Research paper

Exploring the role of auditory analysis in atypical compared to typical language development

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A B S T R A C T

The relationship between auditory processing and language skills has been debated for decades. Previous findings have been inconsistent, both in typically developing and impaired subjects, including those with dyslexia or specific language impairment. Whether correlations between auditory and language skills are consistent between different populations has hardly been addressed at all. The present work presents an exploratory approach of testing for patterns of correlations in a range of measures of auditory processing. In a recent study, we reported findings from a large cohort of eleven-year olds on a range of auditory measures and the data supported a specific role for the processing of short sequences in pitch and time in typical language development. Here we tested whether a group of individuals with dyslexic traits (DT group; n = 28) from the same year group would show the same pattern of correlations between auditory and language skills as the typically developing group (TD group; n = 173). Regarding the raw scores, the DT group showed a significantly poorer performance on the language but not the auditory measures, including measures of pitch, time and rhythm, and timbre (modulation). In terms of correlations, there was a tendency to decrease in correlations between short-sequence processing and language skills, contrasted by a significant increase in correlation for basic, single-sound processing, in particular in the domain of modulation. The data support the notion that the fundamental relationship between auditory and language skills might differ in atypical compared to typical language development, with the implication that merging data or drawing inference between populations might be problematic. Further examination of the relationship between both basic sound feature analysis and music-like sound analysis and language skills in impaired populations might allow the development of appropriate training strategies. These might include types of musical training to augment language skills via their common bases in sound sequence analysis.

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1. Introduction

A number of studies have sought links between auditory processing and language ability, both in typical and atypical language development. Dyslexia, a reading and spelling disorder that cannot be explained by low intelligence or lack of educational opportunity (Lyon et al., 2003) and Specific Language Impairment (SLI), a disorder of spoken language acquisition (Tomblin et al., 1997), have both been associated with deficits of auditory processing, but results have not been consistent in either case. The significance and specificity of the links between auditory processing and phonological, language and literacy skills (called language skills hereafter) remain to be better understood in both typical and atypical development.

To test the idea that auditory deficits lead to well-documented deficits in phonological representation in dyslexia (Snowling, 2000) that would then lead to reading and spelling impairments, a number of previous studies have sought deficits in basic auditory tasks using single sounds or pairs of sounds. Deficits in association with dyslexia or reading disability have been repeatedly reported for frequency discrimination in adults (e.g. Amitay et al., 2002; France et al., 2002; McAnally and Stein, 1996) and children (Halliday and Bishop, 2006a). Similarly, deficits have been shown for the perception of frequency modulation (FM) applied to pure-tone carrier stimuli at rates of 2 Hz and 40 Hz (adults: Ramus et al., 2003; Witton et al., 1998; children: Poelmans et al., 2011).
These FM rates can be argued to be relevant to slow prosodic changes (over several hundreds of ms) and fast formant transitions (over tens of ms), respectively. Deficits in dyslexic children have also been shown for the processing of changes in amplitude, measured in the sensitivity for differences in rise time (Poelmans et al., 2011; Richardson et al., 2004). A number of studies demonstrated correlations in addition to a group difference, but typically across groups. In a re-analysis of previously published data on auditory deficits and correlations and reading abilities (Rosen, 2003) showed that these correlations would change or disappear when examined within as compared to across groups. Other studies failed to find group deficits, for instance in frequency or amplitude discrimination in dyslexic adults (Amitay et al., 2002; Hill et al., 1999), FM detection in children with dyslexia (Bishop et al., 1999) or at high risk of dyslexia (Boets et al., 2007), frequency discrimination in reading disability (Halliday and Bishop, 2006b), or backward-maskning in adolescents or children with dyslexia or specific language impairment (Rosen and Manganari, 2001; Rosen et al., 2009), contrasting the above-mentioned reports of dyslexia and also SLI (e.g. Wright et al., 1997). The success of training and intervention strategies to improve language skills based on such one- or two-sound tasks remains a matter of debate (Gaab et al., 2007; Ramus et al., 2011; Fey et al., 2011; Quen et al., 2008; Rouse and Krueger, 2004; Strong et al., 2011; Troia and Whitney, 2003), suggesting that may be the most relevant levels of auditory processing have not been tapped.

Studies going beyond basic single-sound perception showed dyslexia-related deficits in temporal-order judgements for pairs of tones (“low-high” or “high-low”) (Tallal, 1980) or other sounds (Ramus et al., 2003). Deficits in sound categorization based on more complex spectral changes in non-speech and speech sounds have been reported in children and adults with dyslexia (Vandermosten et al., 2011, 2010). A different set of studies have focused directly on the discrimination or identification of speech-type stimuli in quiet or in noise and demonstrated a significant relationship with both typical and impaired language development, including dyslexia and SLI (Watson and Watson, 1993, 2003; Ziegler et al., 2009, 2011, 2005). Studies assessing higher levels in generic, non-verbal auditory processing are rare to date, despite speech having a complex acoustic structure comprising of spectro-temporal patterns over multiple timescales, from the phoneme level (tens of milliseconds) to the sentence level (thousands of milliseconds) (Chi et al., 1999; Hickok and Poeppel, 2007; Jusczyk, 1999; Klatt, 1976; Liberman et al., 1956; Poeppel, 2003; Poeppel et al., 2004; Rosen et al., 2009; Schowniesner and Zatorre, 2009; Scott, 1982).

In a recent study of a large, non-selected cohort of 210 typically developing individuals (age 11), Grube et al. (2012) tested the relevance of pitch and rhythmic sequence processing compared to more basic tasks of single-sound processing of pitch, time and modulation to phonological language and literacy skills. Their systematic approach based on multiple levels identified short-sequence analysis in pitch and time to be more strongly correlated with language skill than basic auditory processing, supporting the notion of the link between the two domains being in part a function of acoustic complexity (Rosen, 2003). Earlier speech work has demonstrated both pitch contour and rhythm information to provide cues relevant to the parsing of the speech stream, in normal infants as well as in adults (Jusczyk et al., 1992; Smith et al., 1989). Recent work on basic pitch contour processing has reported deficits in dyslexic adults (Santurette et al., 2010), a deficit specific for the detection of local but not global changes in pitch contours in dyslexic children age 11 (Ziegler et al., 2012), as well as a specific, significant correlation for the more abstract “global” perceptual processing of transposed contours with reading ability in typically developing young adults (Foxton et al., 2003). Goswami and co-workers have looked at rhythmic amplitude modulation and musical rhythm processing in relationship to phonological language and literacy skills. The authors report group-level deficits in rhythmic amplitude modulation (rise time) and rhythmic change detection in sequences with varying degrees of musical meter in dyslexic compared to control children, in addition to significant correlations with phonological and literacy measures across groups (n = 64 in total; age 8–13). The authors further present regression analyses of metrical musical perception against basic auditory measures that could indicate group membership (Goswami et al., 2013, 2002; Huss et al., 2011; Overy et al., 2003; Richardson et al., 2004).

The present study tests for deficits and correlations with language skills for the same tasks of auditory processing used by Grube et al. (2012), from single-sound to sequence-based tasks, in a group of individuals with dyslexic traits (DT) compared to a group of typically developing (TD) individuals. The work tests the idea that there might be a difference in the relationship between auditory and language skills in addition to, or instead of an auditory deficit, as one possible underlying factor in atypical language development. We explore here the idea that atypical developers might be considered ‘different listeners’ rather than just ‘poor listeners’. Our a-priori hypothesis is that there might be a difference in the linking between auditory and language skills, which would predict a weaker relationship between aspects of sound perception and language skills than in typical development. Alternatively, the possible finding of stronger correlations would suggest a tighter coupling in language and auditory skills as a possible compensatory strategy for language-specific impairments. This is a first exploratory attempt, in a group of 28 individuals with dyslexic traits, who were part of the same whole-year group as the control group of 173 typically (TD) individuals. The TD group was drawn from the unimpaired group described in Grube et al. (2012). The auditory tasks ranged from single-sound to sound-sequence processing and assessed the domains of pitch, time and timbre. The language-based assessment of language skills used a set of six standardized tests of reading, spelling and related measures. Intellectual skills were also measured, as a potential confound and in order to identify individuals with dyslexic traits. The objective was, firstly, to test for the presence or absence of group differences in auditory skills and, secondly, to test for differences and commonalities in the links between auditory and language skills in the two groups.

2. Methods

2.1. Subjects

The present study sought differences in a group of individuals with dyslexic traits, the DT group (n = 28, 17 male; mean age = 11.46 years, SD = 0.26), compared to a typically developing (TD) group (n = 173, 67 males; mean age = 11.48 years, SD = 0.30). The DT group comprised individuals with dyslexic traits identified by a significant discrepancy between their full-scale IQ (FSIQ) and literacy-related scores, in accord with the DSM-IV (Diagnostic and Statistical Manual of Mental Disorders) discrepancy criterion for dyslexia. Language and intellectual skills were measured using standardized tests (described in Section 2.2) that transform the raw scores into age-independent standard scores with a normal distribution with a mean of 100 and standard deviation of 15. Sixteen individuals fulfilled the DSM-IV criterion of reading and spelling scores that were both lower than their FSIQ by 15 or more standard points; another 12 individuals had a reading or a spelling score plus at least one associated standardized language measure (non-word reading, backward digit recall) with such a discrepancy of 15 or more standard points relative to their FSIQ. Both groups
were part of a whole-year group (year 7; mean age 11.1 years, SD 0.3 years; \( n = 238 \); 99 male) at the comprehensive, non-selective St. Thomas More Catholic School, Gateshead, UK. The TD group consisted of 173 of the 210 individuals studied by Grube et al. (2012), excluding individuals with a full-scale IQ below 85 (1 SD from the mean; \( n = 34 \)) or a verbal or non-verbal IQ below 70 (2 SD from the mean; \( n = 1 \)), and those diagnosed with ASD/ADHD (\( n = 2 \)) in order to provide a more comparable control group for the DT group. The research was approved by the ethics committee of Newcastle University.

2.2. Neuropsychological testing of language and intellectual skills

Tests of language and intellectual ability were administered one-to-one in a quiet room over a 1-hour period on a different day to the auditory sessions. As previously described in Grube et al. (2012), the six standardized tests of phonological language and literacy skills (here referred to as language tasks) were: 1) written rhyme decision (the child reads a list of pairs of words and decides silently for each one whether they rhyme or not: Psycholinguistics Assessment of Language Processing in Aphasia, PALPA (Kay et al., 1992)); 2) spelling (the child writes down the spelling of spoken words: Wechsler Individual Achievement Test, WIAT-II uk (Wechsler, 2005)); 3) word reading (the child reads aloud a list of written words: WIAT-II uk); 4) non-word reading (the child reads aloud a list of nonsense written words: WIAT-II uk – “pseudoword decoding”); 5) non-word repetition (the child repeats back spoken nonsense words: Working Memory Test Battery for Children, WMTB-C – “nonword list recall” (Gathercole and Pickering, 2001)); 6) backward digit recall (the child reproduces in reverse order sequences of digits: WMT-C). Full-scale IQ (FSIQ) was assessed by the Wechsler Abbreviated Scale of Intelligence (WASI (Wechsler, 2005)), which includes 2 verbal and 2 non-verbal subtests. Verbal IQ is assessed by the vocabulary subtest (the child orally defines spoken words) and the similarities subtest (the child orally describes the similar concept that binds together two spoken words). Non-verbal IQ is assessed by the block design subtest (the child produces a copy of a 2D pattern with coloured blocks) and the matrix reasoning subtest (the child indicates a picture from a selection that will complete the pattern presented).

2.3. Auditory testing

Auditory testing was performed in a quiet classroom environment, one class at a time (\( n = 16–30 \)). The class was instructed by the lead researcher for one task at a time; task understanding and compliance were assured by group-level instructions, practice trials, and questions addressed to the whole class, for which each individual was required to raise their hand according to what they perceived to ensure as best as possible that the children understood the task. Each pupil then performed the task independently on their own, running Matlab\textsuperscript{\textregistered}-based standalone executables on individual setups (computer, external soundcard, closed headphones). Four pitch perception tasks, 4 rhythm and timing tasks, and 4 tests of timbre perception based on modulation (Fig. 1) were performed in three sessions of 60–75 min each. All tasks used a

![Fig. 1. Schematic depiction of auditory tasks as in Grube et al. (2012). For each task, one reference and one target example are illustrated with their relevant features; abscissa and ordinate depict time and frequency, respectively (throughout but with varying scales). a Pitch: basic change detection (pairs of tones); local and global pitch change detection (short sequences); key violation: not shown. b Rhythm: single time-interval duration discrimination (pairs of tones); isochrony-deviation detection (short sequences); regularity detection and metrical pattern discrimination (longer sequences). c Modulation: 2 Hz and 40 Hz frequency modulation (FM) detection; dynamic spectral modulation detection (DM) and rate discrimination (DM rate) (dark stripes representing peaks moving across frequency and time). Abbreviations: cpo, cycles per octave; cps, cycles per second. Note that the basic change detection in pitch, the duration discrimination, and the FM and DM detection and discrimination tasks would be classified as basic, single-sound based tasks, as opposed to the remaining tasks testing aspects of sequence analysis in pitch and time.](image-url)
two-alternative forced-choice paradigm. Most tasks used a 2- down-1-up adaptive tracking algorithm estimating the 70.9% cor-
drect threshold (Levitt, 1971), except the three pitch sequence tasks.
Those had fixed difficulty levels with the number of correct re-
sponses being the most immediate outcome measure and used in
the present analysis; for further task details beyond the de-
scriptions below see (Grube et al., 2012).

2.3.1. Pitch (Fig. 1a)
The first three pitch tasks used 250-ms pure-tones, the fourth
used synthetic-piano melodies. The basic pitch change detection task
required the subject to indicate which of two pairs of pure-tones
included a change in frequency. The local and global change detect-
tion tasks (40 trials each, same-different) required the subject to
indicate whether two four-tone sequences were “the same or
different” (adapted from Foxton et al., 2003). In the local task, the
change in frequency of one note preserved the patterns of “ups and
downs”, but not in the global version the change in note caused also
a change in melodic pattern. The key violation detection task from
the Montreal Battery for the Evaluation of Amusia (Peretz et al.,
2002; Rosen, 1992; Scott, 1982) and musical beats (Drake et al.,
2003) required the subjects to indicate whether two melodies
were “the same or different”, with the change in one note violating
the key structure. The first three tests task the perception of pitch
changes found in either speech or music, whilst the fourth is spe-
cific to the tonal structure of Western music.

2.3.2. Rhythm (Fig. 1b)
All four rhythm and timing tasks (Grube et al., 2010) used 500-
Hz 100-ms pure-tones. The basic, single-interval task required
subjects to indicate which of two tone pairs comprised the “longer
gap”. In the isochrony-deviation detection task, subjects were
required to indicate which of two otherwise isochronous five-tone
sequences contained a lengthening or “extra gap”. In the irregularity
detection task, subjects were required to indicate which of two
nine-tone sequences was “overall more regular”. The reference had
an average irregularity of ±30%, due to shortening or lengthening of
individual intervals by 15–45% each, rendering the beat imper-
ceptible (Madison and Merker, 2002). The target had 0% irregularity
initially, which increased adaptively. In the metrical pattern discrimina-
tion task, subjects were required to decide which of three
rhythmic sequences was “different, or wrong” due a distortion in
the rhythm. The reference had a metrical beat of 4 induced purely
by the temporal spacing of 7 tones, with phenomenally accented
tones occurring on each of the 4 intended down-beat locations,
following Povel and Essens (1985)’s behavioural observations
model of metrical beat strength. To minimize stimulus uncertainty,
an extra reference was presented first. The target (third or second)
had a change in timing such that the long intervals were no mul-
tiples of the underlying beat: the pattern would sound “wrong”.
Two intervals were shortened and two lengthened (by the same
percentage and thus cancelling out in total sequence length), with
the four available combinations applied in rotating manner (for
more details see Grube and Griffiths, 2009). Across tasks, inter-
onset-intervals ranged from 180 to 660 ms, corresponding to
time intervals between stress events in speech (Grabe and Low,
2002; Rosen, 1992; Scott, 1982) and musical beats (Drake et al.,
2000; London, 2004).

2.3.3. Timbre (Fig. 1c)
The four tasks of timbre perception included two FM detection
tasks, implicated in reading ability previously (Talbott et al., 2000;
Witton et al., 1998), plus dynamic-modulation (DM) detection
and discrimination tasks based on spectral-temporal modulations
relevant to speech (Chi et al., 1999; Schonwiesner and Zatorre,
2009). In the FM detection tasks, subjects were required to
identify a tone modulated at a rate of 2 Hz, sounding “ringing or
wobbly” or 40 Hz, sounding “rough” against a “flat-sounding” un-
modulated 500-Hz reference. Tone duration was 1000 ms including
20-ms gating times. The threshold was measured in modulation
index [MI, defined as the ratio of maximum frequency deviation
(Hz) to modulation frequency (Hz)] was 3.5 for the 2 Hz FM
equalling ±7 Hz maximum frequency deviation for the carrier) and
0.16 for the 40 Hz FM (equalling ±6.4 Hz maximum deviation).
In the DM detection task, subjects discriminated a modulated
(“alien or laser-like”) target sound against an unmodulated refer-
ence. Sounds were composed of 100 logarithmically spaced com-
ponents per octave, over a range from 250 to 4 kHz, whose
amplitudes were sinusoidally modulated dynamically in frequency
(spectral) and time (temporal) with a rate of 1.5 cycles per octave
(cpu) and 8 Hz, respectively. In the DM discrimination task, subjects
discriminated a target sound with a higher spectral modulation
density (in cpu) against a reference with a spectral modulation rate
of 1.5 cpu, and a temporal modulation rate of 8 Hz, at a modulation
depth of 0.75. Stimulus duration was 1000 ms and amplitude peaks
were moving up in frequency over time.

2.4. Statistical data analysis
The data from the DT group were analysed in comparison to
those from the TD group. A small number of data points were
missing due to occasional absence or failure to complete a test.
Within the DT group, one out of the 28 participants had no spelling
score; one had no rhyme decision, non-word repetition or back-
ward digit recall score; one missed three out of four rhythm tasks;
three missed one or more of the modulations tasks. Within the TD
group, there was an average of 7% missing per measure. Each
analysis was performed on all of the available data.

Firstly, we tested for group differences in auditory, language,
and intellectual ability scores. Significant between-group differ-
ces were determined using the Mann–Whitney U-Test, with
Bonferroni correction applied for the testing for differences in
multiple measures in parallel (auditory, 12; language, 6; intellec-
tual, 3; total, 21).

Secondly, we tested for correlations between auditory and lan-
guage measures and group differences in correlations. Correlations
were estimated with Spearman’s rho, as a number of measures
showed a significant deviation from a normal distribution using the
Lilliefors version of the Kolmogorov–Smirnoff Test for composite
normality (for descriptive statistics see Tables 1 and 2). Correlations
were in all cases corrected for effects of non-verbal IQ, which was
partialed out. As in Grube et al. (2012), a one-tailed Spearman’s rho
was used as a general, positive correlation between auditory and
language skills was predicted. Bonferroni correction was applied to
avoid false-positives for the testing of multiple measures in parallel.
Differences in the correlations in the DT group compared to the TD
group were tested statistically using bootstrapping analysis using
1000 iterations. On each iteration, the Spearman’s rho correlation
coefficient between the two variables of interest was obtained from
a randomly chosen TD subsample the same size as the DT group.
The difference in correlation coefficient between the DT and the TD
group was tested for significance at the level of p ≤ 0.05 (two-
tailed) by z-score evaluation of the DT group’s rho value compared
to the 1000 rho values obtained from the bootstrapping carried out
for the TD group: z > 1.96 and z < -1.96, for significantly higher or
lower, respectively. The same z-score based evaluation was carried
out for the mean correlation coefficient across language tasks, in
order to obtain one overall measure of correlation for each of the
auditory tasks. The evaluation of correlation coefficients was per-
formed only after partialling out non-verbal IQ in order to avoid any
effect of the group difference in IQ.
FM detection; 40 Hz FM detection; DM (dynamic spectral modulation) detection; DM rate discrimination. Shown are the median, mean deviation from the median (MAD), and duration discrimination; isochrony deviation detection using short sequences; regularity detection using longer sequences; metrical pattern discrimination. Modulation: 2 Hz. Pitch: basic change detection using tone pairs; local and global pitch change detection using short sequences; key violation using musical melodies. Rhythm: single-interval regularity task. We report median and MAD, as the majority of measures showed a significant deviation from a normal distribution (*significant deviation at the level of \(p < 0.05\)). The significance level for between-group comparisons is given as the uncorrected \(p\)-value from the Mann–Whitney \(U\)-Test, given alongside are \(U\) and \(z\) values; none of the comparisons yielded a trend in the same direction of better performance in the DT group compared to the TD group.

### Table 1

| Type                        | Typically developing (TD) | Dyslexic traits (DT) | Significance (p value) |
|-----------------------------|---------------------------|----------------------|------------------------|
|                             | Median | MAD | Range | Median | MAD | Range |                      |
| Pitch Basic change (thr. in semitones) | 0.85* | 0.62 | 0.07–2.45 | -0.60* | 0.61 | 2.43–0.22 | n.s. |
| Local change (score correct) | 29*    | 4.04 | 14–39 | 28.5  | 3.92 | 17–37  | n.s. |
| Global change (score correct) | 33*   | 4.65 | 16–40 | 34.0* | 4.14 | 16–38  | n.s. |
| Key violation (score correct) | 21*   | 3.18 | 11–30 | 22.0  | 2.21 | 15–28  | n.s. |
| Rhythm Single-interval duration (thr. in %) | 34.0* | 20.26 | 4.0–118.0 | 33.0* | 14.74 | 14.4–99.0 | n.s. |
| Isochrony deviation (thr. in %) | 15.0*  | 7.78 | 3.3–59.0 | 14.0*  | 1.8 | 3.6–56.33 | n.s. |
| Regularity (thr. in %) | 15.75* | 4.33 | 0.5–25.0 | 17.7  | 3.6 | 3.5–24.0 | <0.01 |
| Metrical patterns (thr. in %) | 21.0*  | 8.98 | 2.0–62.0 | 18.5* | 9.02 | 2.0–63.0 | n.s. |
| Modulation 2 Hz FM (thr. in MI) | 1.68* | 0.57 | 0.62–3.44 | 1.92* | 0.69 | 0.79–3.44 | (0.056) |
| 40 Hz FM (thr. in MI) | 0.074* | 0.022 | 0.028–0.157 | 0.071* | 0.024 | 0.05–0.154 | n.s. |
| DM depth (thr. in MD) | 0.158* | 0.050 | 0.0–0.696 | 0.131 | 0.041 | 0.058–0.338 | <0.01 |
| DM rate (thr. in cpo) | 1.0*   | 0.694 | 0.0–3.53 | 0.78* | 0.74 | 0.15–3.5 | n.s. |

Pitch: basic change detection using tone pairs; local and global pitch change detection using short sequences; key violation using musical melodies. Rhythm: single-interval duration discrimination; isochrony deviation detection using short sequences; regularity detection using longer sequences; metrical pattern discrimination. Modulation: 2 Hz FM detection; 40 Hz FM detection; DM (dynamic spectral modulation) detection; DM rate discrimination. Shown are the median, mean deviation from the median (MAD), and the range (min to max). Except for three of the pitch tasks that were based on same-different paradigm with fixed difficulty-levels and evaluated in terms of the score correct, all other values correspond to thresholds for detecting an adaptively adjusted difference between the target and the reference. Note that for most of the measure therefore lower values (thresholds) indicate better performance, except for the three pitch tasks using score correct and the regularity detection task (where the target has an initial value of 0% irregularity that is adaptively changed to approach the reference value of 20%). The thresholds for the rhythm task, were measured as the proportion change in time intervals (which varied in their absolute duration in ms) for the single-interval, isochrony deviation and metrical task, and as the mean jitter value for the target in the regularity task. We report median and MAD, as the majority of measures showed a significant deviation from a normal distribution (Lilliefors Kolmogorov–Smirnoff test; *significant deviation at the level of \(p < 0.05\)). The significance level for between-group comparisons is given as the uncorrected \(p\)-value from the Mann–Whitney \(U\)-Test, given alongside are \(U\) and \(z\) values; none of the comparisons yielded a trend in the same direction of better performance in the DT group compared to the TD group.

### Table 2

| Type                        | Typically developing (TD) | Dyslexic traits (DT) | Significance |
|-----------------------------|---------------------------|----------------------|--------------|
|                             | Median | MAD | Range | Median | MAD | Range | \(p\) value |
| Rhyme decision (PALPA) | 55*    | 4.63 | 35–66 | 53   | 5.78 | 34–62 | <0.05 |
| Spelling (WIAT) | 104    | 9.46 | 73–128 | 88   | 8.07 | 68–111 | **0.001** |
| Word reading (WIAT) | 103    | 7.78 | 75–129 | 96   | 6.57 | 77–115 | **0.001** |
| Non-word reading (WIAT) | 103*   | 8.0 | 71–121 | 95.5 | 8.64 | 65–109 | **0.001** |
| Non-word repetition (WMTB-C) | 97    | 16.65 | 57–145 | 97   | 14.26 | 65–145 | 0.956 |
| Backward digit recall (WMTB-C) | 105*   | 12.36 | 75–143 | 98   | 12.59 | 68–140 | <0.05 |
| Verbal IQ (WASI) | 102    | 8.24 | 77–132 | 109.0 | 11.46 | 78–133 | **0.001** |
| Non-verbal IQ (WASI) | 100.5  | 8.47 | 75–138 | 111.5 | 7.18 | 86–126 | **0.001** |
| Full-scale IQ (WASI) | 100.5* | 7.09 | 85–127 | 112.5 | 8.25 | 86–133 | **0.01** |

All tests were taken from neuropsychological test batteries for children that are named in brackets by their official abbreviations; for a detailed description of tests see main text. Values displayed here are standard scores with a mean of 100 and standard deviation of 15 for all the tests except rhyme decision (max. 66). We report median and MAD, as the majority of measures showed a significant deviation from a normal distribution (*significant at the level of \(p < 0.05\); Lilliefors Kolmogorov–Smirnoff test). The significance level for between-group comparisons is given as the uncorrected \(p\)-value from the Mann–Whitney \(U\)-Test, given alongside are \(U\) and \(z\) values; comparisons surviving Bonferroni correction for multiple comparisons are marked in bold. Abbreviations: PALPA, Psycholinguistics Assessment of Language Processing in Aphasia; WIAT, Wechsler Individual Achievement Test; WMTB-C, Working Memory Test Battery for Children; n.s., non-significant.

### 3. Results

#### 3.1. Auditory, language and literacy, and intellectual ability scores

Amongst the twelve auditory measures of pitch, time and rhythm and timbre perception, no significant deficit was found in the DT group compared to the TD group (Table 1; Fig. 2). The one task on which the DT group performed borderline significantly poorer than the TD group was 2-Hz FM detection (\(p = 0.056\) before Bonferroni correction, \(U = 1917\), \(z = 1.91\); Mann–Whitney \(U\)-Test). The only significant differences observed between groups were in fact two comparisons with effects in the other direction reflecting better performance: regularity as well as DM detection thresholds were both lower in the DT compared to the TD group (both \(p < 0.01\), not surviving Bonferroni correction; \(U = 3217\) and 3140, \(z = 2.61\) and 3.14; Mann–Whitney \(U\)-Test). A few other measures showed a trend in the same direction of better performance in the DT compared to the TD group, but did not approach significance. There is the possibility of missing a true effect due to the small sample size of the DT group; in order to find a significant effect this group would ideally be of similar size (>130) to the TD group. Moreover, we use Bonferroni correction for multiple comparisons. However, the trend toward better performances in the DT compared to the TD group, with the exception of 2-Hz FM detection suggests that a group-level deficit in auditory processing is unlikely (Fig. 2).

Amongst the language measures, a highly significant difference between the TD and DT groups was found for spelling, reading and non-word reading, with lower scores being achieved by the DT group (all three with \(p < 0.001\) and surviving Bonferroni-correction for multiple comparisons; \(U = 1229\), 1626 and 1799; \(z = –5.21\), –4.16, and –3.58; Mann–Whitney \(U\)-Test; Table 2; Fig. 3). In addition, there was a significant effect of lower scores in the DT compared to the TD group for the rhyme and backward digit recall tasks (\(p < 0.05\), not surviving Bonferroni correction; \(U = 1874\) and 2021; \(z = –2.32\) and –2.30; Mann–Whitney \(U\)-Test). The one task showing not even the slightest trend for poorer performance in the DT compared to the TD group was that of non-word repetition, which is the task relying most crucially on auditory information.
A highly significant difference between TD and DT groups was further found for the verbal, non-verbal, and full-scale IQ, where higher scores were achieved by the DT than the TD group (all three, \( p < 0.001 \) and surviving Bonferroni-correction; \( U = 3696, 4158 \) and 4158; \( z = -3.04, 4.66 \) and 4.66; Mann–Whitney \( U \)-Test; Fig. 3). In order to test whether the absence of an auditory deficit in the DT group might be related to the difference in IQ, a between-group comparison was performed for a closely matched subsample of TD individuals (matched in gender as well as FSIQ mean and variance), and in addition by testing for correlation between the auditory measures and IQ. No significant effects of IQ were found.

### 3.2. Correlations between auditory and language skills

The main objective of this study was to seek deviations in the pattern of correlations between auditory and language skills in the DT group compared to the TD group, which tests the hypothesis that dyslexia may not simply be a function of auditory impairment but associated with differences in the relationship between auditory and language skills. Correlations were analysed between the task-specific measures of auditory and language skills (Tables 3 and 4), and evaluated in comparison to those observed in the TD group after partialling out non-verbal intelligence (Tables 4 and 5).

The correlations observed in the TD group were very similar to those reported by Grube et al. for the more inclusive group (2012), i.e. very little affected by the application of a lower IQ limit to match the DT group and excluding three subjects with ASD/ADHD in the present analysis. We mention in the text those correlations within the DT group that had a \( \rho \geq 0.22 \) (i.e. explaining at least 5% of the variance) after partialling out non-verbal intelligence, and were significant at the level of \( p < 0.05 \) before Bonferroni correction, following the same criteria as in our previous report (Grube et al., 2012). Whilst Bonferroni correction is the most conservative method of avoiding “false positives” due to multiple comparisons, the exploratory nature of the present study and the comparison of a relatively small sample to a relatively large one support an inclusive presentation over an overly strict exclusive one which may overlook potential true correlations due to lack of power. We tested for significant differences in correlations in the DT vs. TD group by bootstrapping of TD subsamples for those correlations that fulfilled the criteria (\( p \leq 0.05 \) and \( \rho \geq 0.22 \)) in at least one of the groups, and for the mean correlation coefficients across language measures for those auditory measures that showed at least one such significant individual correlation. Performance on the two pitch tasks was strongly correlated in both groups (TD: \( \rho = 0.69, p < 0.001, n = 164 \); DT: \( \rho = 0.49, p < 0.01, n = 28 \)) and the correlations with language skills might be due to a common mechanism of pitch sequence processing. To assess such a mechanism, we used principle component analysis to extract the first component as a combined score, which explained 84% and 76% of the variance in the TD and the DT group, respectively, and analysed also the correlations for this combined measure.

Whilst significant correlations between auditory and language measures in the TD group were predominantly found for the three tasks of short-sequence analysis in pitch and time (Table 5; see also Grube et al., 2012), the DT group showed a somewhat different pattern. A tendentious relative decrease in correlations was seen for the measures of short-sequence processing, i.e. the local and global pitch sequences and the isochrony tasks. The largest, near-significant decrease in correlation compared to the TD group (according to bootstrapping analyses on 1000 subsamples matched in size to the DT group) was that for the correlation between the local change-in-pitch sequence tasks and non-word reading (\( z = -1.91 \)). Conversely and more strikingly, there were a number of significant, moderate correlations with \( \rho \) values >0.3 in the DT group that were either lower or absent in TD group. Specifically, those were

**Fig. 2.** Raw auditory data for the group of individuals with dyslexic traits (black open circles) compared to the larger control group of typically developing individuals (grey filled circles). a Pitch; b Rhythm; c Modulation. Individual scores are plotted in the order of ability banding along the abscissa, using the same subject index of 1–238 as Grube et al., 2012. Group medians and mean absolute deviations (see Table 1) are shown by dots with error bars at the far right within each subplot. Note that for all of the measures for which lower values (thresholds) indicate better performance, i.e. all measures expect for the three pitch tasks using score correct and the regularity detection task, signs were reversed so that in all plots “higher up” means “better”. Abbreviations: thr, threshold.
found for the auditory single-sound tasks of basic pitch-change, 2-Hz FM detection and DM discrimination. The largest, near-significant increase in correlation compared to the TD group (according to bootstrapping analyses on 1000 subsamples matched in size to the DT group) was that for the correlation between 2 Hz FM detection and word-reading ($z_{\text{p}}$, 1.91). For both the 2-Hz FM detection and the DM discrimination task, there was an overall increase with the language measures in the DT compared to the TD group, reflected in a significant difference in the mean correlation coefficient ($z = 2.35$ and 2.41), a measure of the overall relevance of each auditory task to language skills.

### 3.3. Results summary

The DT group showed no significant impairment in auditory processing scores compared to the TD group in any of the measures of pitch, rhythm or modulation processing; however, they had significantly lower dynamic modulation thresholds. For the phonological language and literacy measures, the DT group performed significantly poorer than the TD group on reading, spelling and non-word reading (as could in part be expected by the use of these measures for identification). They scored significantly higher on the estimates for FISQ, verbal and non-verbal IQ than the TD group.

Table 3

| Auditory measures | Pitch            | Local/global change detection | Combined local and global | Rhythm | Single-interval duration discrimination | Isochrony deviation detection | Regularity detection | Metrical pattern discrimination | Modulation | 2 Hz FM detection | 40-Hz FM detection | DM detection | DM discrimination |
|-------------------|------------------|------------------------------|---------------------------|--------|----------------------------------------|-------------------------------|----------------------|-------------------------------|---------------|-------------------|-------------------|---------------|------------------|
|                   | Basic pitch change detection | 0.25/0.44                   | 0.28/0.33                 | 0.42   | 0.41                                   | 0.61                          | 0.38                 | 0.36                          | 0.37          | 0.39 (0.28)       | 0.35              | 0.35          | 0.39 (0.24)      |
|                   | Local/global change detection | 0.25/0.44                   | 0.28/0.33                 | 0.42   | 0.41                                   | 0.61                          | 0.38                 | 0.36                          | 0.37          | 0.39 (0.28)       | 0.35              | 0.35          | 0.39 (0.24)      |
|                   | Combined local and global | 0.25/0.44                   | 0.28/0.33                 | 0.42   | 0.41                                   | 0.61                          | 0.38                 | 0.36                          | 0.37          | 0.39 (0.28)       | 0.35              | 0.35          | 0.39 (0.24)      |
|                   | Rhythm | 0.25/0.44                   | 0.28/0.33                 | 0.42   | 0.41                                   | 0.61                          | 0.38                 | 0.36                          | 0.37          | 0.39 (0.28)       | 0.35              | 0.35          | 0.39 (0.24)      |
|                   | Single-interval duration discrimination | 0.25/0.44 | 0.28/0.33 | 0.42 | 0.41 | 0.61 | 0.38 | 0.36 | 0.37 | 0.39 (0.28) | 0.35 | 0.35 | 0.39 (0.24) |
|                   | Isochrony deviation detection | 0.25/0.44 | 0.28/0.33 | 0.42 | 0.41 | 0.61 | 0.38 | 0.36 | 0.37 | 0.39 (0.28) | 0.35 | 0.35 | 0.39 (0.24) |
|                   | Regularity detection | 0.25/0.44 | 0.28/0.33 | 0.42 | 0.41 | 0.61 | 0.38 | 0.36 | 0.37 | 0.39 (0.28) | 0.35 | 0.35 | 0.39 (0.24) |
|                   | Metrical pattern discrimination | 0.25/0.44 | 0.28/0.33 | 0.42 | 0.41 | 0.61 | 0.38 | 0.36 | 0.37 | 0.39 (0.28) | 0.35 | 0.35 | 0.39 (0.24) |

Listed are the positive Spearman's rho values that explained at least 5% of the variance (rho ≥ 0.22) and were significant at the level of $p \leq 0.05$ (none survived Bonferroni correction for multiple comparison); and in addition the mean correlation coefficients across the language measures for auditory measures with at least one individual correlation fulfilling those criteria. In brackets are those with a rho ≥ 0.22, though not significant (but all with $p$ values between 0.05 and 0.13), included for comparison with Tables 4 and 5.
The difference in IQ did not explain the absence of auditory deficits.

Correlations between auditory and language skills were of similar magnitude in the DT group and TD group, with Spearman’s rho correlation coefficients up to 0.4, but showing a somewhat different pattern. The DT group exhibited a relative increase in correlations for some of the basic, single-sound tasks, most strongly so for FM-2 Hz detection and DM discrimination, compared to the TD group, and a relative lack in significant correlations for the sequence tasks, though this may in part be due to a lack of statistical power related to sample size.

4. Discussion

The present study explores the idea that correlations between auditory and language skills may in part be the same but in part differ in typical compared to atypical development. We tested here a range of auditory and language skills in a group of individuals with dyslexic traits for differences in comparison to a control group of typically developing individuals, and for commonalities and differences in the pattern of correlations between auditory and language skills. We assessed auditory and language skills in 28 eleven-year olds with dyslexic traits, the DT group, in comparison to 173 typically developing subjects, the TD group, who underwent the same systematic assessment (Grube et al., 2012). The auditory assessment included tasks of pitch, time and rhythm, and timbre (modulation) processing, using acoustic stimuli that ranged from basic, single sounds to sound sequences. The assessment of language skills used a combination of six standard tests of phonological language and literacy abilities. Firstly, there was no group-level deficit in the auditory tasks in the DT compared to the TD group that could explain their language difficulties. Secondly, the existence and specificity of the links between auditory and language skills was compared between the two groups. The correlations found in the DT group were of similar, small-to-moderate effect size as in the TD group, with rho values up to about 0.4, but showed an in part different pattern.

4.1. Language, auditory and intellectual skills

The DT group comprised a sample of just below 12% of the whole year-group, consistent with the reported frequency of occurrence of developmental dyslexia (Lewis et al., 1994; Meltzer et al., 2000). Highly significant group differences between the DT group and the TD group were observed for the measures of reading, spelling and non-word reading, and borderline significant ones for rhyme

### Table 4
Correlations between auditory and language measures in the DT group after partialling out non-verbal intelligence.

| Language measures | Mean |
|-------------------|------|
| Rym               | Spl  | Wrd  | Nrd  | Nrp  | Dgb  |
|--------------------|------|------|------|------|------|
| Basic pitch change detection | −     | −    | −    | −    | 0.39 (0.24) | 0.22 |
| Local/global change detection | −0.35 | −/−  | −/−  | −/−  | −0.41 (0.25)/−| −0.20 |
| Combined local and global | 0.83  | (0.22) | (0.42) | −    | 0.20  |
| Key violation detection | −    | −    | −    | (0.22) | −    | −    |
| Single-interval duration discrimination | −    | −    | −    | −    | −    |
| Isochrony deviation detection | 0.35  | −    | −    | −    | −    |
| Regularity detection | −    | −    | −    | −    | −    |
| Metrical pattern discrimination | −    | (0.31) | −    | −    | −    |
| 2 Hz FM detection | 0.39  | −    | 0.46 | −    | −    |
| 40-Hz FM detection | −    | −    | −    | −    | −    |
| DM detection | −    | −    | −    | −    | −    |
| DM discrimination | 0.35  | (0.23) | (0.32) | −    | (0.33) | 0.21* |

Listed are the positive Spearman’s rho values that explained at least 5% of the variance (rho ≥0.22) and were significant (at the level of p ≤ 0.05); and in addition the mean correlation coefficients across the language measures for auditory measures with at least one individual correlation fulfilling those criteria. Listed in brackets are rho values that were not significant (but had p values between 0.05 and 0.15), included for comparison with Table 3 and the TD group (Table 5) within which significance is reached easier due to sample size. Asterisks (*) denote those correlations that show a significant deviation (p 0.05, two-sided) from the TD group according to bootstrapping analyses based on 1000 subsamples (abs(z) ≥1.96). Abbreviations: Rym, rhyme decision; Spl, spelling; Word, word reading; Nrd, non-word reading; Nrp, non-word repetition; Dgb, backward digit recall.

### Table 5
Correlations between auditory and language measures in the TD group after partialling out non-verbal intelligence.

| Language measures | Mean |
|-------------------|------|
| Rym               | Spl  | Wrd  | Nrd  | Nrp  | Dgb  |
|--------------------|------|------|------|------|------|
| Basic pitch change detection | −     | −    | −    | −    | −    |
| Local/global change detection | −/−  | 0.22/0.25 | −/−  | −0.22 | 0.23/| 0.22 |
| Combined local and global | 0.22  | 0.25  | 0.22  | 0.22  | 0.20  |
| Key violation detection | −    | −    | −    | −    | −    |
| Single-interval duration discrimination | −    | −    | −    | −    | −    |
| Isochrony deviation detection | 0.39  | 0.31  | 0.30  | −    | −    |
| Regularity detection | −    | −    | −    | −    | −    |
| Metrical pattern discrimination | −    | −    | −    | −    | −    |
| 2 Hz FM detection | −    | −    | −    | −    | −    |
| 40-Hz FM detection | −    | −    | −    | −    | −    |
| DM detection | −    | −    | −    | −    | −    |
| DM discrimination | −    | −    | −    | −    | −    |

Listed are the positive Spearman’s rho values that explained at least 5% of the variance (rho ≥0.22) and were significant (at the level of p ≤ 0.05); and in addition the mean correlation coefficients across the language measures for auditory measures with at least one individual correlation fulfilling those criteria. Marked in bold are those correlations that would survive Bonferroni correction for multiple comparison. Correlations are similar to those reported by Grube et al. (2012), demonstrating that analysing the data from a subsample of 173 (out of 210) in order to match the DT group (by application of a lower limit of IQ, and exclusion of individuals with ASD/ADHD) did essentially not change the results. Abbreviations: Rym, rhyme decision; Spl, spelling; Word, word reading; Nrd, non-word reading; Nrp, non-word repetition; Dgb, backward digit recall.
decision and backward digit recall. The DT group further exhibited significantly higher scores of intellectual skills, both non-verbal and verbal, as well as a significantly higher composite full-scale IQ. The use of a within-subject discrepancy criterion may explain the difference in IQ. It remains remarkable that, despite the overall higher IQ in the DT group, three of the language measures were significantly impaired in comparison to the TD group. However, no significant deficits in auditory skills were found in the DT group compared to the TD group in the three domains of pitch, time and rhythm, and modulation processing, except for a marginally significant trend for the slow (2-Hz) frequency modulation task. To the contrary, a number of auditory measures showed a tendency toward better performance in the DT compared to the TD group. This effect and the absence of group-level deficits could not be explained by the group difference in intellectual skills, as there were also no group deficits compared to an FSIQ-matched TD subsample and no significant correlation between the auditory measures and intelligence in either the DT or the TD group.

The dyslexic traits seen in the present DT group comprising 28 out of a cohort of 238 individuals in total thus cannot be simply attributed to a fundamental auditory deficit. With the only exception of a marginally poorer performance for the 2-Hz FM detection task, 2000; Liberman et al., 1956; Rosen et al., 2009; Schonwiesner and Talcott, 2000; Talcott et al., 2000; Tallal, 1980; Temple et al., 2003; Witton et al., 1998) but practically absent. There was no single correlation between language measures and the basic pitch or duration or any of the single-sound modulation tasks that was significant and explained more than 5% of the variance. In the DT group however, there were a number of correlations between the basic, single-sound tasks and language measures, in particular for the 2-Hz FM detection and the DM discrimination task, and both of those showed a significant increase in the mean correlation coefficient. FM detection at a modulation rate of 2-Hz can be argued to be relevant to suprasegmental processing, whilst the detection of moving spectral peaks at is relevant to the analysis of features like formants. 2-Hz FM detection has been shown before to correlate with non-word reading in a group of typically developing 10-year olds (Talcott et al., 2000) as well as in typically developing and dyslexic adults (Witton et al., 1998). The lack of correlations across both FM and both DM, as well as the basic pitch and duration tasks, found in the present TD group suggests that, as discussed by Grube et al. (2012), despite the presence of the corresponding features in speech (Chi et al., 1999; Jusczyk, 1999; Klatz, 1976; Liberman et al., 1956; Rosen et al., 2009; Schonwiesner and Zatorre, 2000; Scott, 1982), highly accurate auditory analysis of these features might not be needed to process the corresponding cues adequately in typical development. In the DT group, however, significant, moderate correlations were observed for both the 2-Hz FM detection and the DM discrimination, supporting a tighter coupling between sound processing and language skills than in typical development.

4.3. The role for basic auditory processing

In the present group of TD individuals, drawn from the same population as studied by Grube et al. (2012), correlations between single-sound tasks and language skills were not only very low in comparison to previous reports (c.f. Corriveau et al., 2010; Poelmans et al., 2011; Ramus et al., 2003; Talcott et al., 2000; Witton et al., 1998) but practically absent. There was no single correlation between language measures and the basic pitch or duration or any of the single-sound modulation tasks that was significant and explained more than 5% of the variance. In the DT group, however, there were a number of correlations between the basic, single-sound tasks and language measures, in particular for the 2-Hz FM detection and the DM discrimination task, and both of those showed a significant increase in the mean correlation coefficient. FM detection at a modulation rate of 2-Hz can be argued to be relevant to suprasegmental processing, whilst the detection of moving spectral peaks at is relevant to the analysis of features like formants. 2-Hz FM detection has been shown before to correlate with non-word reading in a group of typically developing 10-year olds (Talcott et al., 2000) as well as in typically developing and dyslexic adults (Witton et al., 1998). The lack of correlations across both FM and both DM, as well as the basic pitch and duration tasks, found in the present TD group suggests that, as discussed by Grube et al. (2012), despite the presence of the corresponding features in speech (Chi et al., 1999; Jusczyk, 1999; Klatz, 1976; Liberman et al., 1956; Rosen et al., 2009; Schonwiesner and Zatorre, 2000; Scott, 1982), highly accurate auditory analysis of these features might not be needed to process the corresponding cues adequately in typical development. In the DT group, however, significant, moderate correlations were observed for both the 2-Hz FM detection and the DM discrimination, supporting a tighter coupling between sound processing and language skills than in typical development.

4.4. The role for auditory sequence analysis

Of the tested levels of auditory processing, short-sequence analysis in pitch and time were demonstrated to be most relevant to language skills in the TD group studied here, in accord with our previous report (Grube et al., 2012). There were moderate correlations between the language skills and the local and global change-in-pitch tasks using short melodies, as well as the detection of a deviation from a short, otherwise isochronous rhythm. The underlying processes of auditory-sequence analysis can be thought to be relevant to the ‘parsing’ of the speech stream in real-time (Jusczyk, 1999), consistent with the perceptual organization of phonological representations starting at the higher, suprasegmental level before the analysis of phonemes (Goswami et al., 2002; Metsala and Walley, 1998). In the DT group of the present study, the corresponding correlations between measures of language skills and the processing of short sequences were less prominent and hardly significant, though not absent and the lack of significance may be related to sample size. This supports a universal relevance for sound-sequence analysis in speech and language skills. An important study by Kraus and colleagues demonstrated a relationship between reading ability and accuracy of auditory processing of the speech stream, with specific focus on the amplitude envelope and measured in electrophysiological brain-stem
responses (Abrams et al., 2009). Speech processing has subse-
quently been linked to oscillatory processes in the brain at relevant
periodicities at the prosodic and the syllable level (Ghitza, 2013;
Giraud and Poeppel, 2012). Further, Lehongre and coworkers
(Lehongre et al., 2013, 2011) have demonstrated abnormalities in
the oscillations in dyslexia. Recent work by Leong and Goswami
(2014), appearing in this special issue, tested rhythmic entrain-
ment at the timescales for prosody, syllables, and phonemes in
dyslexic adults and controls using metrically regular nursery
rhymes. Whilst the dyslexics exhibited a different phase angle than
controls at the syllable level (5 Hz), phase-locking to the amplitude
fluctuations was equally strong in both groups (Leong and
Goswami, 2014).
Grube et al. (2012) suggest that the correlations between audi-
tory sequence processing and language in the larger group of TD
subjects are consistent with such mechanisms providing a common
basis for music and speech (Goswami, 2010; Overy et al., 2003;
Patel et al., 2005). The link may be tighter in the domain of
rhythm than pitch (Grube et al., 2013, 2012; Hausen et al., 2013).

4.5. Auditory skills as markers of dyslexia?
The DT group had lower word reading, spelling and non-word
reading scores than predicted by their own intellectual ability
scores, but also in absolute terms when compared to the TD group.
If auditory deficits were the determining causal factor for dyslexia,
this would predict low auditory performance compared with the
typically developing sample. This has been demonstrated in pre-
viously studied samples. Here the raw scores showed no significant
impairment in any of the auditory measures in the DT group. This
absence of group-level deficits is in contrast to some previous re-
ports but not others, supporting the notion that an auditory pro-
cessing deficit is not necessary (nor sufficient) to cause dyslexia or
SLI (Rosen, 2003; Thomson et al., 2006; Bishop et al. 1999).

Despite the absence of group deficits, we have demonstrated
differences in the task-specific correlations in the DT group
compared to the TD group. In contrast to our a priori suggestion,
there was a relative increase in correlation, for the basic tasks of
slow (2-Hz) FM detection and DM discrimination with language
measures. Such an increase would, rather than a lack of “yoking”
between auditory and language skill development, suggest a
somewhat tighter coupling than in typical development. This might
reflect a compensatory use of auditory skills to overcome diffi-
culties with reading and spelling. For the tasks of short sequence
analysis in contrast, there was a relative lack of significant corre-
lation with language skills, which may reflect less relevance than
in typical development at this age. This may, however, be related to
statistical power.
The findings are specific to the present group of 11-year olds
with dyslexic traits and can by no means be generalized to auditory
processing in dyslexia in its entirety, but merit further work in
other cohorts, including those of individuals with clearly charac-
terized phonological deficits. The limitations of this exploratory
study lie in the absence of explicit up-front screening for “atypical
development” in addition to the post-hoc identification of indi-
dividuals with dyslexic traits based on DSM-IV criteria, and the lack
of power to detect or grant significance of effects. This work rep-
resents a first attempt to look at commonalities and differences in
the pattern of correlations with language skills for a range of
auditory skills in atypical compared to typical development.

5. Conclusion
The present data do not directly support the hypothesis that
dyslexia is caused by a simple auditory deficit but suggest subtle
differences in the pattern of the ‘yoking’ between auditory and
language skills. In view of inconsistent findings from previous
studies seeking simple deficits, the approach merits further evalu-
ation. We propose here differences in the pattern of correlations
between auditory and language measures that could be tested in
further studies. The current data suggest that the relationship be-
tween auditory and language skills might differ in subjects within
typical vs. atypical language development, with the implication
that merging data from differing populations might be problematic.
Understanding the relationship between both basic sound feature
analysis and music-like sound analysis and language skills in
impaired populations might in future suggest appropriate training
strategies, possibly including types of musical training to improve
language acquisition.

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