voicing before the release burst: it has a positive voice onset time (VOT). The /p/ on the other hand is voiceless and has a negative VOT: a small lag follows the release burst. In Dutch, voiced and voiceless plosives are characterized by a VOT at -70 ms and 20 ms, respectively (Lisker & Abramson, 1964; Meijers, 1971; Slis & Cohen, 1969). However, the VOT differs for every utterance and can occur at every moment between and around the mentioned values, causing a lot of variability within categories.

During the identification task, participants listen to synthesized syllables with different VOTs along this continuum and have to indicate which phoneme it is. Results of an identification task tell which VOT values are perceived as, for instance, a /b/ and which as a /p/. What is usually expected from such a task is an abrupt shift of identification, which means that close to one certain value the participant experiences some doubt about which sound he or she hears, while moving a little bit further away from this value, almost hundred percent is classified as /b/ or /p/. For Dutch adults, the location of the boundary between /b/ and /p/ is 64 ms (at this point 50% of the cases is classified as /b/) with a width of 29 ms (between the outer boundaries, 25-75% of the cases is classified as /b/) (Kuijpers, 1996).

According to the allophonic representation hypothesis, the boundary between two phonemes should be less abrupt for dyslexics and/or is shifted, compared to controls. Dyslexics have not formed the distinct phoneme categories as the controls have, which would lead to a grey area in which they are not sure which speech sound should be placed in which category. However, the results regarding this task vary: Noordenbos et al. (2012a) found no difference between the dyslexic group and the control group at the ages of 6 and 7 years, using as stimuli utterances of /b/ and /d/. However, Calcus et al (2016), who tested 9-year-old dyslexics did find a different boundary place for dyslexic children compared to both the age-matched and the reading level-matched controls. They used a /d/-/t/ continuum and found that the boundary in dyslexic children was earlier than the boundary in the control groups.

During the phoneme discrimination task, participants have to compare two stimuli and indicate whether they are the same or different. Serniclaes et al. (2004) found that dyslexic participants of 9 years can discriminate better between stimuli of the same phoneme category than controls. Noordenbos et al. (2012a) found that the control group scored higher on the stimuli pairs crossing a phonemic boundary than dyslexics at the age of 6, but after formal reading instruction this difference disappeared. Calcus et al. (2016), however, did not find evidence for a difference in categorical perception in dyslexic children.

The results of these different studies do not show a very consistent view of an allophonic mode of representation. For a more extensive discussion on this subject, see Noordenbos et al.

(2012a). They discuss several more studies that vary in their results. A suggested explanation is that when dyslexics grow older, they learn how to adjust to a more phonemic mode behaviourally, but on a neurological level the allophonic representation mode remains (Noordenbos et al., 2013).

Neurological studies on the allophonic representation hypothesis

To explore the allophonic representation hypothesis also on a neurological level, several studies recorded EEG signals in search of mismatch negativity (MMN). MMN is 'a change-specific component of the auditory event-related potential (ERP), elicited by any discriminable change in auditory stimulation' (Näätänen et al., 2004, p. 140). MMN is among others observed in tasks adopting an oddball paradigm: participants hear a series of (speech) sounds with at random points a deviant sound. If they pick up some regularity in the sequence of standards, they will experience a 'mismatch' when a deviant occurs. This mismatch is visible in the ERP. This is a very useful measure to test the allophonic representation hypothesis, because in this way it is possible to measure whether people can discriminate between two or more different (speech) sounds (for more information on EEG and MMN, see below).

This is exactly what Noordenbos et al. (2012b, 2013) did: they recorded EEG to investigate the difference in phoneme categorization between dyslexic and controls, in both an adult group and a group of children. For the 6-year-old children, they found MMNs in both the controls and the children with a familial risk of dyslexia, using stimuli from different phoneme categories. However, the MMN amplitude was significantly lower in the at-risk group. The deviant stimulus from the same phoneme category elicited an MMN in the at-risk children only. These results support the allophonic representation hypothesis, in agreement with several other EEG studies (Sharma et al., 2006; Schulte-Korne et al., 1998).

The same results were found for the adults: at the neural level, differences were observed between the adults with dyslexia and controls. MMNs were elicited by stimuli from different phoneme categories in both groups, but not by stimuli from the same phoneme category. In this second condition, MMNs were only found in adults diagnosed with dyslexia, not in the controls (Noordenbos et al., 2013; Schulte-Korne et al., 2001). In contrast with the neural measurements, behavioural measurements showed no difference between the two groups of adults (Noordenbos et al., 2013). These findings lend further support to the hypothesis that dyslexics have a more allophonic mode of representing speech sounds instead of a phonemic one. They are still sensitive to distinctions in speech sounds that do not distinguish lexical meaning in their native language, which is an ability that disappears in typical developing people (Kuhl et al., 2006).

As abilities of speech perception are developing from birth, as discussed above, it is to be expected that this allophonic representation system is also already noticeable from a very young age. Indeed, studies show that infants at the age of 6 months with a familial risk of dyslexia already respond with a smaller negative ERP to deviant pseudowords in an oddball paradigm, compared to control children (Leppänen et al., 2002). Also Lyytinen et al. (2001) found a smaller MMN-like deflection in 6-months-old at-risk infants. Even at the age of 2 months (van Leeuwen et al., 2007), mismatch responses found in controls were absent in at-risk children, while behavioural differences were only visible from the age of 2 years onwards (Lyytinen et al., 2001). This means that even before the perceptive system is changed into a language-specific one (between 6 and 12 months), there already is a difference to be observed between at-risk children and controls.

Possible underlying causes

In the literature, a few major theories about a possible underlying cause that explains the deviant categorical perception of dyslexics are proposed. It could be the result of a general auditory deficit (Hämäläinen et al, 2013; Hakvoort, 2016), impaired processing of rapid stimulus sequences (Hari & Renvall, 2001) or sluggish attentional shifting (Lallier et al., 2010b). There is no general consensus yet on what the cause of the phonological deficit in dyslexics is. Therefore several theories are discussed below to give an overview.

There are a number of studies that suggest a general auditory deficit as a cause of developmental dyslexia (see Hämäläinen et al., 2013 for an overview). This would mean that dyslexics do not only have trouble with phoneme categorisation, but also with for instance discriminating non-speech sounds such as tones. Support for this theory is found in differences between typical and dyslexic readers on discrimination of, for example, duration and rise time. Hakvoort (2016) suggests that children with a familial risk of dyslexia are impaired in the processing of amplitude rise time (ART). This is 'the speed with which the amplitude of an acoustic signal rises from sound onset' (p. 18). Modulations in ART lead to perceived differences in rhythm, which are important for the segmentation of speech. If differences in ART are not registered by children with a familial risk of dyslexia, the perception of speech sounds may be affected. However, Hakvoort only found neurological differences in ART processing for children in early childhood, not for older children.

Furthermore, ART processing was not directly related to reading skill. Also Plakas et al. (2013) found a difference in ART and frequency processing between typical and at-risk children, but – contrary to Hakvoort – a relation of ART processing to reading skill as well. However, they found no differences between the typical reading at risk group and the impaired reading at risk group, which suggests that ART processing might be a risk-factor, but not a predictor of dyslexia.

Although differences are found for ART, frequency (Hakvoort, 2016) and pitch (Kujala et al., 2006), there are also auditory features that are processed by dyslexics and controls in the same way: intensity (Hakvoort, 2016; Kujala et al., 2006), duration and presence of a gap (Kujala et al., 2006). This suggests that the proposed general auditory processing deficit might be less general than is in the name of the deficit. Furthermore, there are also studies that do not find any differences between dyslexics and controls in for example tone discrimination (Schulte-Körne et al., 1998).

A second proposed cause of the phonological difficulties among dyslexia is impaired processing of rapid stimulus sequences (RSS) (Hari & Renvall, 2001) which is related to the sluggish attentional shifting theory (SAS) (Lallier et al., 2010b). Hari and Renvall suggest that dyslexics are not able to process stimuli that follow each other in a too fast pace. When learning a language, infants have to process long lines of speech, full of important information that is presented very rapidly after each other. When they are disabled in processing these rapid stimulus sequences, they are not able to establish the correct phoneme representations of their native language, leading to problems with reading later on in life. One of the findings that supports this impaired RSS is the longer 'attentional blink' that dyslexics have. An attentional blink is the time that someone is 'blind' for a second target after he or she has perceived a first target. Typically, this blink is approximately 540 ms for visual stimuli, but for dyslexics this blindness can be some 150 ms longer, up to 700 ms (Hari et al., 1999). This attentional blink has been shown to be amodal: it does not only appear when processing visual stimuli, but also when processing auditory stimuli, although it is much shorter for in the auditory modality: approximately 120 ms (Arnell & Jolicoeur, 1999; Lallier et al., 2010a, 2010b).

An explanation for the impaired processing of RSS could be amodal SAS, which is the inability to disengage the automatic attention system fast enough from item to item (Lallier et al., 2010b). SAS could for example explain the longer attentional blink of people with dyslexia. Because of sluggish attentional shifting, dyslexics are not able to follow successive stimuli at the same speed as controls can (Hari & Renvall, 2001). If the time between two stimuli in speech is fairly short and the attentional system is not fast enough to cut a speech stream into the appropriate parts, (parts of) some stimuli will be 'eaten up' by others. Therefore it is harder to establish the right categories, hence the deficit in phoneme representations.

Neurological model

The theory of SAS is supported by a neurological model (Richlan, 2012), which states a dysfunction of the left hemisphere reading network. According to this model, several regions in the left hemisphere are underactivated in people that suffer from dyslexia during reading. One of these regions is the inferior parietal lobule (IPL), a region that is associated with general attention mechanisms, which could explain the SAS. Two other underactivated areas are the occipito-temporal cortex (OT) and the inferior frontal gyrus (IFG), which are responsible for respectively phonological decoding of (un)familiar letter strings and access to the phonological representations. While the OT and IFG are strongly connected, the interactions between the IPL and these two brain areas are less clear (Richlan, 2012).

Dyslexic adults seem to develop some compensatory systems, which might explain why in behavioural studies fewer differences are found between dyslexics and controls. Shaywitz and Shaywitz (2005) found a positive correlation between reading skill and activation in the left OT and a negative correlation between reading skill and activation in the right OT. This means that the better the reader, the greater the activation in the left hemisphere, while the poorer the reader, the greater the activation in the right hemisphere. This indicates that dyslexics seem to depend more on word form recognition, than on word decoding. Furthermore, these compensatory systems would also explain why dyslexics are often found to be more impaired in reading pseudowords than normal words (Wimmer, 1996; van IJzendoorn & Bus, 1994). If they depend more on word form recognition, they can compensate for known words, but they will not be able to use the same compensatory mechanism for pseudowords.

EEG

EEG is an abbreviation for electroencephalography, which literally means: electricity-brain-writing. It is a non-invasive medical imaging technique, which maps the electrical activity of the brain from the surface of the scalp. EEG has a wide range of applications. It is for instance used to locate damaged areas in the brain after someone has had a seizure. Furthermore, it can be used to investigate neurological disorders, such as epilepsy and sleeping disorders (Baars & Gage, 2010). Another application is the monitoring of brain development (Abhang et al., 2016). Research in the field of linguistics makes use of EEG to, for example, investigate neurological disorders such as dyslexia and aphasia (Bishop, 2007).

During EEG recording, brain responses can be picked up by electrodes. The advantages of EEG over other brain imaging techniques are that it is fairly cheap, non-invasive and has a high temporal resolution. One of the disadvantages is that the spatial resolution is very low and it only measures activity of the cortices, not of the underlying brain structures.

MMN

When a stimulus is repeated and the brain response to this stimulus is measured multiple times and averaged, it is possible to calculate an event-related potential (ERP) from the EEG recordings. Mismatch negativity (MMN) is one of the components of an ERP. It reflects the mismatch of a standard and a deviant stimulus (Bishop, 2007). If someone is listening to a series of a repeating stimulus, he or she unconsciously picks up the regularity in the auditory stream. When a deviant stimulus that violates the regularity is then presented, this causes a mismatch of the standard and the deviant. The mismatch can be observed in an ERP in the form of a negative peak. MMN reflects an automatic and pre-attentive change detection, which means that you do not need to listen attentively to the stimuli (Baars & Gage, 2010). In adults it is usually found at a latency of 100-250 ms after the stimulus onset and is largest at the fronto-central midline of the brain.

MMN in infants can differ from adults in latency, topography and polarity (Dehaene-Lambertz & Gliga, 2004; Kushnerenko et al., 2002). For instance, in young children the MMN is found to be positive instead of negative, and found a little later than in adults, at 250-350 ms (Bishop, 2007). There is no consensus on an explanation for these differences, but it has been opted that this ERP component in infants is comparable to the adult P3a component, which reflects an involuntary attention switch (Alho et al., 1990; Trainor et al., 2001). The method that is usually used in infant EEG is the so-called ‘effect unspecific hypothesis’, which means that there is no clear a priori expectation on when and where an effect is found (Handy, 2005).

The current research

Previous studies show that there is a difference between typically developing infants (TD) and infants with a familial risk of dyslexia (FR) in the way they perceive the phoneme categories of their native language. Native contrasts are less well discriminated by the at-risk children, while other contrasts are better discriminated. To investigate whether Dutch FR and TD infants of 20 months old differ in their abilities to discriminate mid-word vowels, an EEG experiment was carried out. Typical for this study are the age of the children and the use of vowels as the alternating speech sounds. Around the age of 20 months, children will usually have learnt all the phonemic distinctions of their native language. Furthermore, at this age they are able to learn words in a very rapid pace (Fenson et al., 1994), which was important for a different study that was linked to the current one, but will not be discussed in this thesis. Although in many studies contrasting consonant pairs are used (Leppänen et al., 2002; van Leeuwen et al., 2007), this study uses contrasting vowel pairs. To contribute to the growing body of support for the allophonic representation hypothesis, it is important to know whether the hypothesis also holds for vowels.

The experiment exists of listening to the alternating pseudowords /xip/ (*giep*) versus /xIp/ (*gip*) and /xɔp/ (*gop*) versus /xup/ (*goep*). Two vowel contrasts were selected because of the previously mentioned linked study, in which a test pair and a control pair were necessary. In this way, it might also be visible whether possible differences in discrimination are dependent on the vowel that is used. These two particular pairs were chosen because they lie on opposite sides of the vowel space and therefore differ maximally: while /i/ and /I/ and fronted vowels, /ɔ/ and /u/ are back vowels. Differences between the two vowel pairs are not necessarily expected: all vowels are usually acquired by the time children reach the age of 20 months (Beers, 1995).

During the experiment, the brain activity of the infants is recorded with EEG. The task is designed around mismatch negativity: previous research has shown that differences between FR and TD children are often found in pre-attentive measurements, but not in behaviour. If the infants are capable of hearing the differences between /i/ and /I/, and /ɔ/ and /u/, mismatch negativity is expected when they encounter *gip* (or *goep*) while they hear *giep* (or *gop*) most of the time. If their brain does not detect the difference, there will be no mismatch. Both speech sound conditions (*giep-gip* and *gop-goep*), will be divided in a single and multiple speaker condition. This way it is possible to make a distinction between simple acoustic processing and phoneme categorisation. While in the single speaker condition the participants are simply required to distinguish two sounds, they have to group different sounds together in the multiple speaker condition. In the multiple speaker condition twelve different occurrences of all sounds are presented to the child. To be able to notice the deviant sound, it is necessary to group all occurrences of a sound together. If the child succeeds in categorising the phonemes, he or she will perceive two different sounds, while if the child fails to categorise the phonemes, he or she might possibly hear 24 different sounds within one speech sound condition. In this second scenario, there will be no standard and thus also no deviant.

Previous research demonstrates that the speech sound categories of vowels develop around the age of 6 months (Bosch & Sebastián-Gallés, 2003; Polka & Werker, 1994) and also that infants of 14 months are sensitive to word-medial vowels (Mani & Plunkett, 2008). The 20-month-old TD infants will therefore probably be able to hear the differences between the presented words in the multiple speaker condition. However, FR infants have more difficulties with perceiving phoneme contrasts than TD infants. Neurological studies showed that at various ages (2 months: Van Leeuwen et al., 2007; 6 months: Leppänen et al., 2002; 6 years: Noordenbos et al., 2012b; adults: Noordenbos et al., 2013) at-risks or dyslexics show a declined MMN compared to controls in an oddball experiment with speech sounds. In line with these findings, it is to be expected that during the current experiment as well, MMN in FR infants will probably be smaller than in TD infants. In the single speaker condition there is no need of phoneme categorisation, only of acoustical processing. Previous studies do not always show a difference in perception between dyslexics and controls, depending on the acoustical feature that is been tested (Hakvoort, 2016; Kujala et al., 2006; Schulte-Körne et al., 1998). As several features will play a role in telling the two speech sounds apart, MMN is expected to be comparable for both groups in this condition.

Method & Materials

Participants

49 Dutch infants (25 girls, 24 boys) took part in the experiment, which took place in the babylab of UiL OTS at Utrecht University. All infants were healthy, full-term babies. The average age of the infants was 20;9 months (19;0-20;24). This age was chosen because the children will have learnt most of the phoneme distinctions of their native language by then. Therefore any differences between infants with a familial risk of dyslexia (FR) and typically developing infants (TD) will probably be visible at this age. Children were assigned to the at-risk group if at least one of the parents was dyslexic. The dyslexic parent was tested on reading skill and intelligence to make sure that he or she was indeed a poor reader (for more on these tests, see the section on adult tests of dyslexia). 11 infants were assigned to the FR group. Their average age was 20;10 months (19;6-20;24) and the average age of the TD group (n = 39) was 20;9 months (19;0-20;24).

5 infants were also tested but not included in the analysis because they had an ear infection (n = 1), they did not want to put the cap on (n = 3) or they cried too much during the experiment (n=1). None of the participants were bilingual.

All caregivers signed a form of consent to indicate that they agreed to participate in the experiment with their child and received enough information beforehand. The experiment was approved by the ETCL (ethical review committee of linguistics).

Stimuli

The vowel-pairs /i/-/I/ and /ɔ/-/u/ that were used for the stimuli are minimal pairs in the Dutch language. /i/ and /I/ differ in the manner and place of articulation: the /I/ is a little bit more open than the /i/ and the /i/ is slightly more frontal than the /I/. The vowels /ɔ/ and /u/ only differ in manner of articulation: /u/ is a closed vowel while /ɔ/ is more open. According to previous research, typically developing children of the selected age should be able to notice word-medial vowel differences between words (Mani & Plunkett, 2007, 2008). As consonants are easier to discriminate than vowels, vowels were used to prevent any ceiling effects (Nazzi, 2005).

The experiment involves two different speaker condition: in the single speaker condition only one token of a single speaker is presented, while in the multiple speaker condition the words are produced by twelve different speakers. As explained above, in this way it is possible to make a distinction between simple acoustical processing and phoneme categorisation. In the single speaker condition, the participants will be simply distinguishing between two different sounds, while in the multiple speaker condition they have to categorise the speech sounds in the right way to single out the deviants.

Twelve different speakers were recorded while producing the words *giep*, *gip*, *gop* and *goep*. Recordings were made in a sound proof booth, using a *Sennheiser ME-64* microphone. The details on formants and duration of the speech stimuli can be found in Table 1. Two-tailed t-tests confirmed that both the F1 and F2 of *giep* and *gip* differed significantly (F1: $t(11) = -16.09$, $p < .001$; F2: $t(11) = 3.97$, $p = .002$), as did the F1 and F2 of *gop* and *goep* (F1: $t(11) = -9.56$. $p < .001$; F2: $t(11) = -3.07$, $p = .01$). The average fundamental frequency and duration of the fragments did not differ significantly between *giep* and *gip* (F0: $t(11) = 0.78$, $p = .45$; duration: $t(11) = 1.07$, $p = .31$), neither did they for *gop* and *goep* (F0: $t(11) = -0.31$, $p = .76$; duration: $t(11) = -1.68$, $p = .12$).

For the single speaker condition of the experiment, one token of one single speaker was used. The details on the formants and duration of these stimuli can be found in Table 2.

The recordings were played over two *Tangent evo e4 Two-way 10-150 W rms* speakers, using an integrated stereo amplifier from Sony (model: *TA-FE230, 120 W, super legato linear*), with a loudness of approximately 60-65 dB.

Vowel	F0 in Hz	F1 in Hz	F2 in Hz	Duration total fragment in ms
/i/	250 (33.9)	316 (25.8)	2574 (264.5)	346 (9.0)
/I/	240 (45.9)	499 (25.1)	2257 (137.7)	342 (9.9)
/u/	252 (54.5)	360 (27.4)	808 (107.35)	344 (6.8)
/ɔ/	259 (54.0)	535 (79.3)	883 (79.5)	349 (4.2)

Table 1: Averages (standard deviations) of formants and duration of the speech stimuli used in the multiple-speaker condition of the experiment.

Vowel	F0 in Hz	F1 in Hz	F2 in Hz	Duration total fragment in ms
/i/	249	344	2522	340
/I/	228	506	2395	351
/u/	278	348	728	347
/ɔ/	199	477	803	344

Table 2: Formants and duration of the speech stimuli used in the single-speaker condition of the experiment.

The next figures give an overview of the distribution of the stimuli. For both the vowel contrast the stimuli do not overlap.

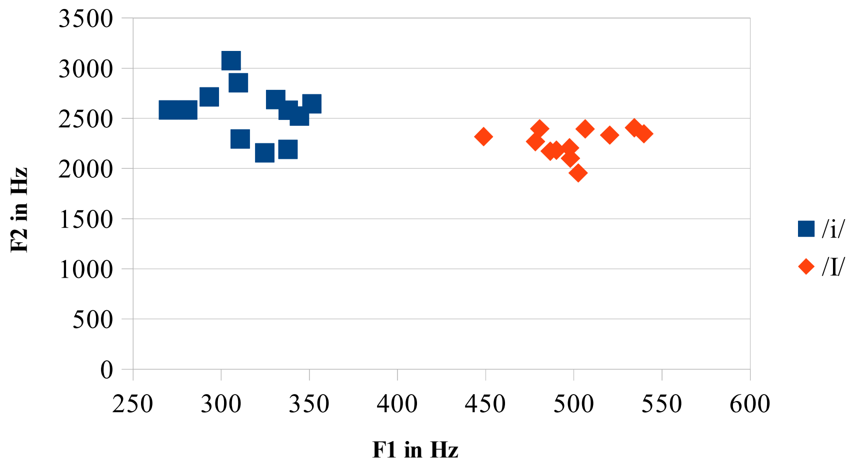

Figure 1: Vowel characteristics of the stimuli (12 speakers per vowel).

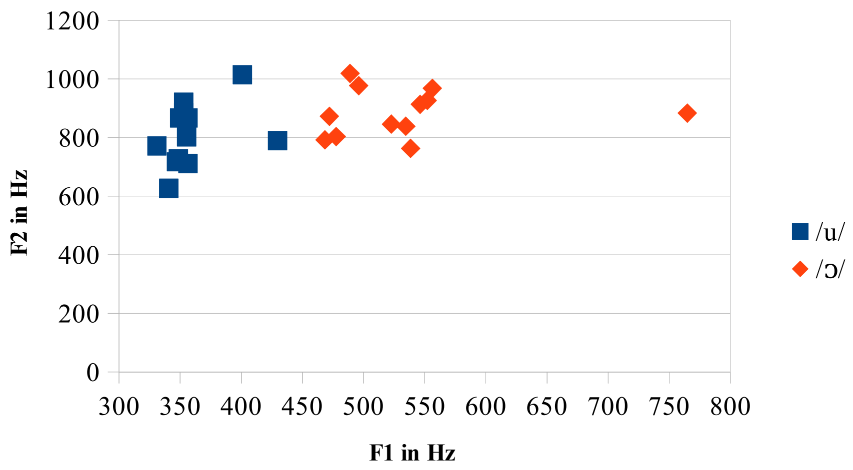

Figure 2: Vowel characteristics of the stimuli (12 speakers per vowel).

Preparation

The child and his or her caregiver were received in the babylab waiting area and from there guided to the experiment room. In the room the child was put in a high chair when he or she was ready (some children needed some time to adjust to the new people and new surroundings). A bear and a doll were placed on the table in front of the child, both with an EEG cap on their heads. The attention of the child was directed towards the toys and their caps, and subsequently to two other caps in front of the child. The experimenter told the child that they were about to do a game with the bear and the doll, and that for this purpose the child also needed to wear a cap. One of the caps was decorated with some flowers, and the other one with stars. In order to prevent the child from saying ‘no’ to wearing a cap, the experimenter asked which one of the caps he or she wanted to wear: the one with the flowers or the one with the stars. Caps were available in two sizes: usually the smaller size (44-48 cm) was used for girls and the larger size (46-50 cm) for boys, but if the child had a larger or smaller head than average, the best fitting cap was used.

When the child had chosen a cap, toys were given to him or her, to make sure he or she was distracted from the preparation. The area of skin behind the ears was cleaned with alcohol to make sure that the two sensors behind the ears would stick to it. After that, the cap was put on and immediately a video was started on the computer screen that was on the table in front of the child, playing children’s songs to distract the child and keeping him or her from pulling the cap of his or her head. The music video usually worked, but when it did not, extra attention was directed to the toys on the table, or a different video was played that was recommended by the caregiver. A little bit of electrode gel was applied to the child’s back of the hand to test whether the child was allergic to it. While waiting for the gel to be absorbed by the skin, the experimenter shortly explained to the caregiver what the next steps were to eventually complete the experiment.

After checking that the child did not have an allergic reaction to the electrode gel, the reference electrodes could be applied behind the ears. The cap was put on before the reference electrodes were applied because children tend to pull the electrodes from their head when they are not ‘hidden’ under the cap. Then all 32 electrode gaps were filled with electrode gel using a syringe and subsequently the electrodes were applied to the corresponding terminals (see Appendix 1 for a list of used electrodes). After checking that every electrode made good contact to the scalp, the child was ready to begin with the experiment.

The caregiver stayed with the child during the experiment and was instructed not to talk to the child because that would interfere with the stimuli that were audibly presented. They could play in silence with the child, hand over toys and give them something to eat or drink. Furthermore they were asked to keep the child from pulling the cap or the sensors. It was possible to stop with the experiment any time they wanted to, they just had to wave to the camera in the room.

After the experiment, the child and caregiver were brought back to the waiting area, where the child was allowed to pick out a book as a gift. Furthermore, the caregiver received a reimbursement for travelling and/or parking costs if necessary.

Procedure

The children listened to pseudowords with a CVC-structure as described above while playing with toys and watching a silent movie of *Dora the Explorer*. The goal of this experiment is to investigate whether the participants are able to detect the difference between two mid-word vowels. The experiment existed of two blocks, one with the words /xip/ and /xIp/ (corresponding to the pseudowords *giep* and *gip* in Dutch) and one with the words /xɔp/ and /xup/ (*gop* and *goep*, respectively).

During the first half of a block, the words are produced by different speakers, while during the second half one single token of one speaker was presented. The order of the blocks was always the same: the first trial consisted of the multiple speaker version of *giep* and *gip*, followed by the one-speaker version of the same words. Then the two trials with the words *gop* and *goep* were presented to the child in the same order: first the multi-speaker version, followed by the one-speaker version.

All trials began with a familiarisation phase of ten standard words, which were *giep* and *gop*, to create a baseline. Subsequently, five hundred stimuli were presented to the child in random order, with a chance of 20 percent that the deviant (*gip* or *goep*) was chosen. All stimuli were approximately the same length, which is 345 ms. The interstimulus interval had a random generated duration that varied between 320 and 400 ms. The number of standard stimuli between two deviants was at least two and at most eight. If the child was restless, started crying, or if for some other reason the EEG signal was noisy during the block, the number of stimuli could be extended to six hundred, to compensate for the lost ones, but usually the blocks were aborted after five hundred stimuli. The whole experiment lasted approximately 25 minutes.

Adult tests of dyslexia

To verify that the parents that indicated to be dyslexic were indeed reading impaired, they were tested on reading abilities and verbal comprehension. They had to perform the EMT (Brus & Voeten, 1973) and Klepel (Van den Bos et al., 1994) reading tests and a verbal comprehension task that is part of the Wechsler Adult Intelligence Scale (WAIS-III-NL)

(Wechsler, 1977). The tests were usually taken after the appointment with the child, but sometimes a separate appointment was made.

EMT

The participant was given a sheet of paper with four columns of words on the back. He or she was told that the list existed of Dutch words and was instructed to read the words out loud as accurately and fast as possible, from top to bottom. If the bottom of a column was reached, he or she could proceed to the next one. It was not allowed to use a finger as an indicator. The participant was allowed to correct him- or herself and got one minute of time to read as many words as possible. During reading, the experimenter registered whether the words were pronounced correctly. The score was calculated by reducing the number of read words within the time limit with the incorrectly pronounced words.

Verbal comprehension task

This task is part of the more elaborate intelligence test WAIS-III-NL and is usually used to measure verbal comprehension and abstract reasoning. For this task the participant was instructed to name the similarity between two words. He or she was given an example in advance in which he or she had to name the similarity between a ring and a necklace. In this case, the answer 'jewellery' was correct. It is also possible to answer with 'they can both be worn as an ornament', but 'jewellery' is a better answer. After instruction, thirteen pairs of words were presented to the participant, always embedded in the sentence 'What is the similarity between X and X?' The answer that was given could fall in three different categories, scored with either two, one or zero points. If the participant did not give a two-point answer at the first try, he or she was asked once to give another similarity or to elaborate. The score was calculated by taking the sum of the scores of the thirteen pairs.

Klepel

This test is very similar to the EMT, but differs in the kind of words that were to be read out loud. The words in this test were non-words that do not exist in Dutch, but were phonotactically legal. The participant was also informed by this. The rest of the instructions were the same as for the EMT, apart from the time limit that was extended to two minutes for this task. The word was labelled as 'incorrect' if the participant's pronunciation would demand a different orthography. The score was calculated by reducing the number of read words within the time limit with the incorrectly pronounced words.

The scores for the three different tests were normalized in terms of the average percentage of people that score the same or lower. If the difference between one of the reading tasks and the verbal comprehension task was equal to or more than 70 percentiles (Kuijpers et al., 2003), the parent was classified as a bad reader, which was the case for all parents that declared to be dyslexic.

EEG Analysis

During the phoneme categorization task, EEG was recorded using a ActiveTwo MKII Analog-to-Digital-Box (*ADC 16-11-803*) and the corresponding software *ActiView version 7.06* with a sampling rate of 2048 Hz. Analysis of the data was done using MATLAB *R2015b* with the plugins *BIOSIG data import*, *Grandaverage*, *ERPLAB* and *EEGLAB* (*eeglab14_1_0b*). Data from the 32 channels (see Appendix 1 for a list of used electrodes) was recorded with additional mastoid electrodes. EEG was resampled to 250 Hz offline. To get rid of low and high frequency artefacts, the data was filtered offline with a passband of 0.3 to 20 Hz. EEG epochs that started 100 ms before stimulus onset as the baseline and ended 600 ms after stimulus onset were averaged offline per stimulus type. Occasional noisy channels were interpolated and epochs with extreme values in one or more of the channels were rejected. This resulted in an average of 229 (48) acceptable epochs in the standard conditions and 76 (17) for the deviant conditions per participant. Among the infants, the ones with the fewest accepted epochs had 93 epochs in the standard condition and 30 in the deviant condition.

A participant was included in the final analysis if he or she had more than 30 trials after artefact reduction. 5 participants were excluded during the data analysis, due to noisy reference channels (n = 4) or not enough artefact-free epochs (n = 1). This resulted in 10 participants in the FR group and 34 participants in the TD group. After removing artefacts, ERPs for each remaining participant were calculated by taking averages per different condition. These were used for further statistical analysis. As mismatch negativity is mainly found in the fronto-central region of the brain, specifically at electrodes F3, Fz and F4, analysis was only performed for these three recording sites (Duncan et al., 2009; Kujala et al., 2007; Näätänen et al., 2007). MMN amplitudes were determined by performing paired t-tests on the ERPs of the standard and deviant in every condition to check whether they are significantly different from each other. This was done for every time window of 50 ms between 0 and 600 ms after stimulus onset (giving a total of 12 time windows). Statistics were performed on the average value of the ERP within a time window.

Results phoneme categorisation

The following pages display the results of the experiment. Recall that there were two different vowel conditions (*giep-gip*, *gop-goep*) and also two speaker conditions (single, multiple).

First, the differences between the standard and deviant of all conditions are discussed. Second, per condition a table with all values and the corresponding graphs are displayed, followed by a scheme (Scheme 1) with a schematic overview of the differences. Finally, the differences between the groups, speaker conditions and electrodes are discussed.

Giep-gip multiple

No differences between the standard and deviant were found at any of the recording sites for the TD group. There were a few trends towards differences, namely at 350-400 ms at F3 ($t(33) = -1.85$, $p = .07$) and at 51-100 ms at Fz ($t(33) = -1.94$, $p = .06$). The FR group did show some significant positive differences: at 151-200 ms and 301-350 ms at F3 ($t(9) = -2.33$, $p = .04$ and $t(9) = -2.40$, $p = .04$, respectively) and at Fz at 201-250 ms ($t(9) = -2.33$, $p = .05$). Around those same time windows, trends towards differences were found too: at recording site F3 between the pre-mentioned time windows (201-250 ms: $t(9) = -2.19$, $p = .06$; 351-400 ms: $t(9) = -2.06$, $p = .07$) and at site Fz at 151-200 ms ($t(9) = -2.14$, $p = .06$). No differences were found at site F4.

Giep-gip single

The TD infants showed a clear difference peak in the 4th time window, that is between 151 and 200 ms, at all three recording sites (F3: $t(33) = -2.43$, $p = .02$; Fz: $t(33) = -2.06$, $p = .05$; F4: $t(33) = -2.30$, $p = .03$). At this time window, the FR infants only showed a significant difference between the standard and deviant at Fz ($t(9) = -2.25$, $p = .05$), a trend at F3 ($t(9) = -2.03$, $p = .07$) and also a trend at the next time window at Fz ($t(9) = -2.09$, $p = .06$). Furthermore, negative differences were found for the FR group between 551 and 600 ms for all three recording sites (F3: $t(9) = 2.46$, $p = .04$; Fz: $t(9) = 3.90$, $p < .01$; F4: $t(9) = 4.25$, $p < .005$). At Fz, differences were also found at 451-500 ms ($t(9) = 2.55$, $p = .03$) and at 501-550 ms ($t(9) = 2.99$, $p = .02$). Also at F4 negative differences were found, namely at 401-450 ms ($t(9) = 2.81$, $p = .02$), 451-500 ms ($t(9) = 3.39$, $p < .01$) and 501-550 ms ($t(9) = 3.54$, $p < .01$). The TD infants showed significant negative differences too at F4 around those times (501-550 ms: $t(33) = 2.20$, $p = .03$; 551-600 ms: $t(33) = 2.22$, $p = .03$) and a trend at Fz (551-600 ms: $t(33) = 1.91$, $p = .07$).

Gop-goep multiple

No differences at all at any of the recording sites and any of the time windows were found between the standard and deviant for the TD group. For the FR group, positive differences were found only at Fz, in the first two time windows (0-50 ms: $t(9) = -2.79$, $p = .02$; 51-100 ms: $t(9) = -2.38$, $p = .04$). Trends towards differences were found at F3, for the same time windows (0-50 ms: $t(9) = -2.17$, $p = .06$; 51-100 ms: $t(9) = -2.16$, $p = .06$).

Gop-goep single

For the TD infants, negative differences were found at the end, at 501-550 ms for all three recording sites (F3: $t(33) = 2.01$, $p = .05$; Fz: $t(33) = 2.81$, $p < .01$; F4: $t(33) = 3.23$, $p < .005$). For Fz and F4, differences were also found at 551-600 ms ($t(33) = 2.40$, $p = .02$ and $t(33) = 2.70$, $p = .01$, respectively). For the FR groups, positive differences were found at all recording sites at earlier time windows, namely at 351-400 ms (F3: $t(9) = 3.83$, $p < .005$; Fz: $t(9) = -4.32$, $p < .005$; F4: $t(9) = -2.83$, $p = .02$) and at 401-450 ms (F3: $t(9) = 2.80$, $p = .02$; Fz: $t(9) = -3.88$, $p < .005$; F4: $t(9) = -2.82$, $p = .02$). At Fz, a difference was also found at 301-350 ms ($t(9) = -2.36$, $p = .04$) and at F4 at 0-50 ms ($t(9) = -2.47$, $p = .04$).

time window	condition	TD			FR		
		F3	Fz	F4	F3	Fz	F4
0-50	std	0.19 (1.60)	0.13 (1.76)	0.34 (1.56)	0.34 (1.22)	0.67 (1.00)	0.50 (1.04)
	dev	0.62 (2.00)	0.59 (1.83)	0.75 (1.99)	0.02 (2.29)	0.22 (2.89)	0.20 (1.70)
51-100	std	2.01 (2.68)	1.96 (2.75)	2.14 (2.49)	2.29 (2.31)	2.52 (1.94)	2.57 (2.4)
	dev	2.69 (3.10)	2.94 (2.86)	2.80 (3.25)	2.51 (3.60)	2.76 (4.24)	2.63 (3.63)
101-150	std	6.30 (3.83)	6.20 (3.65)	6.45 (3.40)	6.97 (3.21)	7.35 (2.80)	7.56 (2.97)
	dev	6.76 (4.29)	6.94 (3.82)	6.97 (4.41)	7.93 (3.84)	8.69 (4.85)	8.03 (4.65)
151-200	std	8.56 (4.20)	8.46 (4.09)	8.93 (3.46)	10.22 (3.95)	10.65 (3.17)	11.06 (3.32)
	dev	9.51 (4.37)	8.98 (4.02)	9.39 (4.39)	12.35 (3.81)	13.04 (4.27)	12.24 (4.65)
201-250	std	9.57 (4.17)	9.28 (4.19)	9.71 (3.99)	11.07 (4.20)	11.12 (3.45)	11.88 (3.27)
	dev	10.82 (5.15)	9.80 (5.40)	10.47 (4.80)	13.49 (4.65)	13.89 (4.59)	13.75 (4.36)
251-300	std	6.86 (4.04)	6.57 (4.27)	6.68 (4.21)	6.87 (3.86)	7.04 (3.27)	7.40 (3.36)
	dev	7.47 (4.63)	6.63 (4.93)	6.52 (4.60)	10.01 (4.75)	9.73 (4.76)	9.48 (4.73)
301-350	std	3.46 (4.25)	3.17 (4.34)	2.98 (4.48)	2.41 (3.87)	2.68 (3.24)	2.81 (3.50)
	dev	4.95 (4.66)	4.22 (4.92)	4.27 (4.69)	6.92 (4.64)	6.03 (4.68)	5.85 (5.31)
351-400	std	2.24 (3.43)	1.83 (3.37)	1.61 (3.87)	2.28 (3.38)	2.24 (3.20)	2.29 (2.96)
	dev	3.78 (4.45)	3.21 (4.36)	3.20 (4.62)	5.86 (4.35)	4.07 (4.14)	4.03 (5.54)
401-450	std	1.94 (3.34)	1.55 (3.08)	1.23 (3.38)	3.09 (3.35)	3.08 (3.25)	3.29 (2.83)
	dev	3.02 (5.14)	2.06 (4.99)	2.15 (5.55)	4.40 (4.75)	2.24 (4.37)	2.55 (5.98)
451-500	std	1.48 (3.09)	1.19 (3.12)	0.80 (3.34)	2.43 (3.18)	2.33 (3.27)	2.13 (2.60)
	dev	2.09 (5.83)	1.26 (5.95)	1.28 (6.29)	2.11 (4.05)	-0.15 (4.02)	-0.30 (5.60)
501-550	std	0.75 (3.04)	0.72 (2.84)	0.01 (2.8)	0.42 (2.65)	0.62 (3.16)	-0.25 (2.66)
	dev	0.54 (5.34)	0.01 (5.82)	-0.42 (5.48)	-0.62 (3.98)	-2.44 (3.50)	-3.36 (5.22)
551-600	std	0.47 (2.66)	0.78 (2.45)	-0.01 (2.39)	0.16 (2.78)	0.48 (3.19)	-0.21 (3.07)
	dev	0.22 (4.74)	-0.34 (5.09)	-0.79 (5.26)	-2.06 (4.02)	-3.00 (4.59)	-4.27 (5.58)

Table 3: Values of the response waves towards the standard and deviant of the giep-gip multiple speaker condition per electrode and time window.

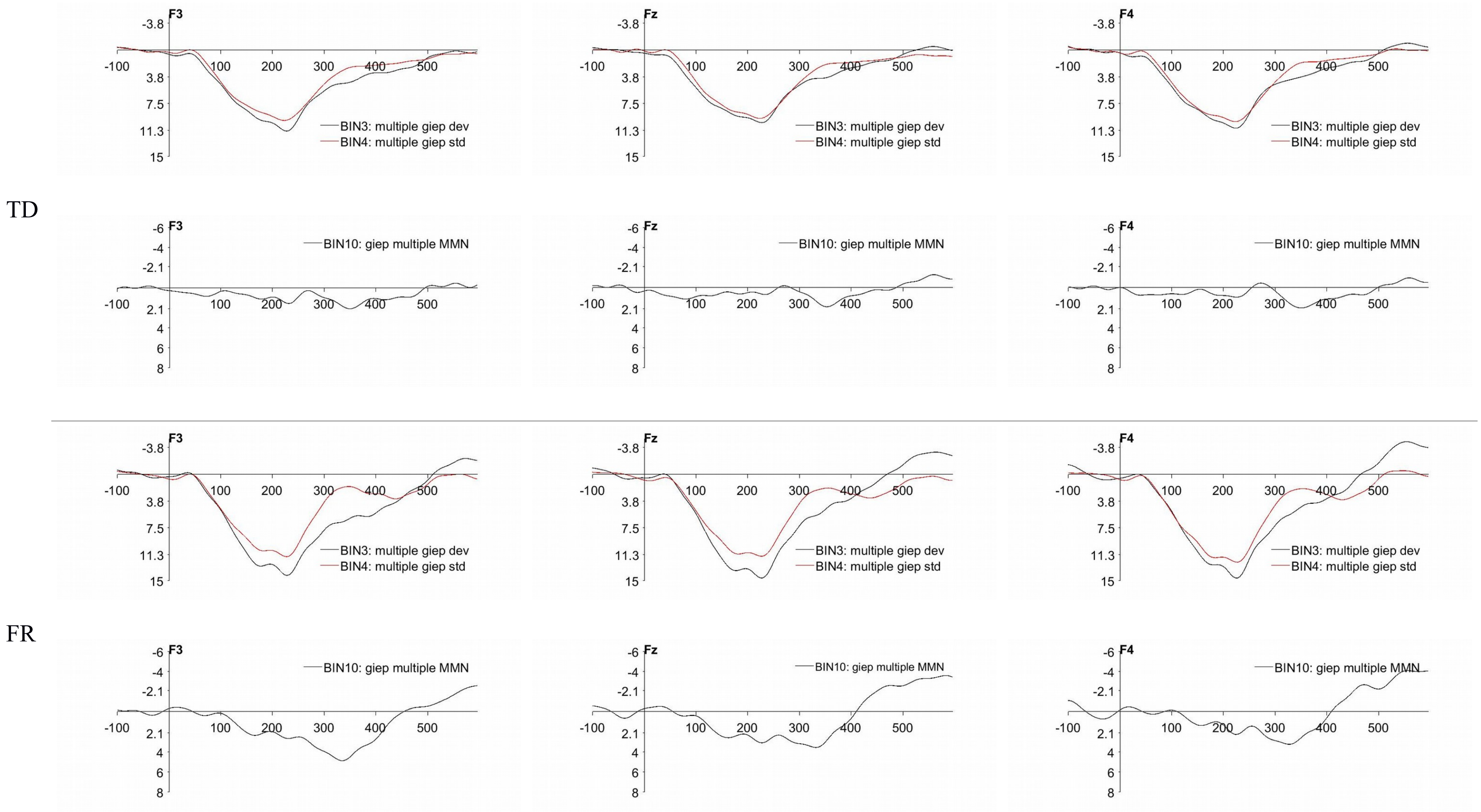

Figure 3: ERPS of both groups for the gop-goep multiple speaker condition. For both groups the response waves of the standard and deviant and the difference wave are displayed.

time window	condition	TD			FR		
		F3	Fz	F4	F3	Fz	F4
0-50	std	0.05 (1.16)	-0.18 (1.35)	-0.11 (1.40)	-0.29 (0.92)	-0.32 (0.89)	-0.28 (0.88)
	dev	-0.12 (2.07)	0.07 (2.11)	-0.2 (1.95)	-0.80 (2.75)	-0.88 (3.32)	-1.15 (2.96)
51-100	std	1.04 (1.53)	0.92 (2.01)	1.00 (1.99)	0.59 (1.40)	0.40 (1.06)	0.61 (1.14)
	dev	0.74 (3.08)	0.63 (2.54)	0.59 (2.22)	0.86 (3.05)	0.98 (3.42)	-0.06 (3.43)
101-150	std	4.17 (2.32)	3.95 (2.33)	4.02 (2.48)	2.49 (2.46)	2.48 (1.89)	3.04 (1.91)
	dev	4.81 (3.96)	4.31 (3.89)	4.55 (3.35)	4.95 (4.35)	5.35 (4.38)	4.31 (4.91)
151-200	std	5.75 (2.97)	5.52 (3.12)	5.54 (2.94)	5.15 (2.77)	4.98 (2.04)	5.61 (2.73)
	dev	7.65 (4.53)	7.19 (4.44)	7.22 (3.87)	7.68 (4.76)	8.39 (4.57)	7.45 (4.91)
201-250	std	6.90 (3.27)	6.55 (3.66)	6.74 (3.29)	6.22 (2.95)	5.78 (2.39)	6.38 (2.97)
	dev	8.10 (5.41)	7.57 (5.51)	7.47 (4.89)	7.82 (3.70)	7.43 (2.88)	6.93 (3.68)
251-300	std	5.03 (3.48)	4.57 (3.70)	4.58 (3.56)	4.02 (3.16)	3.53 (2.92)	3.47 (2.82)
	dev	5.11 (5.27)	4.35 (5.20)	4.02 (4.55)	2.93 (4.13)	2.80 (4.36)	0.99 (4.52)
301-350	std	2.44 (3.23)	2.00 (3.29)	1.79 (3.14)	-0.30 (3.34)	-0.57 (3.35)	-0.73 (3.24)
	dev	3.53 (5.08)	2.57 (5.10)	2.34 (4.95)	-0.49 (4.17)	-1.65 (4.60)	-3.37 (4.75)
351-400	std	1.76 (3.42)	1.42 (3.66)	1.14 (3.12)	0.69 (2.79)	0.21 (3.13)	-0.25 (2.97)
	dev	2.68 (6.10)	1.76 (5.56)	1.60 (5.47)	-0.13 (4.43)	-2.01 (4.56)	-3.22 (4.76)
401-450	std	3.11 (4.26)	2.71 (4.33)	2.38 (3.68)	3.36 (2.69)	3.00 (2.87)	2.74 (3.08)
	dev	2.99 (6.77)	1.93 (6.09)	1.75 (5.69)	1.50 (5.59)	-0.62 (6.22)	-1.85 (5.33)
451-500	std	3.54 (4.13)	3.31 (4.09)	2.97 (3.64)	4.18 (1.80)	3.86 (2.01)	3.84 (2.41)
	dev	3.13 (6.30)	1.89 (6.30)	1.31 (5.80)	1.25 (5.94)	-0.44 (6.16)	-1.94 (5.57)
501-550	std	2.73 (3.30)	2.61 (3.41)	2.09 (3.14)	2.08 (1.68)	2.03 (1.89)	2.02 (1.41)
	dev	1.88 (5.49)	0.94 (5.49)	-0.02 (4.69)	-1.32 (5.76)	-2.50 (5.57)	-4.32 (5.98)
551-600	std	1.76 (2.86)	1.77 (3.06)	1.17 (2.97)	1.36 (2.00)	1.71 (2.21)	1.70 (2.06)
	dev	0.50 (5.06)	-0.14 (5.19)	-1.04 (4.69)	-3.30 (5.72)	-4.67 (5.61)	-6.45 (5.71)

Table 4: Values of the response waves towards the standard and deviant of the giep-gip single speaker condition per electrode and time window.

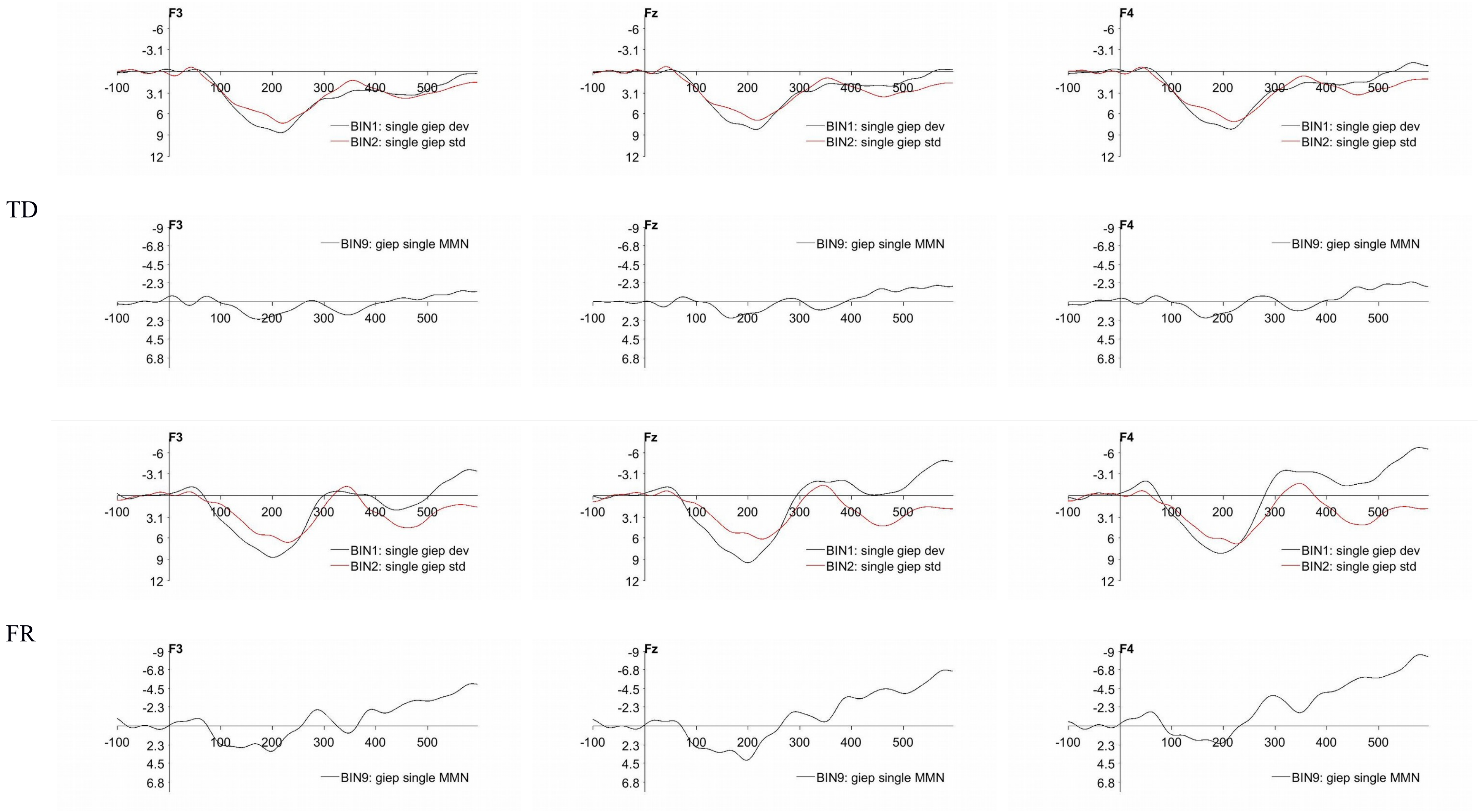

Figure 4: ERPS of both groups for the giep-gip single speaker condition. For both groups the response waves of the standard and deviant and the difference wave are displayed.

time window	condition	TD			FR		
		F3	Fz	F4	F3	Fz	F4
0-50	std	0.30 (1.57)	0.21 (1.56)	0.35 (1.33)	-0.49 (1.48)	-0.12 (1.23)	0.32 (1.05)
	dev	-0.27 (3.03)	-0.21 (2.87)	0.38 (2.62)	1.55 (3.11)	2.21 (2.96)	1.62 (2.18)
51-100	std	1.65 (2.15)	1.39 (2.50)	1.49 (2.20)	0.23 (3.18)	0.88 (2.89)	1.56 (2.56)
	dev	0.91 (3.70)	0.77 (3.83)	1.15 (3.32)	2.68 (2.74)	3.52 (2.96)	2.47 (1.74)
101-150	std	5.05 (3.57)	4.40 (3.68)	4.76 (3.25)	5.17 (4.12)	5.78 (3.79)	6.52 (3.82)
	dev	4.79 (5.76)	4.84 (5.16)	4.93 (4.47)	7.18 (3.14)	7.60 (3.83)	6.94 (3.02)
151-200	std	7.44 (3.53)	6.66 (3.37)	7.04 (3.29)	7.69 (4.13)	8.36 (3.73)	9.18 (3.91)
	dev	7.06 (6.70)	6.94 (5.86)	6.74 (5.05)	9.29 (3.62)	9.05 (4.33)	8.92 (3.06)
201-250	std	8.47 (3.28)	7.39 (3.23)	7.66 (3.22)	7.76 (3.81)	8.31 (3.23)	8.68 (3.25)
	dev	7.91 (6.14)	7.80 (5.57)	7.47 (4.35)	8.50 (4.60)	8.93 (4.98)	8.48 (4.45)
251-300	std	5.07 (3.13)	4.25 (3.08)	4.16 (3.01)	4.44 (4.32)	5.12 (3.81)	4.71 (3.82)
	dev	5.17 (5.63)	5.35 (5.47)	4.87 (4.25)	4.64 (3.54)	5.38 (4.36)	4.53 (4.62)
301-350	std	2.71 (3.61)	2.05 (3.60)	1.99 (3.42)	1.44 (4.11)	1.89 (3.48)	1.18 (3.71)
	dev	2.04 (5.45)	2.39 (5.38)	1.83 (4.66)	2.48 (2.78)	2.85 (3.57)	1.80 (4.37)
351-400	std	1.74 (3.79)	0.84 (3.83)	1.17 (3.66)	0.77 (3.74)	0.82 (3.08)	0.25 (2.82)
	dev	1.84 (5.89)	2.19 (5.84)	1.61 (4.89)	3.21 (3.72)	2.64 (3.73)	1.44 (3.97)
401-450	std	1.42 (4.08)	0.23 (3.80)	0.32 (3.87)	0.74 (3.59)	0.40 (3.04)	0.07 (2.77)
	dev	2.23 (6.09)	2.25 (6.37)	1.97 (5.67)	3.27 (4.44)	1.74 (5.15)	0.84 (5.25)
451-500	std	1.10 (3.88)	-0.17 (3.74)	-0.17 (3.88)	-0.26 (3.93)	-0.65 (3.49)	-0.86 (2.43)
	dev	1.62 (6.24)	1.61 (6.49)	1.10 (5.97)	1.26 (4.57)	-0.24 (5.08)	-1.23 (4.83)
501-550	std	0.76 (3.38)	-0.30 (3.29)	-0.37 (3.25)	-1.41 (3.04)	-1.60 (2.59)	-1.91 (1.67)
	dev	0.26 (6.96)	0.59 (6.99)	-0.09 (6.59)	-1.30 (4.58)	-2.70 (5.30)	-3.20 (4.03)
551-600	std	0.62 (2.86)	-0.27 (2.59)	-0.32 (2.56)	-0.59 (2.10)	-0.74 (2.08)	-1.42 (1.68)
	dev	-0.03 (6.31)	0.34 (6.12)	-0.16 (5.63)	-1.92 (4.76)	-3.28 (5.18)	-3.20 (4.47)

Table 5: Values of the response waves towards the standard and deviant of the gop-goep multiple speaker condition per electrode and time window.

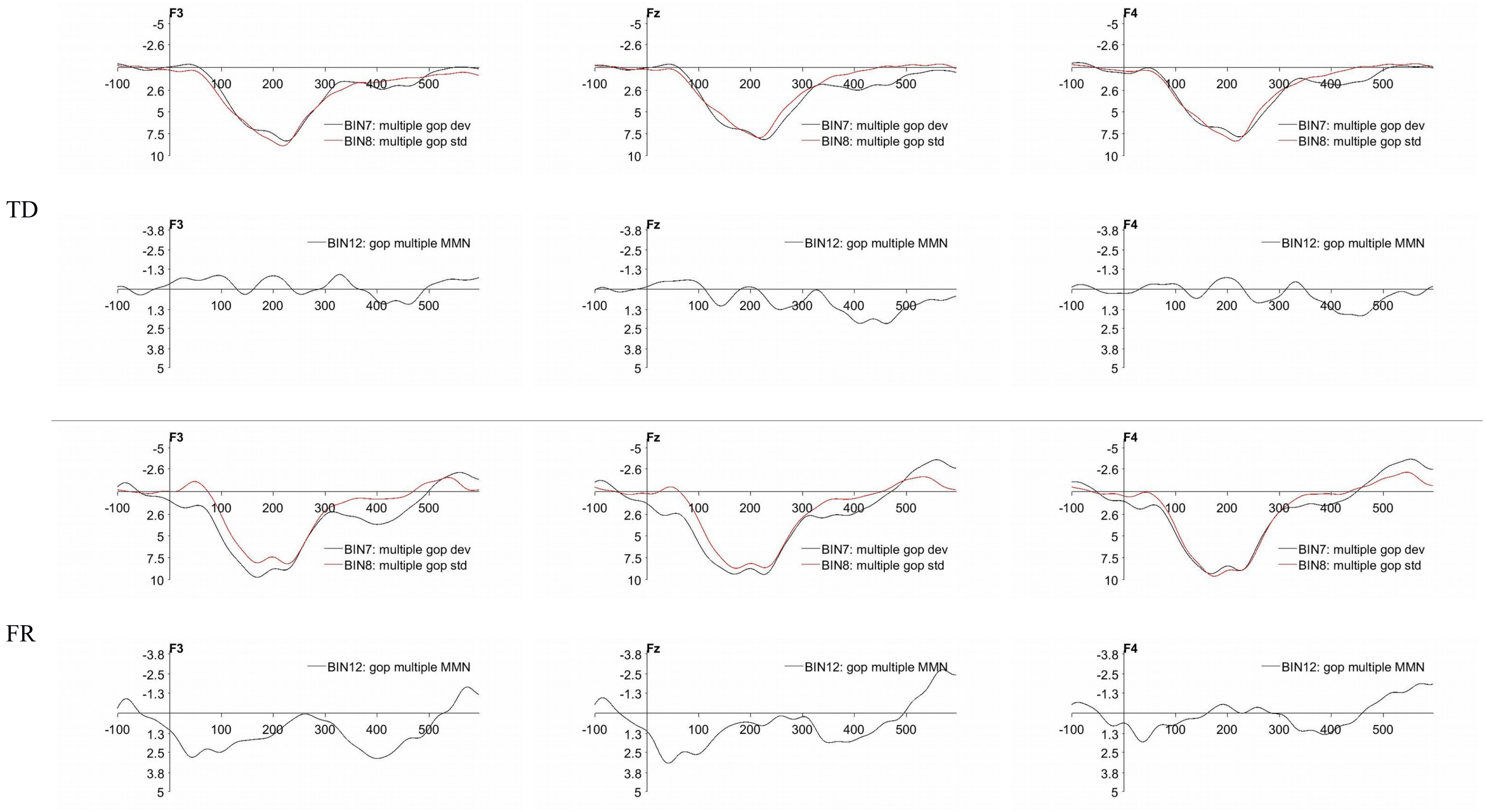

Figure 5: ERPS of both groups for the gop-goep multiple speaker condition. For both groups the response waves of the standard and deviant and the difference wave are displayed.

time window	condition	TD			FR		
		F3	Fz	F4	F3	Fz	F4
0-50	std	0.09 (1.62)	-0.09 (1.78)	-0.13 (1.71)	-0.81 (1.49)	-0.61 (1.68)	-0.76 (1.61)
	dev	0.34 (2.13)	-0.13 (2.35)	0.06 (2.23)	0.40 (1.94)	0.25 (2.20)	0.84 (1.41)
51-100	std	1.05 (2.72)	0.97 (2.88)	0.89 (2.96)	1.00 (2.77)	0.80 (2.76)	0.88 (2.74)
	dev	1.38 (2.85)	0.68 (3.00)	0.76 (3.21)	1.74 (2.65)	1.63 (2.63)	2.56 (2.64)
101-150	std	4.91 (4.06)	4.82 (4.19)	4.98 (4.03)	5.08 (3.13)	4.62 (3.22)	4.97 (3.37)
	dev	4.88 (4.23)	4.15 (3.85)	4.92 (4.11)	6.12 (3.00)	5.80 (3.11)	6.69 (2.43)
151-200	std	7.14 (4.33)	6.93 (4.02)	7.05 (3.99)	7.72 (3.25)	7.42 (3.33)	7.72 (3.48)
	dev	6.94 (4.37)	6.16 (4.15)	6.81 (4.20)	8.06 (2.19)	7.83 (3.03)	8.61 (3.83)
201-250	std	7.30 (4.21)	6.79 (3.58)	7.10 (3.99)	6.74 (3.61)	6.13 (3.40)	6.95 (3.75)
	dev	5.96 (4.37)	5.54 (4.01)	6.06 (4.59)	6.18 (3.43)	6.15 (4.33)	6.25 (4.48)
251-300	std	4.40(3.53)	3.68 (3.33)	4.06 (3.79)	3.84 (3.71)	3.25 (2.56)	3.60 (3.32)
	dev	3.75 (4.98)	2.96 (4.70)	3.14 (4.84)	3.58 (2.61)	3.92 (3.12)	3.58 (3.39)
301-350	std	2.16 (2.93)	1.41 (3.13)	1.85 (3.28)	0.64 (3.90)	0.08 (3.09)	0.55 (3.63)
	dev	1.77 (5.09)	1.03 (4.87)	1.14 (4.42)	2.65 (2.14)	2.78 (2.16)	2.62 (3.93)
351-400	std	0.84 (3.05)	0.25 (3.08)	0.91 (3.30)	-0.52 (4.00)	-1.22 (3.53)	-0.52 (3.38)
	dev	2.34 (5.36)	1.70 (5.37)	2.22 (5.29)	5.67 (2.66)	5.47 (3.01)	4.59 (4.27)
401-450	std	1.52 (3.46)	1.06 (3.13)	1.55 (3.56)	0.39 (3.82)	-1.59 (2.92)	0.21 (3.26)
	dev	2.73 (6.14)	1.81 (5.69)	2.21 (6.04)	6.21 (3.90)	6.30 (3.82)	5.44 (3.86)
451-500	std	2.36 (3.47)	1.92 (3.36)	2.22 (3.62)	2.17 (3.22)	0.87 (3.07)	1.66 (2.56)
	dev	1.72 (6.18)	0.87 (5.39)	0.99 (6.08)	3.51 (4.49)	4.01 (4.41)	2.55 (4.26)
501-550	std	2.04 (3.56)	1.80 (3.17)	1.89 (3.36)	1.58 (2.42)	0.69 (2.38)	1.50 (1.84)
	dev	0.29 (5.70)	-0.52 (4.84)	-0.43 (4.87)	1.07 (4.37)	1.31 (4.88)	0.48 (4.50)
551-600	std	1.22 (2.84)	1.27 (2.64)	1.23 (2.80)	-0.04 (2.07)	-0.62 (2.62)	-0.17 (1.82)
	dev	0.05 (4.98)	-0.71 (4.56)	-0.68 (4.36)	0.33 (4.67)	0.54 (5.43)	0.17 (4.59)

Table 6: Values of the response waves towards the standard and deviant of the gop-goep single speaker condition per electrode and time window.

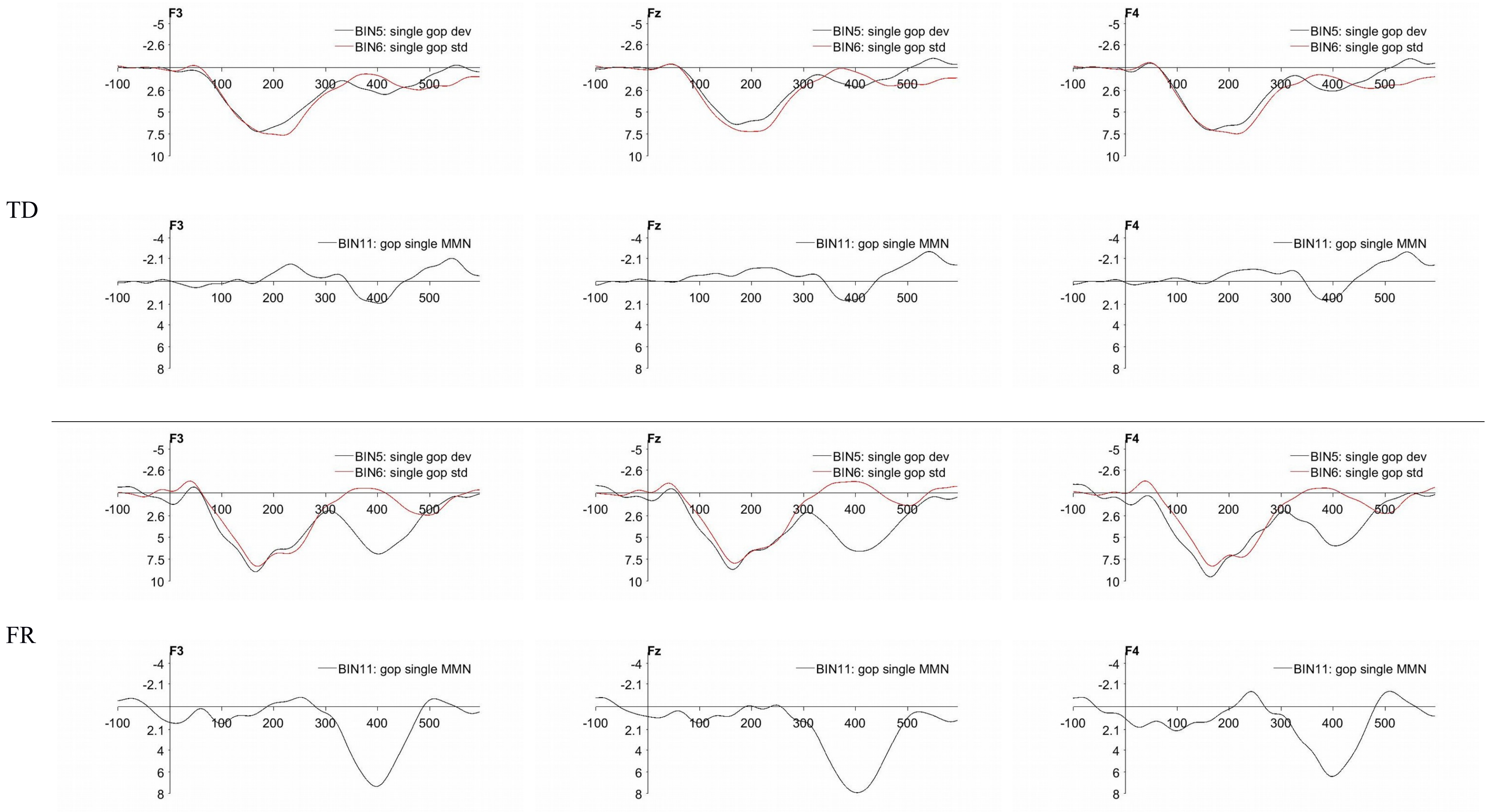

Figure 6: ERPS of both groups for the gop-goep single speaker condition. For both groups the response waves of the standard and deviant and the difference wave are displayed.

Time window	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	501-550	551-600
Channel												
	Giep-gip multiple											
F3				+	+		+	+ +				
Fz		+		+	+							
F4												
	Giep-gip single											
F3				+ +							-	-
Fz				+ +	+				-	-	-	- -
F4				+					-	-	- -	- -
	Gop-goep multiple											
F3	+	+										
Fz	+	+										
F4												
	Gop-goep single											
F3								+	+		-	
Fz							+	+	+		-	-
F4	+							+	+		-	-

Scheme 1: Schematic overview of the differences between the standard and deviant. Blue squares are differences for the TD group, orange squares are differences for the FR group. Saturated colours are significant differences, unsaturated colours are trends. The + and - indicate the polarity of the difference

To see whether there were any differences in the amplitude of the difference wave between the groups, three-way ANOVA's – 2 (group: TD, FR) x 3 (electrode: F3, Fz, F4) x 2 (speaker condition: single, multiple) – were performed for both sound conditions (*giep-gip, gop-goep*) and for every time window. No interactions at all between the groups and electrodes were found, but at several time windows interactions were found between groups and speaker conditions. For *giep-gip* interactions were found at 251-300 ms ($F(1) = 5.40$, $p = .02$, $\eta_p^2 = .02$), 301-350 ms ($F(1) = 7.42$, $p < .01$, $\eta_p^2 = .03$) and 351-400 ms ($F(1) = 4.96$, $p = .03$, $\eta_p^2 = .02$). For *gop-goep* interactions were found at 351-400 ms ($F(1) = 4.63$, $p = .03$, $\eta_p^2 = .02$), 401-450 ms ($F(1) = 8.42$, $p < .005$, $\eta_p^2 = .03$), 451-500 ms ($F(1) = 4.12$, $p = .04$, $\eta_p^2 = .02$) and 551-600 ms ($F(1) = 7.00$, $p < .01$, $\eta_p^2 = .03$).

For these time windows the data was split per speaker condition and two-way ANOVA's – 2 (group: TD, FR; or speaker condition: single, multiple) x 3 (electrode: F3, Fz, F4) – were performed to investigate the nature of the interaction. (Trends towards) effects of group and condition were found. Significant results are displayed in the figures (partially) and tables below:

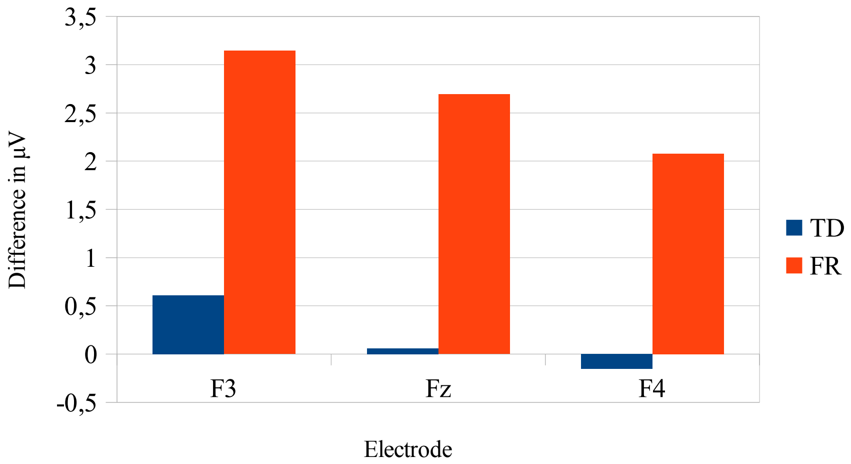

Figure 7: Difference between the TD and FR groups in the giep-gip multiple speaker condition at 251-300 ms.

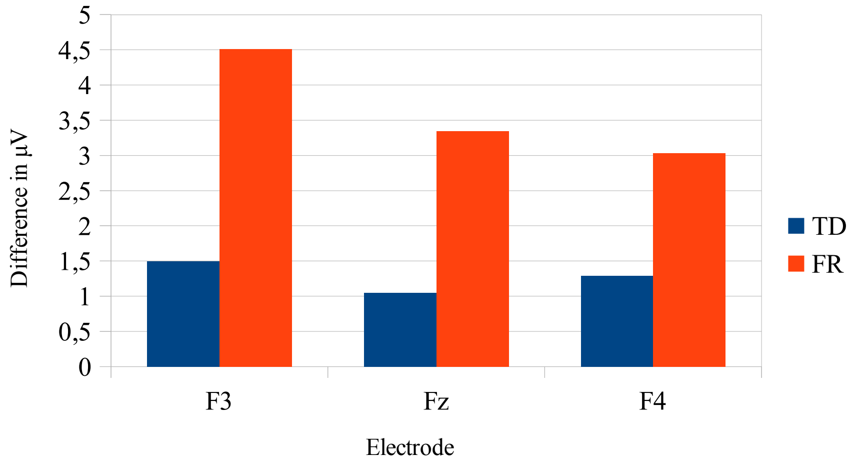

Figure 8: Difference between the TD and FR groups in the giep-gip multiple speaker condition at 301-350 ms.

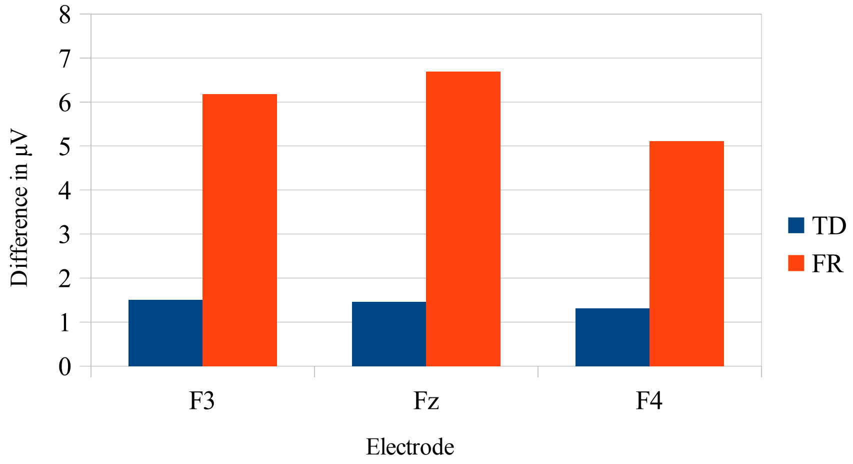

Figure 9: Difference between the TD and FR groups in the gop-goep single speaker condition at 351-400 ms.

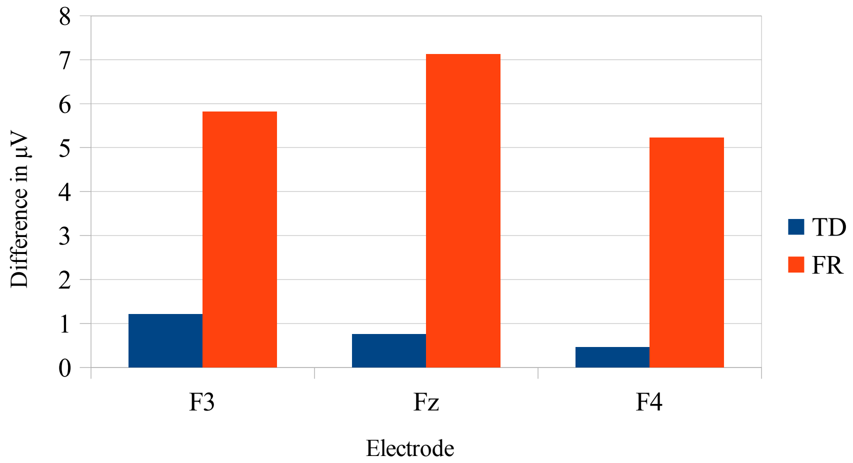

Figure 10: Difference between the TD and FR groups in the gop-goep single speaker condition at 401-450 ms.

Time window	TD: *M (SD)*	FR: *M (SD)*	
Giep-gip multiple			
6	0.17 (5.56)	2.64 (5.19)	$F(1) = 4.61$, $p = .03$, $\eta_p^2 = .04$
7	1.28 (5.72)	3.63 (6.21)	$F(1) = 3.67$, $p = .06$, $\eta_p^2 = .03$
Giep-gip single			
7	0.74 (5.15)	-1.31 (4.42)	$F(1) = 3.81$, $p = .05$, $\eta_p^2 = .03$
8	0.57 (5.55)	-2.00 (4.18)	$F(1) = 5.40$, $p = .02$, $\eta_p^2 = .04$
Gop-goep single			
8	1.42 (5.02)	5.99 (5.10)	$F(1) = 18.58$, $p < .001$, $\eta_p^2 = .13$
9	0.81 (5.38)	6.06 (5.93)	$F(1) = 20.05$, $p < .001$, $\eta_p^2 = .14$
10	-0.97 (5.07)	1.79 (5.56)	$F(1) = 6.41$, $p = .01$, $\eta_p^2 = .05$
12	-1.68 (4.42)	0.62 (4.64)	$F(1) = 6.02$, $p = .02$, $\eta_p^2 = .05$

Table 7: Effects of group on the separate experiment conditions.

Time window	single: *M (SD)*	multiple: *M (SD)*	
Giep-gip FR			
6	-1.44 (4.45)	2.64 (5.19)	$F(1) = 10.08$, $p < .005$, $\eta_p^2 = .16$
7	-1.31 (4.42)	3.63 (6.21)	$F(1) = 12.04$, $p = .001$, $\eta_p^2 = .18$
8	-2.00 (4.18)	2.39 (6.10)	$F(1) = 10.14$, $p < .005$, $\eta_p^2 = .15$
Gop-goep FR			
8	5.99 (5.10)	1.81 (3.50)	$F(1) = 12.97$, $p < .001$, $\eta_p^2 = .19$
9	6.05 (5.93)	1.55 (4.86)	$F(1) = 9.86$, $p < .005$, $\eta_p^2 = .15$
12	0.62 (4.64)	-1.89 (4.23)	$F(1) = 4.50$, $p = .04$, $\eta_p^2 = .08$
Gop-goep TD			
10	-0.97 (5.07)	1.19 (6.64)	$F(1) = 6.73$, $p = .01$, $\eta_p^2 = .03$
12	-1.68 (4.42)	0.04 (6.60)	$F(1) = 4.73$, $p = .03$, $\eta_p^2 = .02$

Table 8: Effects of speaker condition on the separate sound conditions and groups

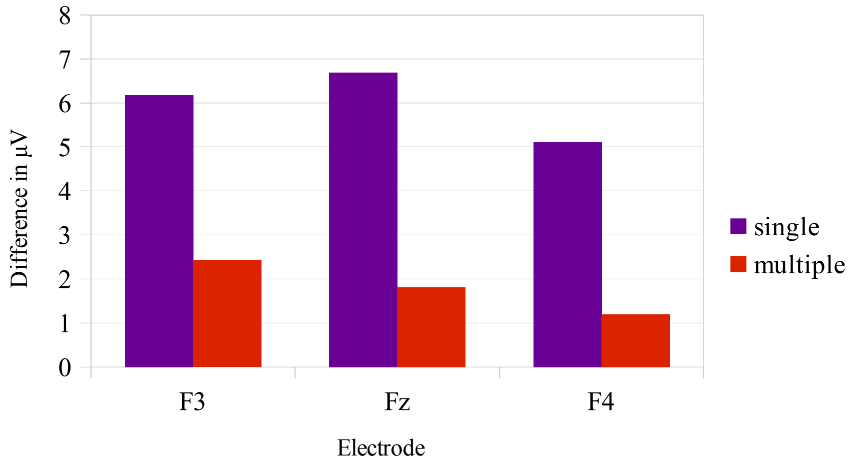

Figure 9: Difference between the single and multiple speaker condition in the gop-goep condition for the FR group at 351-400 ms.

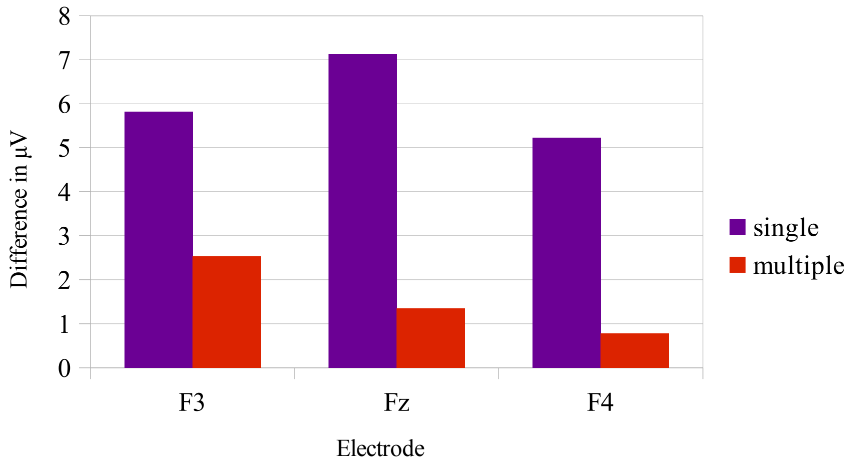

Figure 10: Difference between the single and multiple speaker condition in the gop-goep condition for the FR group at 401-450 ms.

Description of mismatch components

From the results it is clear that one evident mismatch is found, namely for the FR group in the *gop-goep* single speaker condition, approximately 300-450 ms after stimulus onset. The results show also differences between the standard and deviant stimuli at other time windows, but as it is not yet clear of several components of an ERP what they tell about the processing of stimuli, these differences will not be discussed in detail. The focus of the remaining part of the results section and the discussion will be on the time windows where this obvious mismatch is found for the FR group. Although the difference wave is positive instead of negative at this point, it will be interpreted as a mismatch component, because it has been shown before that young children first show a broad positive peak as a reaction to a deviant stimulus, while later they switch to a more adult-like early negative peak (Bishop, 2007; He et al., 2007). In the remains of this section, the findings for every condition will be described. The differences between the groups and conditions will be interpreted in the discussion.

In the graphs of the *giep-gip* multiple speaker condition, the TD group seems to show a positive difference between 300 and 500 ms. Although this difference is not significant, there is a trend towards a difference at 351-400 ms at electrode F3. The FR group also seems to show a more positive response to the deviant than to the standard from 300-400 ms after stimulus onset, but this turns out not to be significant either. However, the two groups do differ significantly from each other between 251 and 350 ms after stimulus onset. The FR children have a more positive difference wave than the TD children at this point.

In the single speaker variant of *giep-gip*, the graphs of the TD group again show a (non-significant) small positive difference at the same time windows as in the multiple speaker variant. The FR group shows a negative difference at this point that extends to 600 ms after stimulus onset. At 300-400 ms, this negativity shows a small peak reaching towards zero. As there is yet no explanation where the negative difference wave comes from, it is hard to say whether the small peak at 300-400 ms could be interpreted as MMN. Again, the two groups differ significantly from each other, but this time a little later: at 301-400 ms the FR children show a negative difference wave, while the TD groups shows a small positivity.

In the graphs of both groups of the *gop-goep* multiple speaker condition a difference can be observed at the discussed time windows, but again this difference is not significant and there no difference between the two groups. For the single speaker version of *gop-goep*, however, there is a very clear mismatch between 300 and 500 ms for the FR group, which turns out to be significant. The results of the TD group are the same as in all three other conditions. The two groups differ from each other significantly: between 351 and 600 ms after stimulus onset, the FR group has a declining positive wave, while the TD children first show a small positivity that declines to negativity at the end.

Results adult tests of dyslexia

The dyslexic parents of the at-risk children all showed a difference of at least 70 percentiles between (at least one of) the reading tasks and the verbal comprehension task. All parents scored in the 90th or 100th percentile for the verbal comprehension task, and between the 10th and 30th percentile for the Klepel. The scores for the EMT varied a little bit more, namely between the 10th and 70th percentile.

Discussion & conclusion

Two important things should be noted before interpreting the results. First, the number of tested participants with a familial risk of dyslexia is quite low. Because it is not yet known whether these children will actually develop dyslexia, this could affect the results in two different ways. If the tested group coincidentally exists of a relatively high ratio of children that later turn out not to be dyslexic, the found effect could actually be absent or diminished in a more heterogeneous group (according to the expectations in line with previous studies). On the other side, if the current group exists of a relatively high ratio of children that are dyslexic, the found effect could give a more trustworthy view. Second, the difference wave of the FR group in the *giep-gip* single speaker condition differs from all other waves: towards the end of the selected time windows, it becomes more and more negative. The precise nature of this deviant ERP is not entirely clear. There is a chance that this deflection influences the mismatch component, which makes it difficult to derive information from it. Bearing these two remarks in mind, an attempt can be made to interpret the results.

At first sight, it seems as if only the FR group noticed a mismatch between the standard and deviant, namely in the *gop-goep* single speaker condition. The TD group seems to show a non-significant mismatch in every condition. Does this mean that, opposed to the hypothesis and previous research, the infants with a familial risk of dyslexia are actually better at discriminating the vowel contrasts than the typically developing infants in this experiment? Possibly, but not necessarily so. This outcome contradicts several other studies, and therefore it is necessary to search for an explanation.

As discussed before, young children first show a late positive component in the difference wave when their brains perceive a mismatch. When they get older, this positive component disappears and an adult-like, negative component in the ERP appears (He et al., 2007). For pure tones this already happens when the children are only a few months old: at the age of 2 months, the ERP shows a late positive component, while at the age of 4 months, an earlier negative component can be observed (He et al., 2007).

As the FR group shows an obvious late positive mismatch in the *gop-goep* single speaker condition, it might be derived that for distinguishing vowels, at least the FR group did not yet switch to an adult-like MMN. A possible explanation for the absence of a mismatch component in the ERP of the TD group is that several of the infants of this group already switched to the adult-like MMN. This would cause a lot of individual variation that on average would give a much smaller mismatch component, as can be observed in the data. This explanation might also explain the difference between the two groups in the *giep-gip* multiple speaker condition, where the FR group has a more positive difference wave than the TD group. To find out if this explanation might be right, it would be interesting to conduct an experiment similar to the current research which includes infants from more different ages, to investigate whether a change in the mismatch component can be observed.

The results also show that, within the two participant groups, there are differences between the single and multiple speaker versions. The FR group shows a larger mismatch component in the single speaker variant of *gop-goep* than in the multiple speaker variant. In the single speaker version of the *giep-gip* condition, however, the difference wave is negative at Fz and F4 around the time the mismatch is expected, while in the multiple speaker version the difference wave is positive. As the difference between the two *giep-gip* conditions is not entirely trustworthy (see remark above), the focus will be on the difference between the *gop-goep* conditions.

In the previous paragraph, the smaller positivity of the TD group compared to the FR group, was explained by the possibility that several of the TD children already might have switched to a negative MMN. The same phenomenon could be used to explain the difference between the two speaker conditions within the FR group. However, it might not be logical that the FR children already switched to a negative mismatch component in the multiple speaker condition, while they have not yet made this switch in the single speaker condition. The single speaker condition shows whether the children are capable of simple acoustical processing. In the multiple speaker condition they also need to categorise the phonemes to single out the deviant ones, which is a more difficult process than simple acoustical processing. Therefore it is probably not to be expected that a part of the FR group switched from a positive to an adult-like mismatch component in the multiple speaker condition. The difference between the two speaker conditions could therefore indicate that the FR children are better in acoustical processing than in phoneme categorisation, as there is a larger mismatch in the first condition compared to the second.

It is unfortunately not possible to derive from the available data that the FR children did not yet change to an adult-like mismatch component. The difference between the single and multiple speaker conditions might also come from other influencing factors. Hari and Renvall (2001) note that the stimulus parameters such as presentation order and interstimulus interval are very important factors in experiments, especially when working with dyslexics (or at-risks). For instance, in the study by Leppänen et al. (2002) it mattered which word was used as the standard and which word as the deviant. The same stimulus, with a different function, caused different responses. In this experiment, the order of the conditions was the same for every participating infant: first *giep-gip* multiple, then *giep-gip* single, followed by the two *gop-goep* conditions in the same order. This might have influenced the results. How the presentation order might have influenced the results is not entirely clear, but to investigate this further it would be good to carry out a similar experiment with the order of the single and multiple speaker conditions reversed. Also, in the *giep-gip* sound condition the long vowel is alternated with the short one, while in the *gop-goep* sound condition the short vowel is alternated with the long one. If in Leppänen et al. (2002) the choice of standard and deviant mattered, it might also be possible that the choice of vowel has an influence.

Contrary to the FR group, the TD group does not show significant differences between the single and multiple speaker conditions at the time windows of the mismatch component. This could mean two things: if part of the group already switched to a negative mismatch component for both simple acoustical processing and phoneme categorisation, this would mean that the TD children can perceive the deviant stimulus in both speaker conditions. It could also be the case that they did make a switch for simple acoustical processing, but not for phoneme categorisation. In this second scenario there would be a difference between their simple acoustical processing abilities and their phoneme categorisation abilities.

Taking all results together and taking into account that the FR group is too small to draw any hard conclusions, there probably still is a good chance that the two groups differ in their abilities to distinguish mid-word vowels from each other. The FR group did show a clear difference between their simple acoustical processing skills and their phoneme categorisation skills, while the TD group did not. While it is still possible that this difference arises from the set-up of the experiment, both groups of participants are exposed to the same stimuli and responded differently to them. It is not sure whether the TD group actually made a switch from a late positive mismatch component to a negative one, but if this is indeed the case, the FR children might lag behind in the development of their brain responses to auditory stimuli. Other research (see for example Noordenbos et al., 2013) shows that dyslexics do show mismatch *negativity* when they grow up.

Because the results of this experiment are not yet unambiguous enough to interpret them clearly, it is difficult to say whether these findings match the current literature on the development of speech perception abilities. However, it seems quite unlikely that the TD children were not able to hear the difference between the two word-medial vowels in any of the experiment conditions, as it has been shown before that before the age of 20 months, infants know all different vowels of their native language (Beers, 1995) and can distinguish them at a medial position in novel words (Mani & Plunkett, 2008). Assuming that there is a reason for why they are capable, but their capabilities do not show up on the ERP – possibly because of the switch towards a negative mismatch – the results fit into the current body of literature.

The findings of this study are unfortunately also not conclusive enough to either support or contradict the above discussed allophonic representation hypothesis of dyslexia, that stated that dyslexics, compared to normal readers, are impaired in their abilities to discriminate native language contrasts, but can distinguish sounds of the same phoneme category better. If further research can show that several infants of the TD group indeed have a more adult-like mismatch component, the results of this study might be interpreted as supportive evidence for the allophonic representation hypothesis: in that case, the FR children do have more trouble with distinguishing native language contrasts. However, further research is needed to explore this switch from positivity to negativity in the context of these auditory stimuli and the influence of the presentation order of the conditions. It would be very interesting to expand this experiment with more children in a wider age range, to investigate whether indeed a switch takes place around the age of 20-months, how the two groups differ from each other on this level and what happens if the single speaker condition is presented first.

In the literature above, possible underlying causes of the allophonic representation hypothesis are discussed. How do the results of this experiment fit in with those different explanations? A general auditory deficit in people with dyslexia would predict a smaller MMN for both phoneme categorisation and simple auditory processing for them compared to controls. Recall that in the simple speaker condition no phoneme categorisation was necessary to tell the standard and deviant stimulus apart. If it is indeed the case that the FR children lag behind in their development and hardly any of them switched to an adult-like MMN yet, then the results of this study support the theory of the general auditory deficit. Especially in the *gop-goep* single speaker version a positive mismatch was found for the FR group, while the TD group has switched. This would mean that the two groups do not only differ in their phoneme categorisation abilities, but also in their simple auditory processing abilities, which is what would be expected if the allophonic mode of representing phonemes is caused by a general auditory deficit.

Other mentioned possible causes were impaired processing of rapid stimulus sequences and, connected to that, sluggish attentional shifting. In this experiment the interstimulus interval is approximately 350 ms, which is almost three times the auditory attentional dwell time of typically developed people (Arnell & Jolicoeur, 1999). With the set-up of this experiment is therefore not possible to say anything about the possible impaired processing of RSS. It is possible to say though, based on the positive mismatch in the *gop-goep* single speaker condition, that infants of 20 months with a risk of dyslexia are capable of distinguishing auditory stimuli that succeed each other every 350 ms.

The above mentioned possible causes of the allophonic representation hypothesis are based on a deficit: either a general auditory deficit, an impairment in processing, or an impairment in shifting attention. It is interesting to note, however, that the current study might not necessarily suggest a deficit at this stage of development, but merely a backlog. The FR children are not performing worse on the oddball task, but their response is different from the TD children. To get a clear vision of the differences, it is necessary to do more research in this direction. As suggested above, it would be interesting to replicate this study with children from a wider age range in both the FR and the TD group. Another interesting case to explore is the other 'side' of the allophonic representation hypothesis: the results from this study might support that FR children are impaired in discriminating native contrasts relative to TD children, but it does not tell us whether the FR children also show enhanced abilities of discriminating within-category speech sounds.

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Appendix 1: List of electrodes

Fp1		Fp2
AF3		AF4
F7		F8
F3	Fz	F4
FC1		FC2
FC5		FC6
T7		T8
C3	Cz	C4
CP1		CP2
CP5		CP6
P7		P8
P3	Pz	P4
PO3		PO4
O1	Oz	O2