Pitch Perception Across Domains and Musical Rhythm Perception in Dutch Dyslexics

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Summary

Previous research has discovered that dyslexics are notably worse than non-dyslexics regarding pitch and rhythm processing in speech. However, whether pitch and rhythm processing in music domain are also impaired remain an issue of controversy. None of the research to date has combined both speech and non-speech pitch in one study, nor did the dyslexic subjects receive foreign language as the stimuli. Most of the studies tested mainly dyslexic children, yet only little is known concerning adult dyslexics' performance on musical and speech pitch perception. The present study used speech and non-speech pitch from both language and music domains, and musical rhythm to discover whether auditory perception was impaired in adult Dutch dyslexics. We suggest that pitch perception skills are not related to reading disability. For dyslexics, perceiving pitch with fast-changing elements (e.g. Chinese lexical tones) or with well-structured patters (e.g. music) is not problematic. Moreover, the dyslexics in our study performed as well as the controls in musical rhythm perception task, favoring the hypothesis that suggests dyslexics do have motor control deficit (e.g. rhythm production), but not in the processing of perception.

Section 1. Introduction

Dyslexia, or specific reading disability, is a syndrome that causes reading disability. Once an auditory processing is damaged, a deficit of interpreting and recognizing sounds appears, which, in turn, makes dyslexics unable to map sound to the corresponding letters (Meng et al., 2005), leading to impaired literacy-related skills even though dyslexics have average intelligence, education, (Ramus, 2003) and syntax (Shankweiler et al., 1995). Over the years, many studies have proposed different sources of developmental dyslexia. For instance, from the auditory perception point of view, phonological processing is believed to be the core deficit (Katz, 1986; Pennington et al., 1990; Stanovich & Siegel, 1994; Morton & Frith, 1995; Snowling, 1995; Breier et al., 2001; Forgeard et al., 2008) as when perceiving incoming linguistic events, dyslexics cannot distinguish similar phonemes, and segment words into phonemes (Bruck, 1992) and syllables (Forgeard et al., 2008). Since the ability to process rapid successive information is fundamental for setting up the phonological system, it is not surprising to see that phoneme perception and segmentation necessary for reading is deficient in dyslexics (Snowling, 1981). Several studies have emphasized that this auditory dysfunction is in fact restricted to speech sound, and irrelevant to other non-speech auditory stimuli. In temporal order judgement (TOJ) experiments, Mody (1993) and Mody et al. (1997) found that a group of dyslexic children who were poor at discriminating acoustically similar speech syllables (e.g. /ba/-/da/) demonstrated no impairment in non-speech pure tone analogues of syllables even with short inter-stimulus interval (ISI) (e.g. 10 ms), indicating that dyslexics have no difficulties handling non-linguistic rapid acoustic events. Nonetheless, this hypothesis has been challenged by other researchers with data supporting that this auditory deficit can also be domain-general, and negatively affect pitch perception of other non-speech acoustic stimuli.

If dyslexics' phonological deficit is restricted to speech sound only, processing of other acoustic stimuli in another domain should not be impaired. However, contradicting results of dyslexics' performance on the perception of non-speech sounds (e.g. pure tones or musical pitch) have been found. Some propose that dyslexics' pitch perception skills are heightened (Overy et al., 2003), while others suggest that their pitch perception skills are impaired (Atterbury, 1985; Baldeweg, 1999; Anvari et al, 2002). As pitch plays a prominent role in both speech and music domains, pitch serves a good tool to examine whether dyslexics' perceptual deficit (if at all) is domain-specific or domain-general. In the current study, we investigated where the auditory deficit (if any) might be by utilizing pitch stimuli

from both speech and non-speech domains. Besides pitch, rhythm perception in dyslexics remains an ongoing debate as well. Whether rhythm perception deficiency in music can be seen in all dyslexics stays disputable. Evidence of impaired musical rhythm perception has been provided (Flaugnacco et al., 2014), while Atterbury (1985) pointed out that dyslexics do not have difficulties with musical rhythm perception but only with production, implying that it may not be the perceptual deficit but the "developmental coordination disorder" (DCD: Kaplan et al., 1998:472) that interferes with the production processing. Furthermore, Overy, Nicolson, Fawcett, and Clark (2003) specified that this deficit in production only appears when dyslexics are asked to reproduce a certain tempo, and the perceptual deficit in rapid auditory tasks is found to exist in a subset of dyslexics, rather than in all population. While speech rhythm deficit in dyslexics is uncontroversial, whether this rhythm deficit can also be seen in another domain, such as music, remains unknown. The arguments in different reports have motivated the current study to discuss a few issues as follows. In contrast to phonological deficit found in most dyslexics, pitch perception across domains and musical rhythm perception among adult Dutch dyslexics have not yet been studied. Earlier findings that observed impaired speech perception have employed speech stimuli from dyslexics' native language. Yet knowing that the main difficulty dyslexics have is phonological deficit, it is not surprising to see the perceptual deficit. In order to disentangle phonological deficit from general auditory deficits, the stimuli in the experiment must not contain the phonological features in dyslexics' own native language. Thus, for Dutch dyslexics to perceive speech stimuli that are not from Dutch (e.g. Chinese tones), it is not their phonological processing that is impaired if any perceptual deficit presents. Rather, it might be their speech-specific or general auditory processing system is impaired. In addition, most previous dyslexia studies testing speech/non-speech pitch perception recruited mainly child subjects. How adult dyslexics perceive speech and non-speech pitch stimuli is still unclear. We cannot simply look at the research results of dyslexic children with pitch/rhythm perception impairment and conclude that dyslexic adults would also have the same perceptual deficit. How dyslexic children and adults perceive acoustic events might be very different as the deficit seen in childhood might be compensated through development. The current research asked what underlay phonological deficit in dyslexics. Testing adult Dutch dyslexics with Chinese lexical and musical tones, as well as musical rhythm would be able to provide more evidence of adult dyslexics' performance on pitch discrimination across domains, and to reveal whether rhythm perception deficiency can be observed in the music domain. Before proceeding to the experiment, how pitch perception in music and language can be related to literacy skills is discussed in

section 2, and how rhythm perception in music and reading ability can be seen together is reviewed in section 3.

Section 2. The relation between pitch perception and literacy skills

Whether pitch perception, either speech or non-speech, influences reading ability is still under debate. For the relation between reading and speech pitch perception, Loui et al. (2010:1) argued that "pitch perception and phoneme perception might share the same frequency discrimination mechanisms, and sensitivity to frequency changes may be important for reading ability as well". Foxton et al. (2003:343) stated that "although reading ability has been related to the processing of simple pitch features such as isolated transitions or continuous modulation (Tallal, 1980; Witton et al., 1998; France et al., 2002), spoken language also contains complex patterns of pitch changes that are important for establishing stress location (Morton, 1965) and for segmenting the speech stream (Jusczyk, 1999)". However, the processing of fundamental frequency (F0) has not been studied thoroughly. As different vowels and the transitions of consonants in speech are realized by frequency distribution, and F0 being another type of frequency, the processing of speech formants and speech pitch might be related. Dyslexics are known for having impaired phonological processing (Snowling 2000), yet what underlies phonological deficit remains unclear, and whether individuals who have dyslexia may also suffer from pitch processing impairment (or vice versa) is still debated. Some argue that the auditory deficit only appears in speech-specific processing (Mody, 1993; Mody et al.,1997), others suggest that such perceptual deficit is not only restricted to speech sound (Baldeweg, 1999; Anvari et al., 2002). To determine where exactly the perceptual deficit lies, using acoustic stimuli across domains thus becomes necessary. In particular, if the perceptual impairment is restricted to speech pitch, the processing of pitch perception in another domain that also highly relies on pitch, such as music, should be intact; if the impairment is domain-general, pitch perception in domains that requires pitch processing (e.g. language and music) would all be hindered. To further exclude the possibility that any perceptual deficit is caused by the phonological deficit, pitch stimuli should not be phonologically contrastive in one's native language. As Chinese lexical tones are phonological non-contrastive in Dutch, it would be possible to separate auditory processing impairment from phonological deficit if any perceptual deficit is observed. How reading and pitch perception in speech/music interact with each other will be examined in the following reviews, including the relevant studies given from three major aspects: 1) how phonological awareness interacts with pitch perception in speech and music; 2) the relation between reading and speech and non-speech pitch perception; 3) how music training helps improve literacy skills.

Phonological awareness and simple frequency/lexical tone perception impairment

The relation between speech pitch processing and reading ability suggests that if one processing is damaged, the other one may be impaired as well. In the case of dyslexia, reading ability is hindered by phonological processing deficit, which might also affect speech pitch perception. Goswami et al. (2011) tested dyslexic and normal reading children of English, Spanish, and Chinese. Children were tested for their phonological awareness, and received psychoacoustic tasks evaluating auditory thresholds for sound rise time, duration, frequency, and intensity. Staircase adapted from Levitt (1971) with a mixed 2-up 1-down, and 3-up 1-down measure was designed. The test ended either after a total number of 40 trials or 8 response reversals. English and Chinese children each received one cluster of frequency thresholds, which was assessed through the last 4 reversals using 3-up 1-down method. Spanish children were not tested on frequency discrimination tasks. Frequency range for the simple sound frequency discrimination was 3 semitones in AXB format, in which children were asked to choose the deviant pitch among other pitch stimuli. Phonological awareness tasks disclosed that dyslexics were significantly slower to rapid naming than their age-matched peers in all three languages. Moreover, Chinese as well as English dyslexic children showed difficulties with simple frequency discrimination (i.e. pure tones). Frequency discrimination predicted phonological awareness in English and Chinese children. As Chinese is a tone language (where pitch distinguishes meanings lexically), Chinese children were tested for their tone awareness, in which they were asked to select the deviant syllable out of sets of four monosyllables. The results indicated that Chinese dyslexic children had significantly poorer tone awareness relative to their non-dyslexic peers. Notwithstanding, the authors only tested Chinese children with Chinese speech sound, and English children with English stimuli. Using speech pitch from one's native language, the stimuli themselves carry the phonological features in his native language. Thus, if any auditory impairment is found, it is very likely that it is this person's phonological processing that is deficient, rather than another auditory processing system. Chinese dyslexics perceiving lexical tone stimuli simply reflected the fundamental phonological deficit in this study. In all, lexical tones are native and speech sound to Chinese children. Pure tones, on the other hand, are non-speech to both English and Chinese children. With evidence demonstrating dyslexic children with difficulties in this two respects, what remains unknown is whether the impairment in pitch perception holds for both speech (yet non-native) and non-speech stimuli. Exploiting speech pitch stimuli that have no lexical functions in dyslexics' native language would be the most appropriate way

to separate auditory processing impairment from phonological deficit.

Other studies have also tested lexical tone awareness and literacy skills among native Chinese speakers. Cheung et al. (2009:726) explained how Chinese tones work by stating that "Chinese syllables obligatorily carry tones that are as critical as segments in determining meaning". Cheung et al. (2009) tested Cantonese-speaking dyslexic and normal reading children with two categorical perception experiments of minimal pairs contrasting in tone (/si$_{55}$/ or /si$_{33}$/) and aspiration (/gi$_{55}$/ or /ki$_{55}$/), respectively. They found that performances on both tasks significantly distinguished children with dyslexia from the age-matched controls, and emphasized that perceiving isolated syllables less accurately imply overall problems in speech perception, and other possible linguistic difficulties, such as dyslexia. The findings of Goswami et al. (2011) and Cheung et al. (2009) concluded that for tone language speakers, where pitch is phonologically contrastive, poor pitch perception does distinguish dyslexics from non-dyslexics. However, to what extent the pitch deficiency found in the aforementioned findings is phonology-specific or general auditory is unknown. Hence, it is necessary to test dyslexics with speech pitch stimuli that are not phonologically contrastive in their native language. By doing so, if the dyslexics are less accurate than normal readers, then it means that dyslexics may have general auditory impairments that go beyond phonological processing deficit. In addition, in order to fully understand whether the pitch perception deficit in dyslexics is speech-specific or domain-general, both speech pitch and non-speech pitch stimuli are required.

Phonological awareness and musical pitch perception impairment

Having discussing how important pitch is to literacy skills, the question now is how pitch perception in a non-speech domain can be related to reading. Pitch forms a good tool to examine auditory processing across domains as it is not only essential to speech, but also to music. Anvari et al. (2002:126) pointed out that "phonological awareness requires the listener to be able to segment speech into its component sounds, and to recognize those sound categories across variations in the pitch, tempo, speaker, and context. The perception of music also requires the listener to be able to segment the stream of tones into relevant units, and to recognize compositions across variations in pitch (key), tempo, performer, and context". Banai & Ahissar (2006:1725) proposed that "the deficits in nonverbal auditory processing is part of the same underlying deficit contributing to the phonological processing deficit and consequently poor reading". That is, the processing of speech and non-speech pitch might

share similar mechanisms, and if dyslexics have difficulties processing speech pitch stimuli, they might also experience impairment in non-speech pitch perception. Many studies have employed musical stimuli to verify if the auditory deficit can also be seen in the music domain in this regard.

Anvari et al. (2002) studied the relations among phonological awareness, music perception skills, and early reading skills in 4- and 5-year-old children. Phonemic awareness was tested by rhyme generation, oddity, blending, and the skills in identifying, segmenting, deleting, and recombining the component of word syllables and sounds. Music stimuli consisted of piano tones presented both sequentially (rhythm and melody) and simultaneously (chord) paralleling the segmentation and blending tasks with speech sounds. The participants were tested for their discrimination of rhythm, melody, and chord in AX format. The stimuli in melody discrimination had a length from 3 to 11 notes and the pitch differences included subtle (one note deviated by 1/12th of an octave) and salient changes (pitch contour reversals). The chords differed in consonance and dissonance with either two or three notes in one chord. Either one or two of the notes were deviant. Anvari and colleagues found that music skills correlated significantly with both phonological awareness and reading development, and further stressed that the performance of music perception predicts reading even after the variance accounted by phonemic awareness was excluded. Therefore, music perception relates to phonological awareness and ultimately, reading. The findings of Anvari et al. suggest that pitch perception deficiency may underlie reading disabilities, and such deficiency may not be restricted to the language domain. Based on this hypothesis, dyslexic children are assumed to show perceptual deficit in musical pitch processing. Nonetheless, Anvari et al. (2002) only tested children, and how adult dyslexics perceive musical pitch remains unclear. If musical pitch perception impairment is visible among dyslexic children, it does not necessarily entail that this impairment will last to adulthood. Rather, such auditory impairment might be compensated during development. Examining how adults perceive pitch in different domains will help us understand whether pitch deficiency forms a core auditory impairment in dyslexia.

It has also been suggested that tone-deafness and dyslexia might share common impaired neural substrates. Loui et al. (2010) hypothesized that tone-deafness and dyslexia are closely related, and might share a common neural basis. In this study, 32 English-speaking children with a mean of 0.4 years of musical training after school (16 females, 16 males, mean age 7.6 years, SD 0.7 years) were recruited. In pitch perception and production tests, 13 pairs of pure tone intervals were presented with a

F0 of 500 Hz on the first tone in each pair. The frequency of the second tone ranged from 267 Hz to 750 Hz with a duration and an ISI of 500 ms. Participants were asked to first reproduce the tone pair by humming (production), and then reported whether the second tone was deviant from the first (perception). The results, independent of age, non-verbal IQ, SES, and musical training, revealed the association between phonemic awareness and pitch awareness, as assessed by the level of agreement of pitch perception and production. The link between musical pitch awareness and phoneme awareness, which is one of the underlying reasons for reading difficulty, brings about the question of whether pitch processing deficit can be observed in dyslexics (i.e. if tone-deafness and reading difficulty are relevant). Interestingly, the authors found that neither perception nor production alone did it correlate with phonemic awareness. This consequently entails that when perception and production are separated, we would not expect to see dyslexics with impaired perception or production processing. The current study looked into the processing of perception only and compared speech and non-speech perception to tackle the question of whether the perceptual deficit (if any) was domain-specific or domain-general.

Contradictory results among musical pitch perception skills in dyslexics

As mentioned earlier that from the domain-general point of view, individuals with dyslexia might also show difficulties in non-speech pitch processing. If the general auditory processing is impaired, then perceiving any other acoustic events might also be hindered. For instance, Baldeweg et al. (1999) tested 10 dyslexics (9 male and 1 female, mean age 32.0 years ranging from 20-51 years) and age-matched 10 controls (mean age 33.4 years ranging from 20-56 years) with electroencephalogram (EEG). In the auditory discrimination, subjects detected 4 deviant tones among other pure tone stimuli by pressing a button. The standard pure tone had a frequency of 1,000 Hz (80% of occurrence), while the deviant tones had a frequency of either 1,015, 1,030, 1,060, or 1,090 Hz (each had 5% of occurrence). The outcome indicated that dyslexics made more errors in tone frequency discrimination relative to the controls. Furthermore, for the dyslexics, MMN latency and the accuracy in detecting deviant tones significantly correlated with reading errors on both regular words and non-words, but not with errors on irregular words. For the controls, on the contrary, no significant difference was found in any of these correlations. Moreover, the severity of the reading problems of dyslexic adults correlated with their difficulties of detecting occasional frequency deviants among standard tones. These results argue for impaired pitch perception in dyslexics, and such deficits may have a neural basis. Moreover,

the absence of a correlation between deviant pitch detection and reading among non-dyslexics suggests that dyslexics may recruit different or more resources in reading compared to non-dyslexics. If so, it could be possible that dyslexics take advantage of pitch information in reading, whereas non-dyslexics do not. Should this be the case, then contradicting Baldeweg et al.'s (1999) findings, dyslexics may outperform non-dyslexics in certain pitch processing tasks, as they rely more heavily on pitch perception skills.

Indeed, there is evidence supporting the hypothesis above. Overy et al. (2003) found that dyslexics perform better on pitch discrimination than non-dyslexics. They tested 15 dyslexic boys (age 7–11, SD = 1.1) and 11 gender- and age-matched controls (age 7-10, SD = 0.9). All children were given the Musical Aptitude Tests (MATs) adapted for this study, including copying and discrimination tasks aiming for rhythm, meter, rapid timing, and pitch skills. In the melody discrimination task, two 3-note melodies were presented as a pair, and children reported whether they were the same or different; in pitch discrimination, children were asked to discriminate between two individual notes; in pitch matching, children spent some time to get familiar with the pitches of 5 marked notes on the keyboard (C3 to G3). A single pitch was then presented, and children chose the same pitch on the keyboard. They authors found that, unsurprisingly, dyslexic children had much poorer results than the controls in the literacy tests, rhythm, rapid timing skills and timbre discrimination. However, the authors observed that dyslexics performed better than the controls on pitch-related tasks, and slightly higher on singing. The enhancement in musical processing was specific to pitch perception, whereas no such enhancement was found in rhythm perception. This piece of evidence argues for the hypothesis that if phonological processing impairment is the core deficit (Snowling, 2000), the processing of other non-speech pitch stimuli should not be problematic for dyslexics. In all, comparing the studies above, both Anvari et al. and Overy et al. recruited dyslexic children, and applied musical pitch stimuli, yet one observed the deficit in musical pitch perception, while the other one did not. The stimuli used in these aforementioned studies contained musical pitch (e.g. Overy et al., 2003, Anvari et al., 2002) and pure tones (e.g. Baldeweg et al., 1999, Goswami et al., 2011). Yet different experimental designs and stimuli may lead to very different results. The inconsistency between these papers lead to the question of how dyslexics differ from non-dyslexics in terms of pitch perception, such as whether dyslexics are facilitated or hindered by reading disability in pitch perception, and whether such facilitation or disadvantage is specific to language. By only looking at non-speech pitch perception, it is still not

enough to conclude whether such perceptual deficit is domain-specific or domain-general. In order to explore where pitch perception deficit lies (if any), both speech and non-speech pitch stimuli need to be included. Additionally, similar to Anvari et al's (2002) study, Overy et al., too, only tested dyslexic children. If children with dyslexia show impaired musical pitch perception, we cannot thus conjecture that adult dyslexics would experience the same difficulties. Since how dyslexic adults perceive musical pitch has not yet been documented, a study testing adult dyslexics is needed in order to compare the processing of musical pitch in dyslexic children and adults To answer these questions, musical experience- and age-matched dyslexics and non-dyslexics should be tested with pitch perception tasks across domains.

Global or local pitch pattern processing deficits

Technically, global pitch violations (e.g., contour) and local pitch changes (e.g., intervals) should be processed by asymmetrical and separate brain structures (Ziegler et al., 2012). It was assumed that dyslexics, having reading disability localized in the left hemisphere, should have problems processing local pitch changes. Ziegler et al. (2012) recruited 15 French-speaking dyslexic children (10.2 years old, range: 8.6-11.9). They listened to 2 continuous 4-tone pitch sequences, and judged if the stimuli were the same or different as shown in Fig. 1. For different trials, the contour was either violated (global condition) or preserved (local condition). In the perception experiment, 40 pairs of 4-tone sequences (half were “same” trials) were given to the participants. In the “different” trials, the deviant tone was adjusted either on the second or the third note randomly, and always remained two notes higher or lower than the initial one. In the pitch direction task, participants discriminated whether a 2-tone pitch sequence differing in F0 was rising or falling in 30 trials (equal number of trials in each condition). Results demonstrated that dyslexics exhibit evident pitch perception deficits in the local, rather than the global condition, and the error rate was significantly higher than controls in pitch direction tests. Accurate encoding of every pitch is presumably more difficult than holding a general pitch pattern in mind. This study showed that dyslexics have impaired pitch discrimination skills when asked to focus on detailed acoustics events that are more delicately organized like speech pitch. In other words, the more demanding the decoding of the pitch is, the more problematic it would become for dyslexics.

In contrast, Foxton et al. (2003) found very different results. They tested 30 non-musician

students (age 19-24 years) with similar experiments. The local task assessed the ability to discriminate actual pitch values over time, asking subjects to detect differences between 2 pitch sequences with the same pitch contour but one deviant pitch; the global task measured the ability to discriminate contour patterns of rises and falls in pitch. Other literacy tests included 2 non-word repetitions to measure phonological skills; Raven's Advanced progressive Matrices and Mill Hill Vocabulary Senior Scale Form for non-verbal and verbal intelligence, respectively; the National Adult Reading Test for reading, and Orthographic Recognition Test for spelling. The findings showed that global sequence task significantly correlates with all literacy tasks. Foxton et al. (2003) stressed that phonological and reading skills can be predicted by the performance of global task, upholding the strong influence of pitch contour processing to literacy. As global task evaluates a more holistic auditory processing than the local task, opposite to Ziegler et al.'s study, this conclusion indicates that the processing of musical pitch is highly related to reading, supporting the impaired musical pitch processing in dyslexics as proposed earlier.

The opposite findings of Ziegler et al. (2012) and Foxton et al. (2004) make the question of how pitch perception correlates and contributes to reading intriguing. Ziegler et al. observed dyslexic children with deficient local pitch processing, while Foxton et al. had adult subjects in the study, and proposed that global pitch processing and literacy skills are specific to the phonological domain. The difference between subjects from very distinct age groups might have suggested how contrastingly children and adults perceive pitch. It is worth mentioning that pitch is used differently in speech and in music. For example, speech prosody exhibits continuous pitch contour rather than discrete keys such as musical notes. Also, compared to music, the pitch difference in speech is coarser. Music makes use of pitch differences as small as 1 semitone, whereas meaningful pitch differences are often larger than 6 semitones in speech (Zatorre, Belin, & Penhune, 2002). Specifically regarding the global/local pitch distinction, pitch pattern in language, such as lexical tones, can be very local and is restricted to a single syllable. It is possible that the processing of speech and non-speech pitch patterns play different roles in reading, and pitch perception may contribute to reading differently in non-dyslexics and dyslexics. Studying speech and non-speech pitch perception skills in dyslexics would help gain more understanding of their performance on acoustic events across domains. Further experimental work is needed to elucidate the questions raised above.

Musical and phonological trainings improve literacy skills

Musical training has been proved to be beneficial for language development, and positively connected to literacy skills. For instance, in a longitudinal study, Moreno et al. (2009) studied 32 8-year-old non-musician children to determine whether musical training improved reading and linguistic pitch processing. The children were pseudo-randomly assigned to either 6 months of music or painting training, and the same tests were used again to test children after training. For measuring reading skills, children were asked to produce print-to-sound correspondences, which differed in degree of complexity. In a total of 48 words (2-4 syllables in each), 24 of them contained simple and consistent non-to-one grapheme-to-phoneme correspondence, the rest 24 had either complex but consistent or complex and inconsistent mapping. In the pitch discrimination session, 90 melodies and 90 Portuguese sentences were given. The musical stimuli were chosen from Schön et al. (2004). For the speech sentences, 35% and 120% of the F0 was increased to get weak and strong incongruity, respectively on the final word in a sentence. Similarly, 1/5 and ½ of a tone was increased to generate weak and strong incongruity, respectively on the pitch of the last note in a musical phrase. Children were asked to judge whether the last word or note was deviant or not. The musical trainings consisted of rhythm training, (improvising rhythms in different tempi and meters), melody (classifying pitch contour and intervals), harmony (discriminating and producing different harmony pairs), and timbre discrimination. After 6 months of musical (but not painting) training, children made fewer errors for both strong congruous and weak incongruities in both music and speech pitch discrimination. Musical training also enhanced reading skills particularly when phoneme-to-grapheme correspondence was complex. The authors explained that these results are in line with the assumption that musical training heightened basic auditory processing and sound segmentation and blending (Lamb & Gregory 1993), which strengthens the phonological representation development crucial for reading (Anvari et al. 2002; Foxton et al. 2003). Using music training to increase musical and speech pitch processing is not astonishing. The important finding is that if musical training can improve reading ability, it is conceivable that the phonological deficit found in dyslexics results from general auditory processing disorder. Hence, we might expect dyslexics to show pitch perception deficits in both speech and music domain.

This relation can be furthered substantiated by the observation of positive transfer from one domain to another. Besson et al. (2007) examined 10 dyslexic and 10 normal-reading children to examine if dyslexics could benefit from phonological training to improve their pitch discrimination

skills. All children were first given the speech pitch discrimination task. Before the training, dyslexic children had much higher error rate (45%) to the strong incongruity in speech (F0 of the last word was increased by 120%), than the controls (4%). Dyslexic children were then received an 8-week combination of phonological training (10 minutes per day with phonological exercises) and audio-visual training (adapted from Magnan et al., 2004. 20 minutes, twice a week). The audio-visual training concentrated on voicing opposition between six minimal pairs of phonemes, namely /p/-/b/; /t/-/d/; /k/-/g/; /f/-/v/; /s/-/z/ and /ch/-/j/. Children listened to a CV syllable and were presented with two printed pairs (e.g. pa or ba) differing in voicing, and judged which printed pair corresponded to what they just heard. Control children received an 8-week painting training (twice a week for 50 minutes). After training, all children were tested again with the same discrimination task, and no significant differences were found between dyslexic and non-dyslexic children. Therefore, the combination of phonological and audio-visual training clearly strengthened the detection of strong pitch incongruities in speech in dyslexics. Thus, it might be possible that pitch perception is linked to phonological processing, and ultimately reading. Yet the limitations in this study, such as having only child subjects made it unlikely to apply the results to another dyslexic population (e.g. adults). Taken together, Moreno et al. observed music strengthened reading ability, especially when phoneme-grapheme correspondence is complex, and Besson et al. discovered enhanced pitch perception through phonological training, proposing that the auditory processing systems of pitch sensitivity and phonological awareness/reading may go in both directions.

Summary

In the current study, we asked the following questions: 1) whether adult dyslexics' perceptual skill of speech pitch was impaired; 2) whether the impairment (if at all) was speech-specific or domain-general. As listeners may process pitch in speech and in music differently (Chen, 2013), examining only one domain would be incomplete to answer how pitch perception relates to reading. Testing dyslexics with speech pitch stimuli from non-native language helped separate perceptual processing impairment (if any) from phonological deficit. Moreover, most of the studies tested mainly children, yet only little is known concerning adult dyslexics' performance of musical and lexical pitch perception. The current study focused on adult dyslexics for two reasons. First, in language development, children approach adult-like performance through learning, but how pitch correlates with reading in adults is still unclear. Without understanding of the contribution of pitch at the final stage, it

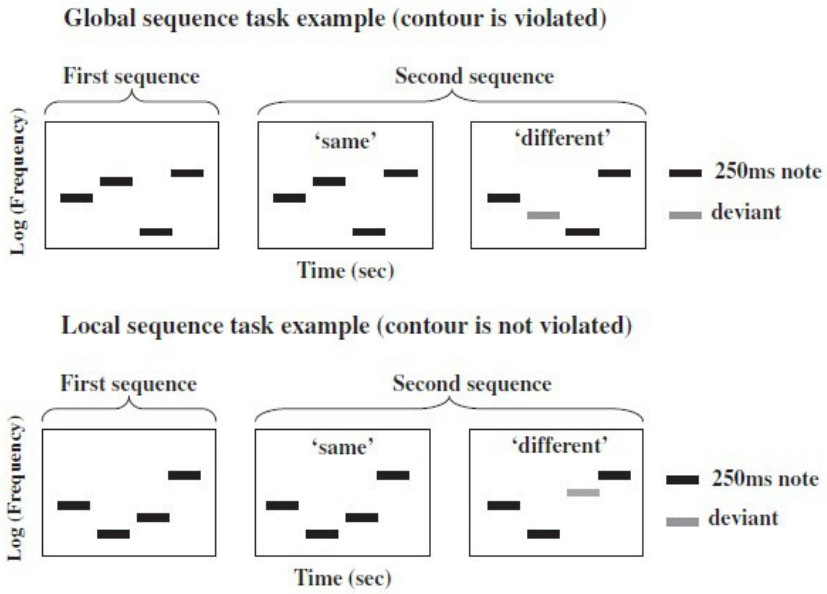
is hard to infer how pitch perception interacts with reading in learning process. Second, dyslexic adults might perceive pitch as well as non-dyslexics. However, this does not entail that dyslexics and non-dyslexics followed the same developmental trajectory from childhood to adulthood. In fact, dyslexics and non-dyslexics may have a different auditory trajectory, but end up at the same level of processing in adulthood. By investigating dyslexics' pitch perception in both music and language domains, we would be able to discover whether pitch perception deficit (if any) resulted from general auditory processing disorder, and whether this general auditory deficit was what accounted for the phonological deficit. The aims of our pitch perception study were threefold.

1. To examine if Dutch dyslexics had difficulties discriminating pitch changes in both speech and music domain.

2. To test Dutch dyslexics with non-native speech sound to conclude whether phonological processing deficit was caused by general auditory processing dysfunction.

3. To provide the baseline for understanding dyslexics' performance on pitch perception skills from a developmental perspective.

Figure 1. Illustration of the global and local pitch change detection task (Ziegler et al., 2012)



Our hypotheses were listed in Table 1: (1) if dyslexics did not show deficits compared to the non-dyslexics in neither musical nor lexical tone discrimination, it was plausible to assume that pitch perception would not form a core deficit in literacy skills; (2) if dyslexics showed deficits in both musical and lexical tone discrimination, we would be able to conclude that it might be their general auditory processing that was impaired, and such deficits would stay regardless of domain; (3) if dyslexics only showed deficit in musical tone discrimination, it was possible that the perception of pitch in speech was spared and the perceptual impairment was restricted to music. As musical tones were well-organized, the third hypothesis also entailed the possibility that the deficit in pitch processing only occurred when dyslexics processed structured melodic phrases, rather than local acoustical information, such as lexical tones; (4) if dyslexics only showed deficit in lexical tone discrimination, it was likely that dyslexics were hindered by their reading disability when perceiving pitch in speech, especially when it involved fast-changing patterns.

Table 1. Hypotheses of all possible results of dyslexics

	Auditory perception	
	Lexical pitch	Musical pitch
Hypothesis 1	O	O
Hypothesis 2	X	X
Hypothesis 3	O	X
Hypothesis 4	X	O

O = unimpaired; X = impaired

Section 3. The relation between rhythm perception and literacy skills

Speech rhythm perception impairment

Over the years, researchers have observed deficit in speech-related temporal skills, too. Since segmentation of speech and syllable detection may depend on rhythm perception (Morgan & Saffran, 1995), it is not surprising to see dyslexic children, who have problems with word segmentation as discussed before, to have difficulties processing temporal sequential information. Recent studies have confirmed the association between speech rhythm and learning to read in language development. For instance, Muneaux et al. (2004) examined whether linguistic beat perception deficit observed in English dyslexic children (Goswami et al., 2002) were due to language-specific properties, or that the deficit could also be seen in another language system with distinct rhythmic features, such as French. With remarkably similar results in both languages, Muneaux et al. (2004:1258) concluded that "deficits in the perception of speech rhythm and contour, as reflected in the slow modulations of the temporal envelope, are universal in developmental dyslexia". If different processes like impaired speech rhythm perception and previously discussed phonological processing deficit can both be found in dyslexics, it is reasonable to ask such deficiency holds for general auditory perception. Accordingly, we would expect to see the impairment in the perception of other non-speech rhythm stimuli. Several studies have proposed the deficit of temporal skills in the speech domain; however, whether the deficit appears in another domain where rhythm also plays an essential role, such as musical rhythm, is still disputable. Moreover, these rhythm perception studies have not yet tested Dutch-speaking dyslexics. The current research test adult Dutch dyslexics' perceptual skills, and to examine whether the processing of fast-changing rhythmic events was a part of the general auditory processing impairment.

Rhythm perception impairment in music

General auditory processing is responsible for the processing of pitch and rhythm in both language and music domains. Rhythm perception, like pitch perception, is also required for processing speech and music. Anvari (2002:112) noted that "research has proposed that some auditory analysis skills used in the processing of language are similar to the skills necessary for music perception, such as rhythmic, melodic, and harmonic discrimination (Lamb & Gregory, 1993)". A few studies have demonstrated that dyslexics perform poorly compared to non-dyslexics when perceiving musical rhythm. Flaugnacco et al. (2014) pointed out that rhythm not only plays an important role in music, but

also in phonology and speech prosody since the processing of musical sound feature, such as *legato* (continuous, smooth) or *staccato* (separated, cut) on string instruments is similar to [ba] and [pa] phoneme discrimination. Accurately perceiving rise time in these rhythmical/metrical structures in music might be essential in phonological development, and consequently reading. Following this idea, an individual that has difficulties processing temporal cues in speech might also show similar deficits in the music domain. As predicted, children with developmental dyslexia scored lower on segmentation and grouping tasks in both speech and music (Petkov et al., 2005). Furthermore, Flaugnacco et al. (2014) investigated the relation between musical temporal skills, as well as phonological and decoding (reading) skills in 46 8 to 11 year-old children with developmental dyslexia, and concluded that musical rhythm perception and production predict reading abilities. The tasks included: 1) psychoacoustic tasks, in which 3 same pure tones were presented to children, and children detected which one was the longest tone; 2) rhythm reproduction of 10 different types of rhythm (3-8 notes in each trial) played on woodblock sound; 3) musical meter tasks where participants made a same-different judgement in 18 trials of distinct metrical composition of a novel of notes. Through logistic analysis, Flaugnacco and colleagues found a strong association between meter perception, rhythm processing, and reading as text reading accuracy and word reading speed could be predicted by the performance of the meter perception, whereas pseudoword reading accuracy was predicted by the performance of rhythm reproduction. This, in turn, substantiates the relation between musical rhythm perception and production and literacy skills. Yet the authors also noted that aside from timing mechanisms, other abilities, such as auditory attention (Facoetti et al., 2010) and working memory (Swanson et al., 1996) that most dyslexics are known for being poor at were also involved, and the authors did not separate these abilities in the study. It may be the case that the dyslexics in Flaugnacco's study also had below-average auditory attention and working memory, leading to impaired rhythmic skills in music. Future research is needed to disentangle the contribution of auditory attention and working memory deficits from rhythmic deficits among dyslexics. In addition, the dyslexic subjects in this study showed impaired musical temporal skills at age 11; however, whether this impairment would continue in adulthood is unknown. If dyslexic children are found with impaired musical rhythm perception, would adult dyslexics also demonstrate the same deficit? Investigation of adult dyslexics' rhythm perception in music is thus needed. Since music and speech share several basic processes (Besson & Schön, 2011), if one has difficulties processing speech rhythm, musical rhythm processing might also be deficient.

Impairment in a subgroup of dyslexics

Nonetheless, other researchers suggest that dyslexics would not necessarily experience difficulties in non-speech rhythm perception. Griffiths and colleagues (2003:1364) emphasized that "auditory deficits are neither necessary nor sufficient to cause phonological difficulties (Bishop et al., 1999; Rosen & Manganari, 2001). Furthermore, the observed associations between auditory processing and phonological processing skills do not speak to the direction of causality or to possible mediating factors". Farmer & Klein (1995:460) also indicated that "a temporal processing deficit will not be found to account for all cases of developmental dyslexia". In short, dyslexics do not necessarily show temporal processing deficits for all auditory stimuli. Although the impairment in phonological processing is well established, the ability to discriminate rapid non-speech acoustic stimuli may stay unaffected. Atterbury (1985) studied reading-disabled children in 3 different age groups, and discovered that it was the production of music that was deficient, rather than the perception skills. The original study included 10 separate rhythm tasks categorized in 3 major sections. The first one measured rhythm discrimination with 3 different presentations; the second assessed clapped rhythm performance; the third was the rhythm part adapted from Primary Measures of Music Audiation (PMMA; Gordon, 1979). Children listened to a tape presenting a language cue (house, shoe, etc.) followed by a pair of rhythm patterns, and were then asked to point at the card with two similar faces when the two rhythm patterns were identical, or with dissimilar faces when the two patterns differed. Twenty 7-year-old and 20 8-year-old children received rhythm discrimination and rhythm performance tasks, and 56 9-year-old children had rhythm discrimination and echo-clapping performance tasks. Each age group consisted of the same number of gender- and socioeconomic status-matched normal-achieving and learning-disabled readers. Differences between dyslexics and non-dyslexics in all three age groups were found. Specifically, both dyslexic and non-dyslexic children discriminated rhythmic patterns similarly but all dyslexics reproduced clapped-rhythm patterns less accurately than normal readers. That is, while the perception remains unimpaired, allowing dyslexics to perceive musical rhythmic patterns as accurately as non-dyslexics, the defective motor coordination led the dyslexics to (re)produce musical phrases more poorly than non-dyslexics. Based on Atterbury's findings, the disassociation between literacy skills and rhythm perception in music is thus suggested. That is, lower literacy skills does not naturally cause impaired perception skills. Rather, the deficient motor control movement is what distinguishes dyslexics and non-dyslexics aside from phonological processing

deficit and reading disability. Therefore, if the deficit only appears in production, the perception skills should stay intact. However, this research only recruited dyslexic children, and whether adult dyslexics would also show the same unimpaired perceptual patterns as dyslexic children needs to be further studied.

In line with Atterbuery's finding, Overy et al. (2003) examined whether dyslexic children performed more poorly on rhythm perception and production relative to non-dyslexics through a series of musical aptitude tests (MATs). Their test included rhythm copying, in which the child copied the perceived rhythm on the keyboard; rhythm discrimination, where children determined whether the two perceived rhythm were the same or different; song rhythm that asked children to tap the rhythm of Happy Birthday on the keyboard while singing the words; tempo copying with a steady beat of 8 taps from 48, 60, 80, 120, to 240 bpm (beats per minute), and children were asked to copy the speed as accurately as possible on the keyboard; tempo discrimination, where two different tempi with 8 beats from 64 to 800 bpm each were presented, and children reported whether the second tempo was faster or slower than the first. The participants were the same as mentioned in chapter 2. Results suggested "a clear pattern" of the dyslexic group performing more poorly than the control group on rhythm-related and rapid-related tasks (e.g., counting the number of taps). However, some meter-related performance (e.g. tempo discrimination, tempo copying) showed that dyslexics scored slightly higher than the controls. The tasks were further regrouped into two major skills, namely motor skills (tempo copying, rhythm copying, song beat and song rhythm) and perceptual skills (tempo discrimination, rhythm discrimination, note order detection, note number detection, note number discrimination) to analyze where the core deficits were. Overy et al. (2003:27) emphasized that "the dyslexic group scored lower on both motor and perceptual timing skills tasks, but the differences were not significant". What made this study crucial is that in the tempo copying tasks, the only significant difference between the two groups was at the speed of 80 bpm, but no other significant differences were found slower or faster than 80 bpm. Overy et al. (2003:32) explained that "being close to the often quoted natural tapping speed of 100 bpm (Clarke,1999), 80 bpm is a particularly sensitive indicator of natural tapping ability". Hence, a study using rhythmic phrases played at a different tempo becomes necessary to verify whether this interpretation is valid if there is any perceptual deficit at all. Most importantly, the authors pointed out that it was a subset of 5 dyslexic children (33% of the group) that were responsible for almost all the significant errors in the rapid temporal processing, whereas the rest of the dyslexics did not

demonstrate any perceptual deficit. Nonetheless, how adult dyslexics perceive rapid rhythmic signals is still unknown. If such a deficit was only observed in a subgroup dyslexic children, it becomes crucial to study whether it is also a difficulty a subgroup of dyslexic adults experiences.

Summary

In an auditory processing research using temporal order discrimination (TOD) and auditory backward recognition masking (ABRM) tasks, Griffiths et al. (2003) specified that in a subgroup of dyslexics who had impaired phonological processing showed intact auditory processing in these tasks. Likewise, there were also participants with normal reading and phonological processing that performed more poorly than other non-dyslexics in the experiment. In addition, the subset of dyslexics who scored lower than other dyslexics were the ones with more severe phonological deficit. Baldeweg et al. also mentioned that the severity of dyslexia in adults correlated with their difficulties of detecting deviant tones among other pure tone stimuli. It should be noted that Overy et al. (2003) did not examine whether the 5 dyslexics responsible for almost all errors also suffered from more serious phonological deficit. It is worth investigating if dyslexics who show any perceptual deficit at all in our study also have more severe phonological deficit. In conclusion, the divergent lines of studies lead to the question of whether rhythm perception in adult dyslexics is impaired. Crucially, the major difference between the studies above and ours is that those studies did not entirely separate rhythm discrimination from pitch perception (e.g. pitch was accompanying rhythm in the rhythm perception tasks) (Atterbury, 1985; Overy et al., 2003). As discussed in section 2 that dyslexics may have difficulties with pitch perception, not separating pitch in rhythm perception tasks might distract dyslexics from concentrating on the rhythm/tempo alone, which might be misinterpreted as the deficit in both pitch and rhythm perception skills. To minimize the parameters, our study applied woodblock sounds in rhythmic phrases, so the participants would not be interfered with any pitch information. As earlier findings have primarily tested dyslexic children, how adult dyslexics react to musical rhythmic events remains unknown. More importantly, the current study aimed to discover if dyslexic adults had impaired or intact rhythm perception in music; if the perceptual deficit (if any) existed only in a subgroup of dyslexics as proposed earlier; whether this perceptual deficit (if any) resulted from general auditory processing disorder. Our hypotheses were as follows: 1) if dyslexics did not show deficits relative to the non-dyslexics in musical rhythm discrimination, then possibly musical rhythm perception recruits different resources compared to temporal skills in speech, and the deficiency of dyslexics is rather

restricted to the language domain; 2) if dyslexics showed deficits in musical rhythm discrimination, it was reasonable to hypothesize that general auditory processing disorder may be what underlies phonological processing, and impairs temporal skills in perception in general.

Section 4. Methodology

Subjects

13 controls (6 males, 7 females) and 14 dyslexics (4 males, 10 females) that matched on education level (at least Bachelor's degree, or WO/HBO in Dutch), handedness (3 left-handed subjects in each group), and age (controls: mean age 22.9 years old; dyslexics: mean age 22.7 years old) were recruited. During the testing period, they were all registered students at Universiteit Utrecht. Among all participants, 7 controls and 9 dyslexics had music training (control group: mean onset: 11.7 years old, mean duration: 5.8 years, SD: 4.89; dyslexic group: mean onset: 8 years old, mean duration: 7.3 years, SD: 2.12), and considered themselves amateurs (1 dyslexics received music education in a conservatory majoring in percussion, others had one-on-one private lessons for at least 2 years). All participants had normal hearing. One dyslexic subject reported having absolute pitch---the ability to vocally produce any note with precise intonation or accurately identify every note played on any kind of instrument without any help from relative notes (Deutsch et al., 2006). Questionnaires (Appendix A) and consent forms were obtained from all subjects.

Pretest

Eleven dyslexic and 13 non-dyslexic participants took 3 pretests to determine whether they fell into the control or dyslexic group before proceeding to the experimental phase. Dyslexic participants who did not take the pretests provided an official diagnosis of dyslexia to continue. The pretests included 3 parts: a) Een-Minuut-Test (EMT; Brus & Voeten, 1972), a test in which the participants were asked to read as many real words as possible in one minute; b) de Klepel (Van den Bos et al., 1994), a pseudo-word reading test, for which the time limit is two minutes; and c) Wechsler Adult Intelligence Scale (WAIS-III of Dutch version; Uterwijk, 2000), the verbal competence test (Analogies) assessing the ability to use language appropriately to have communicative interaction with interlocutors and in a given social situation (Hymes, 1972). Classification of dyslexia was in view of Kuijpers et al. (2003) and Kerkhoff et al. (2013) that if a person's performance was $\leq 25^{th}$ percentile on both the EMT and de Klepel, or was $\leq 10^{th}$ percentile on either the EMT or de Klepel. As a substitute, if a discrepancy of at least 60% appeared between the verbal competence test and the EMT or de Klepel. Since it is mostly their reading and spelling abilities that dyslexics struggle with while having average intelligence

(Ramus, 2003), dyslexics' verbal competence should be similar to that of the controls'. In other words, dyslexia should not affect a person's verbal communicative skills.

4.1 Experiment 1: Chinese monosyllabic tone discrimination

Apparatus and procedure (adapted from Chen, 2013)

The experiment was conducted in a soundproof phonetic lab. A female native Mandarin speaker recorded multiple tokens of monosyllables, including /ba/, /bou/, /bi/, /da/, /dou/, /di/, /la/, /lou/, /li/, /ma/, /mou/, /mi/, /na/, /nou/, /ni/ with PRAAT software (Boersma & Weenick 1997) in a sound-proof booth equipped with a DAT Tascam DA-40 recorder and a Sennheiser ME-64 microphone. The four tones of Mandarin were divided into 2 groups of 4 possibilities: T1-T4/T4-T1, and T2-T3/T3-T2 occurred with equal chance. Chen (2013) noted that after recording, one token of each original syllable were further manipulated to reach the same acoustic properties, such as duration (a range between 380-604 ms) and intensity, across different tones. She explained that the pitch contour of T1 was extracted, and the original pitch contour of the T4 syllables was replaced with the extracted T1 contour to have T1 and T4 stimuli. This resulted in a T1 syllable having identical segmental and intensity information as the original T4 syllable. The same procedure was applied to the stimuli of T2 and T3 by extracting the pitch contours of the original T3 and replacing the original pitch contour of the T2 syllable with the extracted T3 contour, leading to a T3 syllable carrying identical segmental and intensity information as the original T2 syllable. The “same” pairs were constructed by repeating one syllable once within a trial. Before the experimental phase, 4 practice trials with immediate feedback on a computer screen was introduced for familiarization. After the practice phase, 120 auto-paced trials of monosyllabic pairs without any feedback were presented in AX format. Subjects sat down comfortably in front of a computer screen and were informed about the procedure verbally. They were asked to respond as fast as possible to each trial and judge whether the two tones were identical or not by pressing the button box labeled with “same” and “different”. For example, T1 v.s. T1 for “same”, or T2 v.s. T3 for “different”. Within each trial, two syllables with the same segments were presented to the participants with an inter-stimulus interval of 1500ms, and the response window for the participants was 1000ms. If the participants failed to give any answer within the response time, they missed one trial. The order of the stimuli was randomized across the participants. Only results from the experimental phase were recorded.

4.2 Experiment 2: Chinese bisyllabic tone discrimination

Subjects

Same subjects from experiment 1 also participated in Experiment 2.

Apparatus and procedure (adapted from Chen, 2013)

The apparatus and procedure were exactly the same as in Experiment 1. Subjects were asked to respond as fast as possible to each trial and judge whether the two pairs of tones were identical or not by pressing the button box labeled with "same" and "different". Within each trial, four syllables with the same segments were presented to the participants with an inter-stimulus interval of 1500ms, and the response window for the participants was 1000ms. The difference between experiment 1 and 2 was that the total number of trials was 180 in Experiment 2, and subjects made judgment based on more complicated stimuli of bisyllabic sequences. For example, if T3T3 sequences appeared as the first pair, the participants needed to indicate whether or not the second pair of T2T3, T3T2, or T2T2 bisyllabic sequences were identical to T3T3. Similarly, if T4T4 sequences were the first pair, participants made judgement on whether or not the second pair of T1T4, T4T1, or T1T1 were identical to the first pair. In the experimental design, Chen (2013) specified that in order to make sure the lexical tones were the only distinction between the syllables with the same segments, she manipulated the bisyllabic sequences by concatenating T1 and T4 to generate T1T4, T4T1, T1T1, and T4T4 sequences. By concatenating T2 and T3 in the same way, it resulted in T2T3, T3T2, T2T2, and T3T3 sequences. Thus, participants could only rely on the lexical tones when discriminating between sequences, and not bothered by other phonological information. The "same" pairs were constructed by repeating one syllable twice within a trial, and the possibility of each tone pair was equally distributed.

4.3 Experiment 3: the Musical Ear Test (MET)-melody discrimination

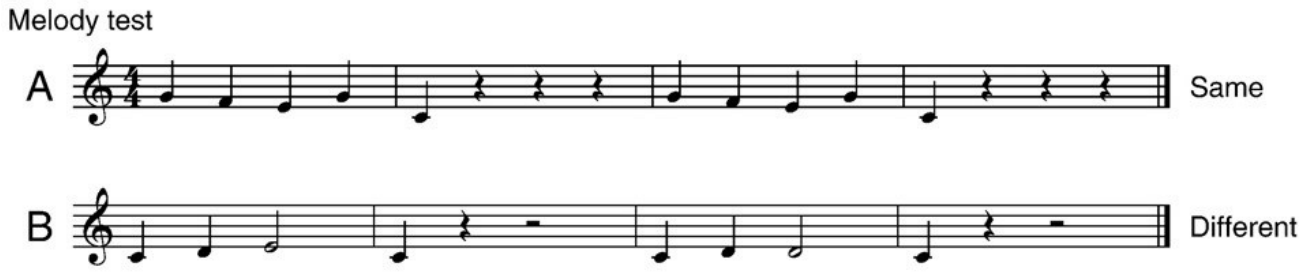
Subjects

Same subjects from experiment 1 also participated in Experiment 3.

Apparatus and procedure (adapted from Wallentin et al., 2010)

The experiment was conducted in a soundproof phonetic lab. In this task, participants judged whether the second melodic phrase was the same as or different from the first one as shown in Fig. 2. Before the experimental phase, 2 practice trials with immediate feedback were introduced for familiarization. The main test contained 52 auto-paced trials played on a sample grand piano without any feedback consisted of simple notes, such as half notes, quarter notes and eighth note. Half of the trials were identical. Each phrase had 3 to 8 tones, and lasted at least two bars played at a tempo of 100 bpm. In the "different" trials, the two melodic phrases differed maximally in one note, and contour violation was composed in half of the "different" trials. In these 52 trials, 25 of them consisted of non-diatonic tones, while the rest 27 contained 20 trials composed in major key, and 7 in minor key. The order of the trials was fixed. Subjects were informed about the procedure verbally. They were asked to respond as fast as possible to each trial by crossing the yes/no box on an answer sheet. The response time was 1000ms. Only results from the experimental phase were collected.

Figure 2. Example trials from the Musical Ear Test (MET). For each pair of melodies the subject made a same/different judgment (Wallentin et al., 2010).



4.4 Experiment 4: the Musical Ear Test-rhythm discrimination

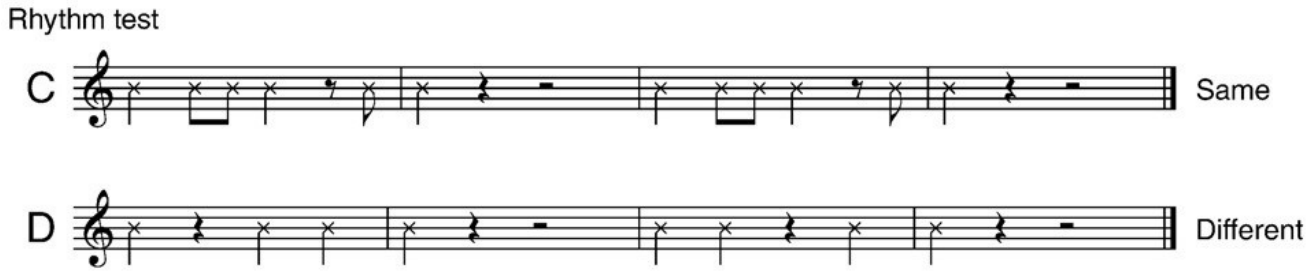
Subjects

Same subjects from experiment 1 also participated in Experiment 4.

Apparatus and procedure (adapted from Wallentin et al., 2010)

The procedure was exactly the same as in Experiment 3. In this task, participants judged whether the second rhythmic phrase was the same as or different from the first one as shown in Fig. 3. The auditory stimuli in this experiment contained 52 auto-paced trials of wood block sound without any feedback, therefore no pitch changes were involved. Each trial had 4 to 11 beats, and lasted at least two bars played at a tempo of 100 bpm. In these 52 trials, 21 of them had triplets to increase the complexity, while the rest 31 had even subdivisions of the beat. The "different" trials had maximally one beat violation. 37 trials began on the first beat of a bar. The order of the trials was fixed. The response time was 1000ms. Only results from the experimental phase were collected.

Figure 3. Example trials from the Musical Ear Test (MET). For each pair of rhythmic the subject made a same/different judgment (Wallentin et al., 2010).



As seen above, the experimental phase consisted of 4 tasks separated in 2 sessions, namely Chinese session and music session. Participants spent approximately an hour to complete all of the tasks (3 pretests requiring 10 minutes altogether, and each task lasted 10 minutes in the experimental phase). The order of the sessions was counterbalanced. As Chinese monosyllabic task was easier for the participants to get familiar with how the experiment should go, it always preceded bisyllabic task, and melody discrimination always preceded rhythm discrimination (i.e. half of the participants in each group received monosyllabic, bisyllabic, melody, and rhythm tasks in this order; the other half received melody, rhythm, monosyllabic, and bisyllabic tasks in this order). All participants were given a 10-minute break before proceeding to the next session to prevent fatigue.

4.5 Data analysis

Before running the statistical analysis, all raw scores from each task were converted into

percentage scores. All the forced choice tests were simply marked as correct or incorrect. Correct answers referred to “same” responses to the same pairs, and “different” responses to the different pairs. In the discrimination tasks, the percentage equaled to the correct answers divided by the number of total trials. The missed trials that the participants failed give an answer within the response window were considered wrong answers. In order to discover whether there was significant difference between the controls and dyslexics concerning pitch and rhythm perception, one-way ANOVA with 95% level of confidence intervals was conducted. Two groups of participants (dyslexics and non-dyslexics) were set as independent variables, and all tasks in the pretests and in the experimental phase were set as dependent variables. For the correlation between ungrouped (that controls and dyslexics were not divided into two groups) literacy skills and pitch/rhythm discrimination tasks, Pearson correlation significance was analyzed with 95% confidence intervals.

Section 5. Results

Pretests

One non-dyslexics and 3 dyslexics did not take the pretests, resulting in 12 and 11 participants in the control group and the dyslexic group, respectively. Table 2 showed the mean pretest scores and age of the two groups. As expected, dyslexics had significantly lower scores compared to controls in EMT and de Klepel, but not in WAIS-III, meaning that dyslexics have poor reading and spelling abilities but normal communicative skill and intelligence as the controls [EMT: $F(1, 21) = 28.524$, $p < .001$, two-tailed; de Klepel: $F(1, 21) = 163.408$, $p < .001$, two-tailed; WAIS-III $F(1, 21) = 1.395$, $p > .05$, two-tailed)]. Fig. 4 showed the mean scores of the two groups from the pretests.

Chinese monosyllabic and bisyllabic discrimination

All subjects participated in the Chinese tasks, thus the number of subjects in the control and dyslexic group was 13, and 14, respectively. The difference in mean accuracy rate between the two groups was not significant in any task [Monosyllabic pairs: $F(1, 25) = .719$, $p > .05$, two-tailed; Bisyllabic pairs: $F(1, 25) = .098$, $p > .05$, two-tailed]. Table 3 showed the mean accuracy rate and standard deviation of both groups in each lexical pitch discrimination tasks.

Melody and rhythm discrimination

All subjects participated in the musical tasks, thus the number of subjects in the control and dyslexic group was 13, and 14, respectively. The difference in mean accuracy rate between the two groups was not significant in any task [Melody discrimination: $F(1, 25) = .034$, $p > .05$, two-tailed; Rhythm discrimination: $F(1, 25) = .016$, $p > .05$, two-tailed]. Table 4 showed the mean accuracy rate and standard deviation of both groups in each music discrimination tasks. Fig. 5 showed the mean accuracy rates of the two groups from experiment 1-4.

The relation between reading and pitch perception skills

Pearson's r was calculated for the correlation between EMT, Klepel and the pitch and rhythm tasks. The data were not grouped into dyslexics and non-dyslexics. Rather, scores of EMT and de Klepel (n=23) were collected to directly compare with the performance on pitch-related tasks. The correlation between these two pretests and pitch/rhythm perception skills was weak (all statistic results indicated p >.05, two-tailed). Table 5 showed the r values of the correlation among the literacy skills and pitch/rhythm discrimination tasks. This correlation is consistent with the group-level analysis in the pitch and rhythm discrimination tasks.

Table 2. Mean and standard deviation of age, and mean scores from verbal competence, de Klepel, and EMT of the control and dyslexic groups.

		Age (in years)	EMT (%)	de Klepel (%)	WAIS-III (%)
Controls	Mean	22.9	0.73	0.90	0.98
(n=12)	S.D.	2.81	19.129	12.060	9.342
Dyslexics	Mean	22.7	0.29	0.26	0.95
(n=11)	S.D.	2.92	20.260	12.136	5.774
	Significance	p > .05	p < .01	p < .01	p > .05

Table 3. Mean accuracy rate and standard deviation of the control and dyslexic groups from Experiment 1-2 .

		Monosyllabic pairs (%)	Bisyllabic pairs (%)
Controls	Mean	0.86	0.85
(n=13)	S.D.	9.110	10.548
Dyslexics	Mean	0.83	0.86
(n=14)	S.D.	10.281	7.600
	Significance	p > .05	p > .05

Table 4. Mean accuracy rate and standard deviation of the control and dyslexic groups from Experiment 1-2.

		Melody discrimination (%)	Rhythm discrimination (%)
Controls	Mean	0.73	0.77
(n=13)	S.D.	7.338	7.557
Dyslexics	Mean	0.73	0.77
(n=14)	S.D.	8.979	9.061
	Significance	$p > .05$	$p > .05$

Table. 5 Correlation between reading skills (EMT and de Klepel) and pitch/rhythm discrimination tasks

	EMT	De Klepel
	r values	r values
Monosyllabic task	.32	.26
Bisyllabic task	.04	.01
Melody task	-.01	-.13
Rhythm task	.31	.24

Figure 4. Mean scores of the two groups from the pretests

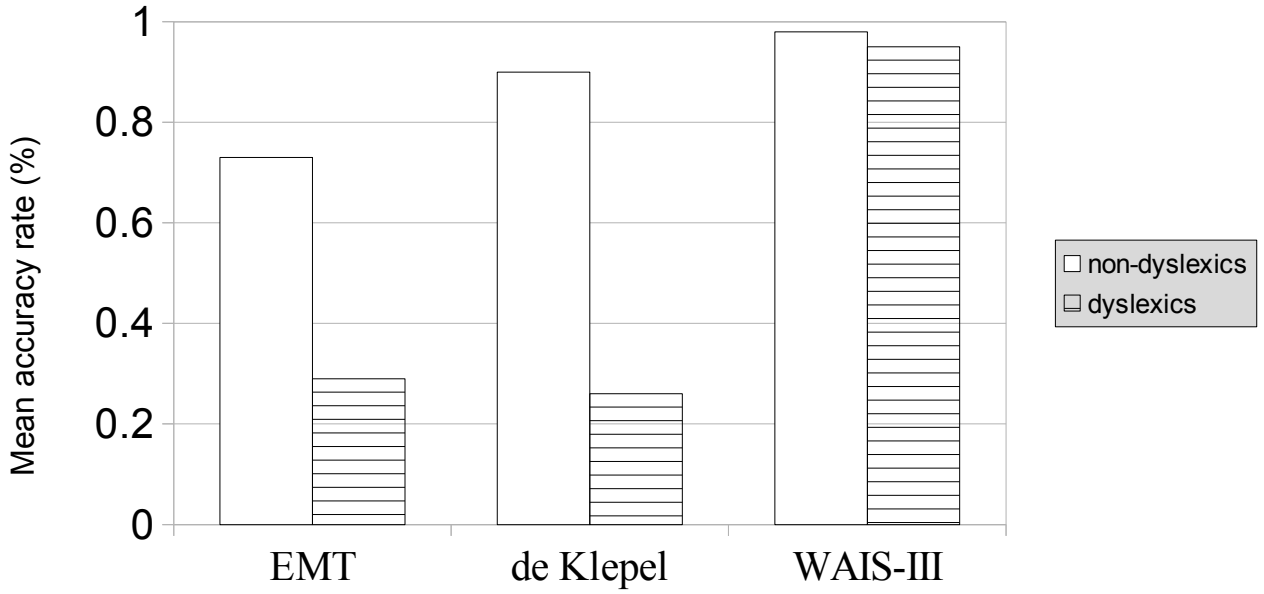
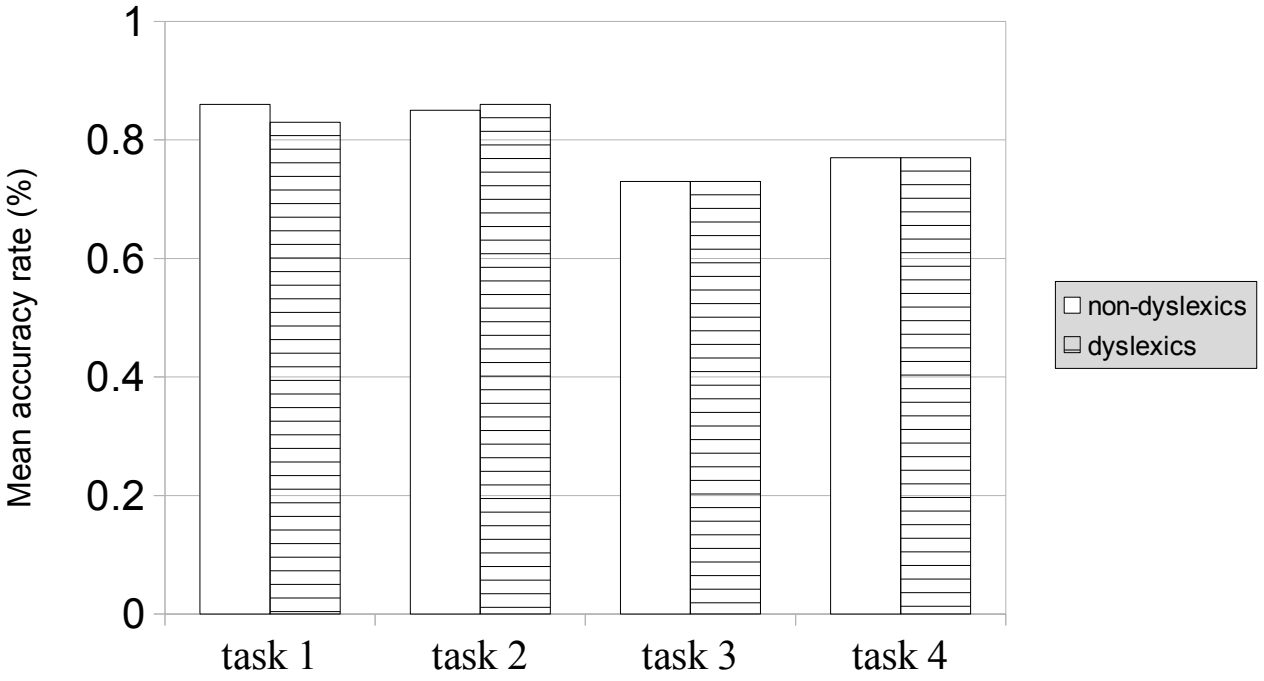


Figure 5. All mean accuracy rates of the two groups from Experiment 1-4



Section 6. Discussion

The current research failed to find group-level difference among adult Dutch dyslexic and normal-reading participants on musical pitch, lexical tone, and musical rhythm discrimination tasks. We propose that pitch perception skills across domains and rhythm perception skills in music may not be related to dyslexia. To account for the results of pitch perception skills in our subjects, one possible explanation might be that Dutch is a language that requires more sensitive pitch perception in speech. Although it was proposed that dyslexics may have impaired pitch perception skills in previous research (Atterbury, 1985; Baldeweg, 1999; Anvari et al, 2002), it should be noted that these experiments tested English native speakers. For example, Cutler & van Donselaar (2001) concluded that stressed syllables always have full vowels, whereas the ones in unstressed syllables are almost constantly reduced in English. On the contrary, unstressed syllables in Dutch contain full vowels. Under this view, speech pitch, being one of the prosodic features, presumably plays a more prominent role in Dutch, and Dutch speakers seemingly have developed heightened pitch sensitivity compared to other language users. This explanation needs to be further verified through more numbers of dyslexic and non-dyslexic subjects of Dutch and non-Dutch speakers in one study to determine whether Dutch speakers do have strengthened pitch processing due to Dutch phonology. It is recommended to also test both Dutch children and adults in one study to reveal whether adults exhibit enhanced pitch sensitivity.

Another possibility may be due to the age difference. Many pitch discrimination papers recruited mostly child participants (e.g. Atterbury, 1985; Anvari et al., 2002; Ziegler et al., 2011), while we tested adults. Bailey & Snowling (2002) mentioned that when dyslexic adults no longer have reading problems, it might be the case that some reading difficulties presented in childhood were compensated through learning, thus disappear after adulthood. Yet “a failure to find a difference between dyslexic adults and controls in an auditory processing task does not rule out the possibility that a deficit earlier in development compromised the development of phonological representations. Slow or delayed development of one process (albeit along normal lines) may alter the course of development of a related process in a sensitive period”. Cheung et al's (2009) study has shown that dyslexics' literacy and phonological skills are significantly worse than non-dyslexic age-matched peers, yet no difference was found between dyslexic children and reading-level matched counterparts (2 years younger than the dyslexic group). This entails that dyslexics' phonological processing development (and consequently

reading ability) is slower than age-matched children. Deficient pitch perception, likewise, might suggest that pitch perception is not yet mature in dyslexic children. The auditory development of dyslexic children may be delayed, but would become as good as the normal readers in the end. That is, after adulthood, dyslexics should be able to perceive pitch changes as similarly as non-dyslexics in both speech and non-speech domains. Therefore, the age difference might explain the inconsistency between the findings of other studies and ours. To support Bailey & Snowling's findings, dyslexic children found with impaired pitch perception should be tested again after adulthood to discover whether the perceptual impairment stays.

Thirdly, the task simplicity and difficulty might as well play a crucial role between several pitch perception studies. The structures of the deviant lexical tones in our study may have been too simple for the subjects to detect. As there was only one deviant tone in a pair of two tones and two deviant tones in a pair of four, the tasks may not have been sensitive enough to cause group-level difference compared to studies that included 4 deviant tones in 100 tone stimuli (e.g. Baldeweg et al., 1999). The tone pairs contained only two different pairs, namely T1-T4, and T2-T3. Since each Chinese tone is realized by its unique F0 contour, adding all possible tone pairs should increase the difficulty level in future study. Baldeweg and colleagues (1999) also tested adults, yet observed impaired pitch perception in dyslexics. However, they used pure tones as the pitch stimuli, whereas the current study had well-structured melodic phrases. Pure tones, for example, target at frequency discrimination, while melodic phrases have rich musical content (i.e. harmonic relation, structural patterns) that may have helped the participants to detect the pitch changes more easily. Hence, our participants might have experienced less difficulty discriminating musical pitch. Interestingly, Overy et al. (2003) also used musical melody to test English-speaking dyslexic children but concluded that dyslexics were superior in pitch perception. They noted that “pitch is also known to be processed predominantly in the right hemisphere of the brain (Zatorre, 1992), and dyslexics’ cortical abnormalities are generally thought to be focused in the left-hemisphere (Galaburda et al., 1987), thus leading to a greater reliance on the right hemisphere (West, 1991)” (2003:31). Nonetheless, we found no evidence to support the enhanced pitch perception skills in dyslexics.

To consider the outcomes rhythm perception skills in our participants, one interpretation is that not all dyslexics encounter difficulties when perceiving rapid non-speech rhythmic signals. Rather, these difficulties are only visible in a subgroup of dyslexics. Overy et al. (2003) clarified that it was a

subset of dyslexics in the study responsible for all significant errors in rapid temporal processing, and deficit in transient timing skills can lead to specific auditory perception problems (Tallal, Miller, and Fitch, 1993). This entails that if individual has difficulties processing rapid sound, rhythm perception would also be impaired since it is a part of auditory perception. Overy et al's study conforms to Marshall et al.'s (2001) study reporting that 4 out of 17 dyslexic children (24%) were found with rapid timing processing difficulties of complex tones. These observations support the assumption that only a subtype of dyslexia would experience temporal processing deficit. Using rhythmic stimuli played at 80bpm and 100 bpm is suggested to be another reason why we did not find auditory deficit in our study. As the rhythmic phrases were played at 100 bpm in the current research, Overy et al. stated that 100 bpm is closer to natural tapping speed (Clarke, 1999) than 80 bpm. As a result, acoustic stimuli with 100 bpm may be perceived more easily, and the difficulty level in our study, in turn, was decreased.

Secondly, Atterbury (1985) found that dyslexic children (7-9 years) had difficulties reproducing clapped-rhythm patterns relative to normal-achieving children. This was possibly due to the disorder of "the combination of demand for simultaneous or imitative performance and a short time delay (accompanying or immediately following)", but no impairment was observed when dyslexics discriminated rhythmic stimuli. This implies that only the (re)production processing is hindered by the deficits underlying integrative motor control skills, leaving the perception skills intact. Consequently, in an experiment that only asks dyslexics to perceive acoustic events like ours, they might not show any perceptual deficit. Since none of the subjects dropped out of the experiment or missed any trials in the music tasks, it was impossible to artificially improve the overall scores in either group. However, such auditory deficits might exist in a subset of dyslexics, and the 14 dyslexics in our study could have all been the majority of dyslexics. Having limited sample size in the current study might have explained why we failed to observe any group-level difference in all tasks. In all, the current research found no significant difference in speech and non-speech pitch discrimination, or in musical rhythm perception processing between the dyslexic and non-dyslexic groups.

Section 7. Conclusion

The findings in the present research have led to another observation that dyslexics are neither better nor worse than non-dyslexics at pitch and rhythm perception, in favor of our hypothesis 1. We did not find evidence supporting the theory that Dutch dyslexics have impaired processing of speech pitch with fast-changing elements (e.g. Chinese lexical tones) or non-speech events with well-structured patters (e.g. music). Accordingly, what underlies phonological deficit may be less likely to be the general auditory perception disorder since reading disability may stem from phonological processing deficit, rather than other auditory processes responsible for speech and non-speech pitch stimuli. It is worth investigating whether there is any fundamental neuro-cognitive differences between dyslexics and non-dyslexics in pitch perception for future research. In addition, more efforts should be made to keep track of dyslexics' developmental pattern of pitch perception to reveal whether dyslexics have a different developmental trajectory in pitch perception compared to normal readers. Individuals diagnosed with dyslexia at different age (e.g. 7-8 years, 11-12 years, or later) should be furthered divided into several groups to discover whether diagnosis at an early age helps dyslexics perceive pitch better due to early mediation. A study with rhythm perception in both music and language, as well as rhythm (re)production task in music is highly suggested in order to conclude more widely if temporal skill impairment (if at all) is domain-specific or domain-general, and whether only (re)production skill is impaired.

References

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of experimental child psychology*, *83*(2), 111-130.

Atterbury, B. W. (1985). A comparison of rhythm pattern perception and performance in normal and learning disabled readers, aged seven and eight. J*ournal of Research in Music Education*, 31, 259–270.

Bailey, P. J., & Snowling, M. J. (2002). Auditory processing and the development of language and literacy. *British Medical Bulletin*, *63*(1), 135-146.

Baldeweg, T., Richardson, A., Watkins, S., Foale, C., & Gruzelier, J. (1999). Impaired auditory frequency discrimination in dyslexia detected with mismatch evoked potentials. *Annals of neurology*, *45*(4), 495-503.

Banai, K., & Ahissar, M. (2006). Auditory processing deficits in dyslexia: task or stimulus related?. *Cerebral Cortex*, *16*(12), 1718-1728.

Besson, M., Schön, D., Moreno, S., Santos, A., & Magne, C. (2007). Influence of musical expertise and musical training on pitch processing in music and language. *Restorative neurology and neuroscience*, *25*(3), 399-410.

Besson, M., and Schön, D.(2011).“What remains of modularity?” in *Language and Music as Cognitive Systems,* eds P. Rebuschat, M. Rohrmeier, J. Hawkins, and I. Cross (Oxford: Oxford University Press), 283–291. doi: 10.1093/acprof:oso/9780199553426.003.0029

Bishop, D. V. M., Carlyon, R. P., Deeks, J. M., & Bishop, S. J. (1999). Auditory temporal processing impairment: Neither necessary nor sufficient for causing language impairment in children. *Journal of Speech, Language, and Hearing Research, 42*, 1295–1310.

Boersma P., Weenink D. (1997). Praat. Retrieved in 2012 from University of Amsterdam. Website: http://www.fon.hum.uva.nl/praat/

Breier, J. I., Gray, L., Fletcher, J. M., Diehl, R. L., Klaas, P., Foorman, B. R., & Molis, M. R. (2001). Perception of voice and tone onset time continua in children with dyslexia with and without attention deficit/hyperactivity disorder. *Journal of Experimental Child Psychology*, *80*(3), 245-270.

Brus, B. Th . & Voeten, M. J. M. (1979). Een-Minuut-Test. Vorm A en B [One minute Test]. Amsterdam: Pearson Assessment and Information B.V.

Chen, A. (2013). Universal biases in the perception of Mandarin tones: From infancy to adulthood. LOT dissertation series, 315.

Cheung, H., Chung, K. K., Wong, S. W., McBride-Chang, C., Penney, T. B., & Ho, C. S. (2009). Perception of tone and aspiration contrasts in Chinese children with dyslexia. *Journal of Child Psychology and Psychiatry*, *50*(6), 726-733.

Clarke, E. F. (1999). Rhythm and timing in music. *The psychology of music*, *2*, 473-500.

Cutler, A., & Van Donselaar, W. (2001). Voornaam is not (really) a homophone: Lexical prosody and lexical access in Dutch. *Language and speech*, *44*(2), 171-195.

Deutsch, D., Henthorn, T., Marvin, E., & Xu, H. (2006). Absolute pitch among American and Chinese conservatory students: Prevalence differences, and evidence for a speech-related critical perioda).*The Journal of the Acoustical Society of America*, *119*(2), 719-722.

Facoetti, A., Trussardi, A. N., Ruffino, M., Lorusso, M. L., Cattaneo, C., Galli, R., ... & Zorzi, M. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of cognitive neuroscience*, *22*(5), 1011-1025.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic bulletin & review*, *2*(4), 460-493.

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., ... & Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in human neuroscience*, *8*.

Forgeard, M., Schlaug, G., Norton, A., Rosam, C., Iyengar, U., and Winner, E. (2008). The relation between music and phonological processing in normal-reading children and children with dyslexia. *Music Percept.* 25, 383–390.

Foxton, J. M., Talcott, J. B., Witton, C., Brace, H., McIntyre, F., & Griffiths, T. D. (2003). Reading skills are related to global, but not local, acoustic pattern perception. *Nature neuroscience*, *6*(4), 343-344.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., and Griffiths, T. D. (2004). Characterization of deficits in pitch perception underlying "tone deafness". *Brain* 127(Pt 4), 801–810.

France, S. J., Rosner, B. S., Hansen, P. C., Calvin, C., Talcott, J. B., Richardson, A. J., & Stein, J. F. (2002). Auditory frequency discrimination in adult developmental dyslexics. *Perception & psychophysics*, *64*(2), 169-179.

Galaburda, A. M., Corsiglia, J., Rosen, G. D., & Sherman, G. F. (1987). Planum temporale

asymmetry: Reappraisal since Geschwind and Levitsky. *Neuropsychologia*, 25, 853–868.

Gordon, E. (1979). *Primary Measures of Music Audiation*. Chicago: GIA Publications.

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences*, *99*(16), 10911-10916.

Goswami, U., Wang, H. L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2011). Language-universal sensory deficits in developmental dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience*, *23*(2), 325-337

Griffiths, Y. M., Hill, N. I., Bailey, P. J., & Snowling, M. J. (2003). Auditory temporal order discrimination and backward recognition masking in adults with dyslexia. *Journal of Speech, Language, and Hearing Research*, *46*(6), 1352-1366.

Hymes, D. (1972). On communicative competence. *Sociolinguistics*, *269*, 293.

Jusczyk, P. W. (1999). How infants begin to extract words from speech. *Trends in cognitive sciences*, *3*(9), 323-328.

Kaplan, B. J., Wilson, B. N., Dewey, D., & Crawford, S. G. (1998). DCD may not be a discrete disorder. *Human movement science*, *17*(4), 471-490.

Katz, R. B. (1986). Phonological deficiencies in children with reading disability: Evidence from an object-naming task. *Cognition*, 2*2*(3), 225-257.

Kerkhoff, A., De Bree, E., De Klerk, M., & Wijnen, F. (2013). Non-adjacent dependency learning in infants at familial risk of dyslexia. J*ournal of child language*, *40*(01), 11-28.

Kuijpers, C., A. Van der Leij, P. Been, T. Van Leeuwen, M. Ter Keurs, R. Schreuder & K.P. Van den Bos. (2003). Eesproblemen in het voortgezet onderwijs en de volwassenheid. *Pedagogische Studiën*, 80, 272-287.

Lamb, S. J., & Gregory, A. H. (1993). The relationship between music and reading in beginning readers. *Educational Psychology*, *13*(1), 19-27.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. Journal of the Acoustical Society of America, 49, 467–477.

Loui, P., Kroog, K., Zuk, J., Winner, E., & Schlaug, G. (2010). Relating pitch awareness to phonemic awareness in children: implications for tone-deafness and dyslexia. *The relationship between music and language*, 58.

Magnan, A., Ecalle, J., Veuillet, E., & Collet, L. (2004). The effects of an audio-visual training program

in dyslexic children. *Dyslexia, 10*(2), 131-140.

Meng, X., Sai, X., Wang, C., Wang, J., Sha, S., & Zhou, X. (2005). Auditory and speech processing and reading development in Chinese school children: Behavioural and ERP Evidence. Dyslexia, 11, 292–310.

Mody, M. (1993). *Bases of reading impairment in speech perception: A deficit in rate of auditory processing or in phonological coding?* Unpublished doctoral dissertation, Speech and Hearing Sciences, City University of New York.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding?. *Journal of experimental child psychology*, *64*(2), 199-231.

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., and Besson, M. (2009). Musical training influences linguistic abilities in 8-year-old children: more evidence for brain plasticity. *Cereb. Cortex* 19, 712–723.

Morgan, J. L., & Saffran, J. R. (1995). Emerging integration of sequential and suprasegmental information in preverbal speech segmentation. *Child development*, *66*(4), 911-936.

Morton, J., & Jassem, W. (1965). Acoustic correlates of stress. *Language and Speech*, *8*(3), 159-181.

Morton, J., & Frith, U. (1995). Causal modelling: a structural approach to developmental psychopathology. *Manual of developmental psychopathology*, *1*, 357-390.

Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: Evidence from French. *NeuroReport*,*15*(8), 1255-1259.

Overy, K., Nicolson, R. I., Fawcett, A. J., & Clarke, E. F. (2003). Dyslexia and music: measuring musical timing skills. *Dyslexia*, *9*(1), 18-36.

Pennington, B. F., Orden, G. C., Smith, S. D., Green, P. A., & Haith, M. M. (1990). Phonological processing skills and deficits in adult dyslexics. *Child development*, *61*(6), 1753-1778.

Petkov, C. I., O'Connor, K. N., Benmoshe, G., Baynes, K., & Sutter, M. L. (2005). Auditory perceptual grouping and attention in dyslexia. *Cognitive Brain Research*, *24*(2), 343-354.

Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensori motor dysfunction?. *Current opinion in neurobiology*, *13*(2), 212-218.

Rosen, S., & Manganari, E. (2001). Is there a relationship between speech and nonspeech auditory processing in children with dyslexia? *Journal of Speech, Language, and Hearing Research, 44*, 720–736.

Schön, D, Magne C, Besson M. (2004). The music of speech: music facilitates pitch processing in language. *Psychophysiology*. 41: 341—349

Snowling, M.J. (1981). Phonemic deficits in developmental dyslexia. *Psychological Research,43,* 219-234.

Snowling, M. J. (1995). Phonological processing and developmental dyslexia. *Journal of research in reading*, *18*(2), 132-138.

Snowling, M. J. (2000). *Dyslexia*. Blackwell publishing.

Stanovich, K. E., & Siegel, L. S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology*, *86*(1), 24.

Swanson, H. L., Ashbaker, M. H., & Lee, C. (1996). Learning-disabled readers' working memory as a function of processing demands. *Journal of Experimental Child Psychology*, 6*1*(3), 242-275.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and language*, *9*(2), 182-198.

Tallal, P., Miller, S., & Fitch, R. H. (1993). Neurological basis of speech: A case of the preeminence of temporal processing. *Annals of the New York Academy of Science*, 682, 27–47.

Uterwijk, J. (2000). WAIS-III Nederlandstalige bewerking. Technische handleiding [WAIS-III Dutch version. Technical manual]. Lisse: Swets & Zeitlinger.

Van den Bos, K. P., Lutje Spelberg, H. C., Scheepstra, A. J. M. & De Vries, J. R. (1994). *De Klepel. Vorm A en B. Een test voor de leesvaardigheid van pseudowoorden* [A test for the reading ability of pseudo-words]. Amsterdam: Pearson Assessment and Information B.V

Wallentin, M., Nielsen, A. H., Friis-Olivarius, M., Vuust, C., & Vuust, P. (2010). The Musical Ear Test, a new reliable test for measuring musical competence. *Learning and Individual Differences*, *20*(3), 188-196.

West, T. G. (1991). In the mind's eye: Visual thinkers, gifted people with learning difficulties, computer images, and the ironies of creativity. Buffalo NY: Prometheus Books.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., ... & Green, G. G. R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current biology*, *8*(14), 791-797.

Zatorre, R. J. (1992). Lateralization of Phonetic and Pitch Discrimination in Speech Processing. *Science*, 256, 846–849.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: music and speech. *Trends in cognitive sciences*, *6*(1), 37-46.

Ziegler, J. C., Pech-Georgel, C., George, F., & Foxton, J. M. (2012). Global and local pitch perception in children with developmental dyslexia. *Brain and language*, *120*(3), 265-270.

Appendix A

Questionnaire

Personal information

Name:_____

Date of birth:_____

Gender: _____

Native language(s):_____

Education level:_____

E-mail address: _____

Contact number: _____

☐right-handed ☐ left-handed

☐ parents are both musicians ☐ parents are both non-musicians ☐ one of them is musician

☐ parents are both dyslexics ☐ parents are both non-dyslexics ☐ one of them is dyslexic

Have you ever been diagnosed with dyslexia? ☐ yes, at age:_____/☐no

If so, have (had) you taken any treatment/training to remediate reading difficulties? ☐ yes /☐no

Have you ever been professionally trained in music (including composition) or attended conservatory in order to become a musician? ☐ yes /☐no/☐amateur (experience in after-school/ in-school music program, choir, and student orchestra are considered amateur unless you also received private one-on-one lessons at least once a week with intensive and constant practice)

If so, at what age did you start receiving the training?_____,

how many years in total? _____, what instrument?_____.

Do you have absolute pitch? ☐ yes /☐no Do you have hearing loss? ☐ yes /☐no

Have you ever studied tone language(s) (Thai, Chinese, Cantonese, Vietnamese, etc)? ☐ yes /☐no

If so, at what age did you start learning it?_____ how many years in total? _____,

level of proficiency: ☐basic ☐intermediate ☐advanced based on listening, speaking, writing, and reading skills.

Have you ever participated in pitch perception/production experiment before? ☐ yes / ☐no

If so, what type of tone was that (music/speech/pure tone)? _____.