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Published in:
Brain and Cognition

DOI:
10.1016/j.bandc.2016.09.004

Brain and Cognition 109 (2016) 75–83

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Dichotic listening as an index of lateralization of speech perception in familial risk children with and without dyslexia

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ARTICLE INFO

Article history:
Received 19 October 2015
Revised 11 September 2016
Accepted 12 September 2016
Available online 17 September 2016

Keywords:
Lateralization
Language
Dichotic listening
Dyslexia
Familial risk
Speech processing

ABSTRACT

Atypical language lateralization has been marked as one of the factors that may contribute to the development of dyslexia. Indeed, atypical lateralization of linguistic functions such as speech processing in dyslexia has been demonstrated using neuroimaging studies, but also using the behavioral dichotic listening (DL) method. However, so far, DL results have been mixed. The current study assesses lateralization of speech processing by using DL in a sample of children at familial risk (FR) for dyslexia. In order to determine whether atypical lateralization of speech processing relates to reading ability, or is a correlate of being at familial risk, the current study compares the laterality index of FR children who did and did not become dyslexic, and a control group of readers without dyslexia. DL was tested in 3rd grade and in 5/6th grade. Results indicate that at both time points, all three groups have a right ear advantage, indicative of more pronounced left-hemispheric processing. However, the FR-dyslexic children are less good at reporting from the left ear than controls and FR-nondyslexic children. This impediment relates to reading fluency.

1. Introduction

Dyslexia, or developmental reading disorder, is characterized by slow, effortful reading despite adequate instruction and a normal intelligence (Snowling, 2000). A poor awareness of the phonological structure of language is generally thought to be at the root of the reading problems (Vellutino, Fletcher, Snowling, & Scanlon, 2004). This may impede the process of mapping of speech sounds onto letter symbols, required for reading. What underlies this phonological deficit is still debated. Following findings by Tallal (1980), who found a relation between reading and auditory processing, researchers have increasingly focused on the relation between auditory and speech processing and reading (related) skills (e.g. Noordenbos & Serniclaes, 2015). In parallel, the organization of processes involved in auditory and speech perception in the brain has become of great interest (Habib, 2000; McCandliss, Cohen, & Dehaene, 2003; Schlaggar & McCandliss, 2007). It is thought that atypical organization of underlying functions related to reading may result in less efficient processing networks, giving rise to literacy problems (Price, 2012).

Neurophysiological evidence as well as evidence from structural and functional neuroimaging shows a predominant role for the left hemisphere (LH) in processing spoken language in right-handed individuals (Dehaene et al., 1997; Price, 2012; Tervaniemi & Hugdahl, 2003). Current models of speech perception identify ventral- and dorsal streams in the LH that are involved in speech perception, relating to speech recognition and production, respectively (Hagoort & Indefrey, 2014; Hickok & Poeppel, 2004, 2007). Language functions that contribute to literacy skill also appear to be predominantly located in the LH. Dehaene et al. (2010) have found reading to activate a large portion of the LH networks for speech processing, and literacy skill to enhance phonological activation to speech input. In the majority of right-handed typical readers, the involvement of LH ventral- and dorsal networks for phonological decoding and visual word recognition has been demonstrated (McCandliss et al., 2003; Price, 2012; Sandak, Mencl, Frost, & Pugh, 2004). In dyslexia, however, the LH networks are less activated during reading compared to typical readers (McCandliss et al., 2003; Richlan, Kronbichler, & Wimmer, 2009; Sandak et al., 2004; Simos et al., 2002). Some studies have observed a heightened activation in the right hemisphere (RH) instead of the LH during reading and reading-related phonological tasks (Dufor, Serniclaes, Sprenger-Charolles, & Démonet, 2007; Pugh et al., 2000, 2008; Shaywitz et al., 2002; Simos et al., 2002). Taken

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http://dx.doi.org/10.1016/j.bandc.2016.09.004
0278-2626/

together, the results from these neuroimaging studies suggest that more symmetrical activation possibly reflects suboptimal processing, resulting in slower reading (Sandak et al., 2004).

Lateralization of speech processing has not only been addressed on a neurobiological level, but also behaviorally. In the past few decades, many researchers have made use of the dichotic listening (DL) method to assess hemispheric specialization for speech processing (Hugdahl, Carlsson, Uvebrant, & Lundervold, 1997; Obrzut & Mahoney, 2011). The method involves presenting stimuli to both ears simultaneously. Kimura (1961) showed that right handed subjects reported significantly better from their right ear. There are several explanations for this phenomenon, that on the one hand relate to structural brain organization, and on the other hand on information processing strategies (Obrzut & Mahoney, 2011). On a structural level, the right ear advantage (REA) might stem from the left hemisphere dominance for speech processing as such, but it can also find its origin in the suppression of ipsilateral pathways when competing dichotic information is processed through ascending auditory networks in the brainstem (Tollin & Yin, 2002), as it enters the central auditory cortex (Scott & Wise, 2004), and/or the superior crossover connections of the right auditory cortex to the contralateral hemisphere (Hiscock & Kinsbourne, 2011). Related to the latter point, speech presented to the left ear first has to ascend through the right hemisphere and then be transferred to the dominant left hemisphere. Crucial to this process is the transfer of auditory information via the corpus callosum, which, if less effective, may contribute to a larger REA due to lower left ear reports as well (Musiek & Weihing, 2011). On an information processing strategy level, alternative explanations for the presence of a REA find their origin in attentional mechanisms, where it is thought that the REA stems from a reduced capacity to focus attention on the left ear (Kinsbourne, 1970). This may be a result of asymmetrical attentional mechanisms, that cause a bias to the right for linguistic and non-linguistic stimuli (Takio, Koivisto, & Hämäläinen, 2014).

The presence of a REA is commonly tested in a free-recall condition, where the participants can freely report what they heard from either ear. The presence of the REA has been demonstrated in several studies (Hugdahl, Carlsson, & Eichele, 2001; Obrzut, Boliek, & Bryden, 1997; Obrzut, Boliek, & Obrzut, 1986), and neuroimaging studies have shown a link between the REA and LH speech processing. Using magnetoencephalography (MEG), Alho et al. (2012) have shown the REA as measured by DL to be associated with processing of speech sounds in the contralateral hemisphere. It has also been associated with a processing speed advantage of the contralateral hemisphere (Eichele, Nordby, Rimol, & Hugdahl, 2005). The fact that a REA has been found in several studies does not automatically imply that speech is exclusively processed in the LH. Evidence from lesion studies has led models of speech perception to include bilateral processing networks (see Hickok & Poeppel, 2007). However, although bilateral activation is observed, the incoming speech signal is not analyzed identically. Hickok and Poeppel (2004) suggest that right hemisphere networks may play a different role in speech perception compared to the LH, resulting in a more dominant role for the LH. The REA phenomenon thus corroborates current neurobiological models of speech perception, in which a dominant role is proposed for LH networks (Hickok & Poeppel, 2004, 2007).

Although the REA is relatively robust in free recall tasks, it might be influenced by attentional processes. Its stability can be tested in a directed attention (DA) condition, where the participant is instructed or primed to focus on the input presented to either the right- or left ear. Left ear reports may increase on trials that require left ear reporting. Indeed, several studies found an increase in left ear reports when participants were told to attend to the left ear, as the number of right ear reports on these trials decreased (Alho et al., 2012; Asbjørnsen & Hugdahl, 1995; Morton & Siegel, 1991). This suggests that the output can be directed by top down attentional processes, though the REA might not necessarily disappear (e.g. Obrzut et al., 1986). Therefore, the REA is considered to be a robust behavioral measure of language lateralization (Hugdahl, 2011).

In the search for risk factors that contribute to the development of dyslexia, the DL method has been used in order to assess possible attenuation in hemispheric specialization for language (Obrzut et al., 1997). Some, but not all studies have shown impeded REA performance on DL tasks in individuals with dyslexia when using the free recall paradigm. In a study with adults, Hugdahl, Helland, Færevaag, Lyssand, and Asbjørnsen (1995) showed that right-handed participants with dyslexia have a decreased REA compared to normal readers. In dyslexic children between Grades 2 and 6, a less pronounced REA has been found as well (Bryden, 1970; Thomson, 1975). The outcomes of these behavioral tasks corroborate the findings of neuroimaging studies, that suggest hypoactivation of language processing areas in the LH when, for example, processing words and pseudowords (Sandak et al., 2004). However, Brunswick and Rippon (1994) and Heiervang et al. (2000) found no differences in performance between dyslexic and normal readers. Interestingly, Morton and Siegel (1991) and Moncrieff and Black (2008) found a lower report from the left ear in 10-year old children with dyslexia compared to controls, but not from the right ear. Similar patterns were found in a subgroup of dyslexics in a study by Cohen, Hynd, and Hugdahl (1992). Given the findings of several neuroimaging studies that homologous right hemisphere areas are more activated in dyslexia when reading or processing speech (e.g. Pugh et al., 2000), reduced left ear reports are unexpected. Possibly, however, these findings are task dependent: Most of the DL studies made use of either a dichotic digit task, or a task where participants had to report CV syllables. Moncrieff and Black (2008) have shown that the direction of the ear advantage depended on the type of stimuli that were used: When tested on digits and words, children with dyslexia showed a poorer left ear performance, whereas they showed poorer performance from their right ear when tested on CV syllables. Only when words were used, a robust REA was found in all participants, though dyslexic participants still obtained lower scores overall due to lower left ear scores. The authors suggest that the experimental paradigms may have influenced these findings; since their dichotic word task required participants to focus attention and CV condition did not. Yet, Asbjørnsen and Bryden (1996) used a directed attention paradigm for CVs and words and showed that the ear advantage was more prone to change in a CV condition, too. In this case, the difference cannot be ascribed to different types of paradigms. Possibly, the more sub-lexical CV condition might rely on other neural circuits than the more lexically oriented digit and words test (Hickok & Poeppel, 2004). Another possibility is that meaningless CV syllables evoke a similar response as pseudowords do, in which case hypoactivation of LH processing networks could explain this finding (Pulvermüller, Kiff, & Shtyrov, 2012). Possibly, these unfamiliar syllables only become strongly left lateralized after articulatory learning, which draws on a greater involvement on LH networks (Pulvermüller et al., 2012).

Studies have also focused on the relation between attentional control and dyslexia using the DA paradigm, to address the stability of the REA. Kershner (2014) found that adults with dyslexia showed a more persistent REA than controls, even when asked to focus their attention on the left ear. Similarly, studies by Moncrieff and Black (2008) and Hugdahl et al. (1998) showed that dyslexic children are unable to enhance their left ear performance when instructed to direct their attention to this ear. Taken together, these findings suggest that, in addition to stimulus type and age, performance on DL tasks in people with dyslexia may be affected by attentional processes.

Although it can be derived from the DL literature that the REA and poor reading are related, the nature of this relation is not clear-cut. After all, in some studies, REA is larger in poor readers whereas in other studies it is smaller. The latter may reflect more symmetrical processing as previously evidenced by neuroimaging studies (e.g. Sandak et al., 2004) rather than hyperactivation of RH networks relative to LH networks. In order to shed more light on the relation between DL and reading ability, it is firstly important to note that previous studies compared children or adults with and without dyslexia without controlling for familial risk (FR; i.e., one or both parents have a history of dyslexia). This may lead to a confound given the heritable component of dyslexia (for a review, see Carrion-Castillo, Franke, & Fisher, 2013), as most children in the poor reading groups that were measured will have an FR whereas control children usually do not have an FR. From studies that examine FR children with dyslexia (FRD) and FR children without dyslexia (FRND), it can be observed that FRND children often show subclinical deficits in, for example, phonological awareness (PA; e.g. Snowling, Gallagher, & Frith, 2003; Van Bergen, de Jong, Plakas, Maassen, & van der Leij, 2012) and nonword repetition (NWR; de Bree, Rispens, & Gerrits, 2007; De Bree, Wijnen, & Gerrits, 2010; Melby-Lervåg & Lervåg, 2012; Moll, Loff, & Snowling, 2013). Deficits in these areas are therefore not exclusively linked to reading ability, but rather to FR. Deficits in rapid automatized naming (RAN), however, are typically associated with reading status, as these are not found in FRND children and thus may play a protective role (Moll et al., 2013). Hence, in order to investigate the role of lateralization of speech processing in the development of reading problems, it is important to disentangle the relation between dyslexia and FR and thus to include at risk children who do not develop dyslexia in addition to at risk children who do (e.g. Van der Leij et al., 2013).

Secondly, to shed more light onto the underlying development of children with (FR of) dyslexia, it is of interest to investigate the relations between lateralization of speech processing and reading-related phonological skills such as PA, RAN, and NWR (Wagner & Torgesen, 1987), because scores on phonological tasks have long since been known to predict reading fluency (e.g. Thompson et al., 2015) and because neuroimaging studies have shown atypical organization of reading related processes such as print- and phonological processing in dyslexia (e.g. Dufor et al., 2007; Pugh et al., 2000; Simos et al., 2002). A secondary aim of this study is therefore to investigate the relation between lateralization of speech processing as measured by DL, and phonological skills.

1.1. The current study

The current study aimed to investigate the role of hemispheric asymmetry in the development of dyslexia. This was done by assessing speech perception as measured by dichotic listening performance in FRND and FRD children and controls who took part in the longitudinal Dutch Dyslexia Programme (Van der Leij et al., 2013). Based on the DL literature, two possible outcomes can be expected: either a larger REA, due to less left ear reports, in dyslexic children, indicating a larger asymmetry, or a smaller REA indicating more symmetrical processing. If more symmetrical processing of linguistic information is a factor in dyslexia, and thus relates to reading status, we expect to find a reduced REA in FRD children but not in controls and FRND children. Such a finding would imply networks underlying speech processing in dyslexia to rely relatively more on right hemisphere involvement compared to fluent readers, in line with findings of recent neuroimaging studies (e.g. Dufor et al., 2007). If more symmetrical processing is found in FRD and FRND children but not in controls, then we conclude that more symmetrical processing relates to FR status. A larger role for the right hemisphere in processing speech in such a case would then not be a factor that drives reading skill, since FRND children show normal reading ability. It is possible, however, that FRND children are able to compensate using higher-order linguistic processes. Similarly, if a larger REA is found in FRD children only, we conclude that this relates to reading status, whereas if it is found in all FR children, it relates to familial risk.

To investigate language laterality at different points in development, and the effects of attention on the DL performance of the children, participants completed two DL tasks. In Grade 3, a free recall dichotic digit test was administered. In Grade 5/6, a DL task with CV syllables was administered, to also be able to address possible stimulus effects (Moncrieff & Black, 2008). This task included a free recall and directed attention condition to assess the stability of the REA (Hugdahl et al., 1998; Kershner, 2014). Additionally, information on participants' reading-related phonological skills in Grade 3 (PA, NWR, and RAN) and Grade 6 (PA, RAN) were collected, in order to investigate the concurrent relations between language laterality as measured by the DL tasks, reading-related phonological measures, and reading fluency using correlation analyses.

2. Methods

2.1. Participants

A sample of 69 right-handed children (26 controls, 26 FRND, and 17 FRD children) was included in this study. None of the parents reported their child to be diagnosed with auditory processing disorders. The children comprised a sub-sample of children who participated in the Dutch Dyslexia Programme (DDP; Van der Leij et al., 2013). They were included here because they had taken part in the measurements that took place in Grade 2, Grade 3, and Grade 5 or 6. Based on these measurements, their reading status was assessed as follows.

If one or both parents were dyslexic, children were assigned to the familial risk group. In order to assess parents' reading fluency, they were presented with Dutch norm-referenced tests for word- and pseudoword reading (Brus & Voeten, 1973; Van den Bos, Lutje Spelberg, Scheepstra, & de Vries, 1994; see Materials). If parents scored below the 15th percentile on either test and not higher than the 50th on the other, or below the 20th percentile on both tests, their children were assigned to the familial risk group.

In order to be assigned to the familial risk group of children who develop dyslexia (FRD), FR children had to perform poorly on a word- and pseudoword reading test the last time that these tasks were administered in Grade 6 and at least on one out of the two times these tasks were administered earlier: at the end of 2nd grade and in Grade 3. Poor performance was defined as obtaining a score below the 10th percentile on one of the tests, and 40th percentile on the other test, or below the 25th percentile on both tests. These criteria were set as such to ensure a severe and persistent deficit in reading fluency (Hakvoort, van der Leij, Maurits, Maassen, & van Zuijen, 2015).

3. Materials

Word reading fluency. The *Een-minuut-test* (EMT; Brus & Voeten, 1973) was used in Grade 3 and in Grade 5/6, and the second list of the *Drie Minuten Toets* was used (DMT; Verhoeven, 1995) in Grade 2 to measure and assess word reading fluency. The EMT consists of a list of 116 mono- and polysyllabic words, increasing in difficulty. The administered list of the DMT consists of 150 monosyllabic words. The score used for the analyses was the number of words read correctly in one minute for both tests. Standardized scores were used for the selection of participants.

Pseudoword reading fluency. The Dutch norm-referenced task *De Klepel* (Van den Bos et al., 1994) was used to measure pseudoword-reading fluency. It was administered in Grade 2, 3 and 5/6. It consists of a list of 116 mono- and polysyllabic pseudowords. The score used for the analyses was the number of words read correctly within two minutes. Standardized scores were used for the selection of participants.

Phonological awareness. PA was assessed in Grade 3 and Grade 5/6 using a phoneme deletion task (de Jong & van der Leij, 2003). The task consisted of three parts and was administered using paper and pencil in Grade 3. The first part consisted of nine monosyllabic pseudowords (e.g. *tral*), and the second and third part consisted each of nine bisyllabic pseudowords (e.g. *memslos*). Items were presented orally. Children were asked to delete one consonant phoneme (e.g. what is *memslos* without /l/?) in the first and second part. During the third part, the consonant they were asked to delete occurred twice in each word (e.g. what is *gepgral* without /g/?). The test ended when six consecutive items were answered incorrectly in the first, or three in the second part. The score on this task was the total number of items correct. The maximum score was 27.

In Grade 5/6, the test was computerized and shortened. Items were presented via headphones. Each of the three parts now consisted of four items. Two practice items preceded the first and third parts of the test. The score on this task was the total number of items correct. The maximum score was 12. For the purpose of comparing scores on both PA tasks, scores were transformed to proportion correct.

Nonword repetition. NWR is used as a measure of verbal short term memory, and was measured in Grade 3. Children listened to 36 nonwords, which they were asked to repeat as accurately as possible. The nonwords consisted of at least 3 (e.g. *kummigar*) and at most 5 syllables (e.g. *nammonniffumnem*) and were presented in a fixed order (Scheltinga, Van der Leij, & Struiksma, 2010). The score was the total number of words repeated correctly.

Rapid automatized naming. RAN in Grade 3 and Grade 5/6 was assessed using a digit-naming task. Children named a total of 50 digits as quickly and as accurately as they could. The digits 2, 4, 5, 8, and 9 were presented in five columns of ten digits each. Time in seconds and errors were recorded and used to calculate the total number of digits read correctly within one minute.

Dichotic digit test Grade 3. A dichotic listening task (Neijenhuis, Snik, van den Broek, & Neijenhuis, 2003) was administered in Grade 3 to address the listener's capacity to process two simultaneously presented stimuli. Children were presented with three monosyllabic digits (e.g. *two, three, four*) in one ear, and three in the other. In Dutch, there are ten monosyllabic digits to choose from: 1–6, 8, 10–12. The stimuli were presented at 70 dB. Participants were instructed to name as many items as possible (free recall). In total, they completed 5 practice items and 20 trials. The score was the total number of correctly reported digits from the right ear and the correctly reported digits from the left ear.

Dichotic listening test Grade 6. A dichotic listening task with speech-sound syllables was developed for Grade 5/6, similar to the task used by Hugdahl et al. (1998). A free recall condition as well as a directed attention condition was added to the paradigm. Natural speech syllables /bɑ/, /dɑ/, /gɑ/, /pɑ/, /tɑ/ and /kɑ/ were recorded, read by a female native speaker of Dutch with intonation held constant. Recordings were volume-adjusted to 80 dB/mono using Audacity for Windows (Audacity, Pittsburgh, USA) and Adobe Audition (Adobe Systems Inc., San Jose, USA).

In the free recall condition, participants were presented with trials that consisted of two different stimuli, where one stimulus was presented to the right ear, and one to the left. Each combination of stimuli was presented twice. The ear in which each stimulus was presented was reversed on the second presentation, so that each stimulus was presented once in each ear, e.g., *pa(left)_ta(right)* and *ta(left)_pa(right)*. This resulted in a total of 30 trials. Additionally, six control items were added that consisted of two of the same stimuli, e.g. *ba_ba.* Participants were asked to report the item which they had heard best (see Hugdahl et al., 1995; for a similar approach). The order of the trials was random. The sum of correctly reported items from the left ear and the sum of correctly reported items from the right ear were used in the analyses.

In the directed attention condition (DA), participants were first presented with a probe (a 400 ms tone) in either the left (DA-left condition) or the right ear (DA-right condition). One second after the probe, the trial was presented. Children were asked to report the stimulus that was presented to them in the probed ear. Stimuli were identical to the ones in the free recall condition. Each participant was offered one of three randomized lists, consisting of 60 test trials of which 30 had a right ear probe, and 30 had a left ear probe. The test items were interspersed with 12 control items. The total number of correct reports per ear for left- and right-probed items were used in the analyses.

Nonverbal IQ. To measure nonverbal IQ in Grade 3, the Block Design subtest of the WISC (Wechsler, 2005) was used. Children completed block designs with coloured blocks, using an example that was presented to them on a card. First, an experimenter demonstrated the task. Then the participant was asked to complete the design on the presented card. Each trial had a time limit of 45 s. The number of blocks that had to be used increased per presented trial. The maximum number of trials was 15. The task ended when the child failed or exceeded the time limit.

Verbal IQ. To measure vocabulary in Grade 3, the Vocabulary subtest of the WISC was used (Wechsler, 2005). The children were asked to give the meaning of words (e.g. What is a tree?). In total, there were 35 items. Each item was awarded with 0, 1, or 2 points depending on the description given. If four subsequent items rendered a score of 0, the task was aborted. The maximum score was 70.

4. Results

4.1. Data screening

Prior to analysis, data were checked for multivariate and univariate outliers on the variables. No multivariate outliers were detected. Univariate outliers were identified based on z-transformed scores of the dependent variables (i.e., scores exceeding −3.29 or +3.29) and found on the total number of correct items in the Grade 6 DL task, both in the Free recall and DA condition. Two children from the FRD group and one child from the FRND group were excluded. An additional two children (one FRD, one control) were excluded because their data on the free recall condition was not available. In total, 25 controls (14 boys), 25 FRND (12 boys), and 14 FRD (9 boys) children were included. DL data were screened for normality. Kolmogorov-Smirnoff tests indicated DL data were normally distributed.

4.2. Phonological skills, reading skills and IQ

Group differences in reading skill, PA, RAN, NWR, and IQ were addressed using ANOVAs with post hoc Bonferroni tests. Effect sizes were addressed using Cohen's d, where effects below 0.30 are regarded as small, between 0.30 and 0.50 as moderate, and above 0.50 as large (Cohen, 1988). On all word- and pseudoword reading tests, controls and FRND children obtained scores that were significantly higher than those of FRD children. Similar patterns were observed on PA and RAN. On NWR and IQ, no significant group differences were observed. Results are displayed in Table 1.

4.3. Dichotic listening Grade 3

To address differences in preferred ear between groups, a repeated measures ANOVA with within subject factor Ear (Left, Right) and between subjects factor Group (Controls, FRD, FRND) was conducted. Results are shown in Fig. 1. A main effect was found for Ear, $F(1,61) = 23.91$, $p < .001$. Overall, more items were reported correctly from the right than from the left ear. A main effect for Group was found, $F(2,62) = 10.17$, $p < .001$. Planned post hoc Bonferroni tests showed that control children in total reported more items correctly compared to FRD ($p < .001$) and FRND children ($p = .029$). No differences were found between the two FR groups. Note, that this result shows that overall recall scores are higher for control children and that the overall recall performance is related to FR, but this result does not relate to lateralization. To address lateralization differences, the presence of interaction effects between Group and Ear is of importance, specifically. Indeed, an interaction effect was found for Group and Ear, $F(2,61) = 3.59$, $p = .033$. Post-hoc Bonferroni tests indicated that control and FRND children reported significantly more items from the left ear than FRD children, $p < .001$; and $p = .029$, respectively). No differences were found in the reports from the right ear. Taken together, the results suggest that each group has a right ear advantage, and that the FRD group has a disadvantage on left ear reports compared to both groups of fluent readers. This indicates that for each group, the right ear is dominant, but that in the FRD group, left ear scores are lower, which results in a larger REA.

4.4. Dichotic listening Grade 5/6

In Grade 5/6, differences in scores on the free recall and DA condition were addressed using a repeated measures ANOVA with factors Ear (Left, Right), Condition (free recall, DA Left Probe, DA Right Probe) and between factor Group (Controls, FRND, FRD). Huynh-Feldt corrections were applied where necessary. Results are displayed in Fig. 2. A main effect was found for Ear, $F(1,61) = 33.17$, $p < .001$. Generally, more items were reported from the right than from the left ear. An interaction was found between Group and Ear, $F(2,61) = 5.84$, $p = .005$, where controls and FRND children reported more from the left ear compared to FRD children ($p = .031$ and $p = .013$, respectively), and FRD children reported more from the right ear than FRND children ($p = .015$). This indicates that for FRD children, ear scores are more asymmetrical because of their lower left ear (as for the Grade 3 results) and higher right ear report. As a result, their REA is larger. Lastly, an

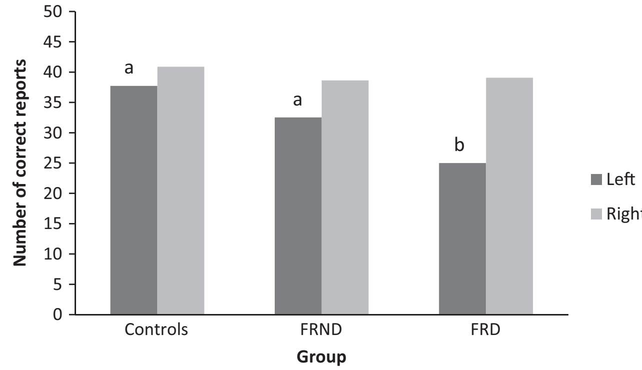

Fig. 1. Total reports from the left- (solid bar) and right ear, per group. The Group × Ear interaction effect is indicated by letters: Shared letters indicate no significant differences. The maximum score per ear was 60. The chance level to correctly report an item was 3/10 for each ear.

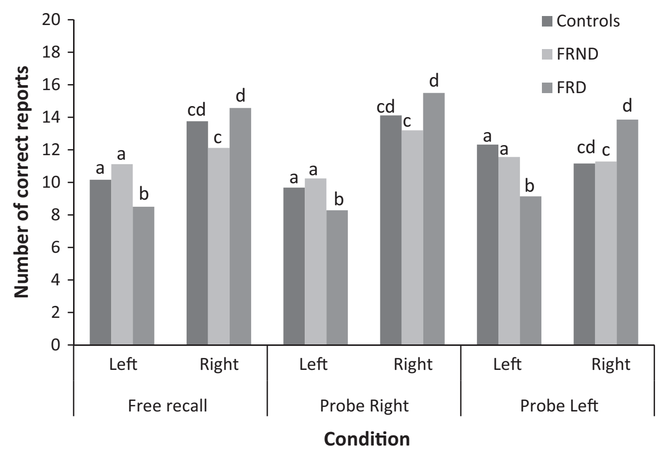

Fig. 2. Total reports from the left- and right ear, per group, per condition. The Group × Ear interaction effect is indicated by letters: Shared letters indicate no significant differences. The maximum score per condition was 30. The chance level of correctly reporting an item was 1/6 for each ear.

Table 1
Information on participants' average reading scores, phonological, IQ and group comparisons.

	C ($n = 25$)	FRND ($n = 25$)	FRD ($n = 14$)	(df) F	Cohen's d		
	$M(SD)$	$M(SD)$	$M(SD)$		C vs. FRND	C vs. FRD	FRND vs. FRD
Age 3rd graders	8.72(0.32)	9.00(0.37)	8.92(0.42)	–	–	–	–
Age 5/6th graders	11.71(0.60)	11.85(0.60)	11.59(0.56)	–	–	–	–
WRF 2	$70.76(17.18)_a$	$65.76(17.69)_a$	$29.86(12.37)_b$	$(2,61)32.25^{***}$	0.29	2.73	2.35
PWF 2	$39.00(11.61)_a$	$37.48(14.07)_a$	$16.29(6.49)_b$	$(2,61)18.96^{***}$	0.05	2.41	1.93
WRF 3	$62.04(10.87)_a$	$57.84(13.20)_a$	$31.50(10.88)_b$	$(2,61)32.33^{***}$	0.35	2.81	2.18
PWF 3	$47.04(13.88)_a$	$43.12(16.21)_a$	$21.14(7.26)_b$	$(2,61)16.96^{***}$	0.26	2.34	1.75
WRF 6	$80.28(12.31)_a$	$75.84(10.97)_a$	$47.71(10.28)_b$	$(2,61)39.85^{***}$	0.38	2.87	2.65
PWF 6	$67.96(17.75)_a$	$62.44(18.48)_a$	$34.50(8.80)_b$	$(2,61)19.52^{***}$	0.30	2.39	1.93
PA 3	$76.44(15.15)_a$	$66.82(20.80)_a$	$51.32(15.64)_b$	$(2,61)9.07^{***}$	0.53	1.63	0.84
PA 6	$90.67(12.10)_a$	$86.67(19.25)_a$	$76.19(16.62)_b$	$(2,61)3.63^{*}$	0.25	0.99	0.58
NWR 3	$17.12(4.09)_a$	$14.40(5.42)_a$	$13.64(13.18)_a$	$(2,61)3.48^{*}$	0.57	0.36	0.08
RAN 3	$109.22(21.67)_a$	$116.13(15.80)_a$	$87.02(15.00)_b$	$(2,61)11.77^{***}$	−0.36	1.19	1.89
RAN 6	$137.45(22.90)_a$	$138.79(20.96)_a$	$112.57(17.49)_b$	$(2,61)8.06^{***}$	−0.06	1.22	1.36
Nonverbal IQ 3	41.48(10.48)	42.68(11.43)	41.86(7.88)	(2,61)0.08	−0.11	−0.04	0.08
Verbal IQ 3	32.84(5.76)	31.96(5.86)	29.64(4.91)	(2,61)1.46	0.15	0.60	0.43

Note. WRF = word reading fluency, PWF = pseudoword reading fluency, PA = phonological awareness, displayed in proportion correct, NWR = nonword repetition, RAN = rapid automatized naming, C = control children, FRND = familial risk, non-dyslexic children, FRD = familial risk dyslexic children.

interaction was found between Condition and Ear, $F(1.53, 143.18) = 8.85$, $p = .001$, $\varepsilon = 0.76$. The number of correct left ear reports was significantly higher in the DA-left probe condition than in the DA-right probe condition ($p = .011$). Conversely, the number of right ear reports was significantly higher in the DA-right probe condition compared to the left probed condition ($p = .003$). This is the case for all groups. No other main effects or interactions were found. Taken together, these results indicate that, overall, regardless of condition, right ear reports were most frequent for all groups, and that controls and FRND children reported more from their left ear than FRD children. The number of left ear reports and right ear reports increased as a function of probe.

4.5. Laterality index

To assess the magnitude of lateralized processing, a laterality index (LI; Eichele et al., 2005) was calculated for Grade 3 and the Grade 5/6 free recall conditions, by subtracting the number of left ear reports from the number of right ear reports, divided by the total number of correct responses. The resulting measure is a proxy of left-lateralized processing: when the score is positive, processing is more left-lateralized. When the score is more negative, it is more right-lateralized. Because the Grade 3 and 6 tests were different, LI scores were standardized for the purpose of comparing Grade 3 and Grade 6 scores.

A repeated measures ANOVA with within-subjects factor Grade (3, 5/6) and between-subjects factor Group (Controls, FRND, FRD) was conducted to attest laterality index differences. No differences between Grade 3 and 5/6 were found, and interactions with Group were absent. It thus seems that language laterality is stable from Grade 3 to Grade 5/6 across groups. A main effect was found for Group, $F(2, 61) = 7.71$, $p < .001$. Post-hoc tests showed controls ($M = -.14$) and FRND children ($M = -.18$) to differ significantly from FRD children ($M = .57$, $p = .003$ and $p = .002$, respectively). In poor readers, the right ear advantage is larger than in good readers and ear reports are thus more symmetrical in good than in poor readers.

4.6. Correlations between lateralization indices, reading, and phonology

Correlations (Table 2) were calculated between Grade 3 and Grade 5/6 reading-, phonological-, and lateralization indices. Significant correlations were found between all reading- and reading related measures in Grade 3 and 6. Additionally, correlations were found between word- and pseudoword reading fluency and the lateralization index of Grade 3, where more symmetrical processing relates to higher word reading fluency scores. No correlations were found between the Grade 6 LI and reading fluency.

5. Discussion

This study investigated the role of lateralization of speech processing in dyslexia, by examining whether more symmetrical processing of language is a characteristic of familial risk, or whether it is related to reading status. To this end, the dichotic listening method was used in Grade 3 (free recall) and in Grade 5/6 (with a free recall condition, as well as directed attention conditions) in controls and FR children who did and did not become dyslexic from the Dutch Dyslexia Programme (Van der Leij et al., 2013). The findings of a right-ear advantage might indicate that language is predominantly processed in the left hemisphere in all groups. If more symmetrical processing indeed related to reading fluency, FR children with dyslexia were expected to show a smaller right-ear advantage based on the idea that language is processed in the contralateral hemisphere (Kimura, 1961; Obrzut & Mahoney, 2011). However, this was not the case. Instead, FR children who have dyslexia report less from their left ear across conditions, which can either indicate smaller involvement of the right hemisphere, or which may stem from reduced activation of ascending auditory pathways leading up to the right hemisphere. These results are found at both time points. The magnitude of the difference in ear reports is larger for FRD children, which according to Moncrieff (2011) in itself may be reflective of (ab)normality, rather than the direction of the ear advantage. Because only the FRD group showed this pattern, we conclude that a reduced number of left ear reports relates to reading status. A second aim of our study was to investigate whether lateralized processing as measured by DL related to phonological processing. No relations were found between lateralization indices in Grade 3 and 5/6, and phonological processing.

LH dominance for speech processing is found in Grade 3 children and persists into early adolescence in Grade 5/6. No differences were found in laterality indices of Grade 3 and 5/6, suggesting the REA to be stable. Although the methods used were different during each measurement, the results are highly similar, suggesting that different tasks and instruction did not influence our findings. The finding that the REA is stable is in line with previous results that show left lateralization of language in children from age 7–12 (e.g. Obrzut, Hynd, Obrzut, & Leitgeb, 1980) and with previous findings in the field of speech perception that ascribe an important role to the LH in speech processing (Hickok & Poeppel, 2007; Price, 2012). However, our results are not in line

Table 2
Correlations between reading, phonology, and lateralization index.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. WRF 3										
2. PWF 3	.84***									
3. RAN 3	.51***	.48***								
4. PA 3	.54***	.55***	.16							
5. NWR 3	.31**	.24	.12	.41***						
6. WRF 5/6	.84***	.78***	.66***	.47***	.32**					
7. PWF 5/6	.75***	.83***	.50***	.50***	.25*	.79***				
8. RAN 5/6	.44***	.49***	.72***	.20	.10	.66***	.56***			
9. PA 5/6	.51***	.45***	.24	.50***	.53***	.45***	.41***	.18		
10. LI 3	−.30*	−.26*	−.15	−.16	−.12	−.24	−.17	−.17	−.19	
11. LI 5/6	−.12	−.04	−.08	.15	.07	−.18	−.18	−.07	.16	−.09

Note. WRF = word reading fluency, PWF = pseudoword reading fluency, RAN = rapid automatized naming, PA = phonological awareness, NWR = nonword repetition, LI = lateralization index.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

with the idea that more symmetrical language processing might contribute to literacy problems (e.g. Sandak et al., 2004). If this had been the case, we would have expected to find a diminished REA in dyslexia. We did not find a diminished REA in the FRD group, all groups showed a REA. This suggests that, both in normal readers and in dyslexic readers, the LH is dominant in processing speech. However, of course we must make note of the fact that ideally, this conclusion would have to be corroborated using neuroimaging methods. Using neuroimaging methods would also allow for a closer investigation into the origin of the lower left ear scores (smaller RH involvement, or reduced activity in the ipsilateral ascending pathways).

Instead of finding a diminished REA in the FRD group, we found that FRD children report less from their *left* ear. As a consequence of a diminished left ear report and a normal right ear report, the lateralization index for the FRD group was higher compared to the controls and FRND children, suggesting that linguistic processing is more asymmetrical in dyslexic children. This result is in line with previous findings by Morton and Siegel (1991), Moncrieff and Black (2008), and Cohen et al. (1992). Since it was the case in Grades 3 as well as 5/6, this pattern seems to persist throughout development. Neuroimaging studies have previously evidenced a larger right hemisphere activation in dyslexia (e.g. Dufor et al., 2007). A lower left ear report does not appear to corroborate these findings. Yet, it appears that this finding cannot be ascribed to task specificity: Despite the use of different tasks and stimuli, the results are consistent. Based on Hickok & Poeppel's model of speech perception (2007), the left ear deficit could point toward a differential role of speech processing networks in the right hemisphere that leads to impoverished speech recognition. Possibly, communication from the right auditory cortex to lexical processing mechanisms in the LH is impeded, or right hemisphere speech processing could be slower in dyslexia. Alternatively, reduced activity in LH ipsilateral ascending pathways can be at the base of the reduced left ear reports. It is important to note that FRND children do not show impoverished left ear reports, which suggests that this phenomenon is a characteristic of dyslexia, and not of FR. No differences in ear advantage are found. However, it is unclear whether this phenomenon precedes the reading impairment, or whether it is a consequence of the reading impairment. Longitudinal studies measuring DL performance at a pre-reading age could further shed light on this issue. Additionally, the presence of auditory processing disorders was not investigated within this study. Since these are known to interfere with DL performance, it is of importance to address this in future studies.

In Grade 5/6, a DA paradigm was included to address the effect of directed attention on ear reports. Children were either probed to report from their right, or from their left ear. Overall, the REA was stable, even when attention was forced, although the number of right ear reports increased as a function of a probe in the right ear compared to the left probe condition, and left ear reports increased in number when the left ear was probed compared to the right probe condition. The presence of a Group $\times$ Ear interaction and the absence of a Group $\times$ Ear $\times$ Condition interaction suggests that, across conditions, the FRD group obtained lower left ear scores than controls and FRND children – even when they were probed to report from their left ear they did not attain an equal level of left ear reports. Similar results were found by Hugdahl et al. (1998). Again, this finding could be explained by right hemisphere underactivation in response to spoken language. Alternatively, these results may stem from weaknesses in the ipsilateral ascending auditory pathway from the LE. Another possible interpretation for these findings is that children in the FRD group have a processing bias toward the LH, because of a poor ability to activate attentional control in the RH (Hugdahl et al., 2009), or a poorer response-inhibition which may lead to less efficient processing (Kershner & Morton, 1990). As a result, they report less from the left ear which causes the REA to persist (Kershner, 2014). Takio et al. (2014) have suggested asymmetrical attention mechanisms to be at the root of asymmetrical task-related activation. Moreover, Hari and Renvall (2001) suggested that problems of attention to the left hemispace contributes to dyslexia. Possibly, this may have caused the difficulty of the FRD group to report from the left ear. Using fMRI, Jäncke and Shah (2002) in fact observed different activation patterns in a DA-right versus a DA-left condition. They suggest that different strategies are used when focusing on the left or right ear. This may further support the idea that attentional shifts are more difficult for FRD children, though this remains to be tested using other experimental paradigms. Speculatively, the observed REA advantage in dyslexia caused by overall lower left ear reports might thus not be a sign of more left lateralized processing, but result from the inability to divide attention or inhibit a right ear response (Hiscock & Kinsbourne, 2011; Hugdahl et al., 2009; Takio et al., 2014). In fact, the obtained free-recall results might also be explained in this light. FRD children show a diminished left ear report in this condition in both Grade 3 and Grade 6 as well. As Bryden, Munhall, and Allard (1983) noted, free recall paradigms give room for the free deployment of attention and, consequently, to report from either ear, thereby possibly diminishing an REA in comparison to a DA condition in which participants are forced to report from their right ear. If dyslexic participants are indeed less able to freely deploy attention, then this might explain their lower left ear performance in the free recall condition, too (Hiscock & Kinsbourne, 2011). However, it must be observed that the results from the free recall paradigms also suggest that top-down control of attention is not the only mechanism that drives an REA, as an REA persistently surfaces in all groups (Hiscock & Kinsbourne, 2011). Right-ear reports are still being made more often than left ear reports, most likely because of the LH bias for processing of speech (Scott & Wise, 2004).

Interestingly, though unrelated to the lateralization of language, the overall ear report scores obtained in Grade 3 were related to familial risk and not to reading status. Control children generally reported more items correct in total. Not all studies investigating DL and dyslexia note differences in overall report, probably since the focus lies on the ear advantage. Obrzut et al. (1980) and Moncrieff and Black (2008) found learning disabled and dyslexic participants to obtain overall lower scores compared to controls. Our Grade 3 results extend these findings to familial risk, as it appears that familial risk status affects overall performance, instead of reading status. In Grade 5/6, group differences in overall report were absent. Possibly, the Grade 3 task may have put a larger strain on verbal short term memory, which has been shown to be impeded in dyslexia (e.g. Torppa, Eklund, Van Bergen, & Lyytinen, 2015) due to the larger amount of stimuli per trial compared to the Grade 5/6 task.

We also addressed the relation between DL performance and phonological processing, which, to our knowledge, has not been done previously. Relations between reading and phonological processing measures were all attested, in line with the literature (e.g. Moll et al., 2013; Thompson et al., 2015). Additionally, we found significant negative correlations between word- and pseudoword reading fluency and the laterality index in Grade 3, but not Grade 5/6. Kershner and Morton (1990) observed significant negative correlations between a laterality index, and reading and spelling in children at age 12 using a dichotic digit task. Possibly, the absence of correlations in Grade 5/6 relates to the experimental design of our study, since the observed correlations were yielded with dichotic digit tasks, not CV syllable tasks. Although neuroimaging studies have demonstrated lateralized processing when completing reading-related tasks (e.g. Sandak et al., 2004), none of our phonological processing measures (RAN, NWR, and PA) significantly correlated with the laterality indices. This suggests that the different measures of phonological processing and laterality of speech processing as measured with the DL task are not related. Possibly, this can be explained by the different levels of processing that are addressed in phonological processing tasks (primarily lexical), and the DL tasks (primarily sublexical) or the higher task demands of the phonological tasks, which likely involve frontal networks as well (e.g. Pugh et al., 1996). We acknowledge that the DL method might just not be refined enough to be able to relate to phonological processes.

6. Conclusion

The main aim of this study was to assess differences in lateralization of speech processing in children at familial risk of dyslexia who did and did not have dyslexia, and controls. It was found that all groups showed left hemispheric dominance for speech processing, both in Grade 3 and Grade 5/6. However, FR children with reading difficulties showed a diminished left ear report in Grade 3 and Grade 5/6, both in free-recall tasks as well as in directed attention tasks. It can be concluded that a diminished left ear report relates to reading status, and we speculate that this might be due to the inability of the FRD group to shift attention.

Acknowledgement

This research was funded by grant no. 360-89-040 of the Netherlands Organisation for Scientific Research (NWO). We thank the DDP parents and children for their contribution to our study.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandc.2016.09.004.

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