

# Auditory Sensory Processing and Phonological Development in High IQ and Exceptional Readers, Typically Developing Readers, and Children With Dyslexia: A Longitudinal Study

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Phonological difficulties characterize children with developmental dyslexia across languages, but whether impaired auditory processing underlies these phonological difficulties is debated. Here the causal question is addressed by exploring whether individual differences in sensory processing predict the development of phonological awareness in 86 English-speaking lower- and middle-class children aged 8 years in 2005 who had dyslexia, or were age-matched typically developing children, some with exceptional reading/high IQ. The predictive relations between auditory processing and phonological development are robust for this sample even when phonological awareness at Time 1 (the autoregressor) is controlled. High reading/IQ does not much impact these relations. The data suggest that basic sensory abilities are significant longitudinal predictors of growth in phonological awareness in children.

Learning to read is a crucial educational skill, and yet some children fail to learn to read efficiently in every world language, irrespective of the sound structure of words in the language (phonology) and of the orthographic (spelling) system of the language (e.g., Ziegler & Goswami, 2005). Unexpected failure to acquire reading is termed developmental dyslexia, and the core cognitive difficulty across languages is identified as achieving “phonological awareness,” the ability to identify or manipulate component sounds in words at different linguistic “grain sizes” (e.g., syllable, rhyme, phoneme). Children with dyslexia who speak a wide variety of languages have difficulties with both subword phonology, for example making decisions about whether words rhyme with each other (“cat”–“hat”), and also show phonological impairments at

the suprasegmental and phrasal levels, having difficulties in perceiving prosodic structure and syllable stress (Goswami, 2015, for review). Although there has been debate over whether a complex condition like dyslexia could arise from lower level deficits in basic sensory or perceptual processes, there is growing evidence regarding the core cognitive deficit in phonology that dyslexic difficulties are related to auditory sensory impairments, particularly regarding discrimination of amplitude envelope rise times (e.g., Goswami, 2015; Hämäläinen, Salminen, & Leppänen, 2013). Accordingly, the developmental relations between auditory sensory impairments and phonology are the focus of the current study.

Amplitude rise time sensitivity measured in preschoolers, before reading is formally taught, is related to a range of phonological precursors for reading (Vanvooren, Poelmans, De Vos, Ghesquière, & Wouters, 2017), is predictive of growth in phonological skills measured during schooling (Corriveau, Goswami, & Thomson, 2010; Law, Vandermosten, Ghesquiere, & Wouters, 2017; Plakas,

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van Zuijen, van Leeuwen, Thomson, & van der Leij, 2013), and is predictive of growth in reading itself (Boets et al., 2011). Indeed, infants at family risk of dyslexia already show impaired discrimination of amplitude rise times by 10 months of age, long before either reading or phonological awareness are acquired (Kalashnikova, Goswami, & Burnham, 2018). Furthermore, these same infants show impaired phonological learning in toddlerhood (Kalashnikova, Goswami, & Burnham, 2019a). Accordingly, the relation between auditory sensory impairments and the development of phonological skills, and consequently reading, appears to be a causal one.

However, the theoretical view that sensory impairments could affect the development of complex cognitive skills like phonological awareness and reading remains highly controversial (Perrachione et al., 2016). Accordingly, theories arguing that basic auditory processes are governing individual differences in phonological development and thereby reading must address various concerns, including that perceptual deficits may not be present when linguistic rather than nonlinguistic stimuli are used, that the perceptual problems may have small effect sizes, and that the causal direction may be the opposite to that proposed (i.e., from phonological skills to auditory sensory processing, see McArthur & Bishop, 2001). Although some auditory sensory theories are indeed impacted by these concerns, a sensory/neural theory linking amplitude envelope rise time discrimination to phonological development and dyslexia has proved robust across linguistic and nonlinguistic stimuli, with large effect sizes (Hämäläinen et al., 2013; Lallier, Molinaro, Lizarazu, Bourguignon, & Carreiras, 2017). This is “Temporal Sampling” theory (Goswami, 2011). The temporal sampling framework proposes that childhood difficulties in processing aspects of amplitude envelope structure, such as amplitude rise time, is an important developmental factor in explaining the *phonological* difficulties that characterize children with developmental dyslexia across languages.

The acoustic structure of the amplitude envelope appears to be important for phonological development as it plays a core role in neural encoding of the speech signal. Adult multitime resolution models of speech processing foreground the importance of amplitude modulation at different rates for linguistic processing, and amplitude rise times are sensory cues to amplitude modulation rates (Ghitza & Greenberg, 2009; Poeppel, 2003). Modeling the speech signal of child-directed speech shows that

the perception of amplitude modulation at different rates is important for many different aspects of phonological awareness (Goswami & Leong, 2013). In particular, *amplitude modulation phase hierarchies* in the speech signal yield the perceptual experience of linguistic prosodic hierarchies (prosodic feet, syllables, onset-rimes, phonemes; Leong & Goswami, 2015). Further, amplitude modulation patterns in speech automatically entrain neural oscillatory activity, as demonstrated for children by Power, Mead, Barnes, and Goswami (2012, 2013) and Molinaro, Lizarazu, Lallier, Bourguignon, and Carreiras (2016). Rise times (the time taken to reach peak signal intensity) in the amplitude envelope are critical linguistic perceptual events governing this neural entrainment (Gross et al., 2013). Indeed, recent studies show that rise time discrimination is mechanistically related to the development of phonological awareness (Goswami, 2018).

Differences in sensitivity to rise time between dyslexic and control groups have been found in many languages, including English, Spanish, French, Dutch, Chinese, Finnish, and Hungarian (Goswami, 2011, 2015 for overviews). A comprehensive review of over 60 studies of auditory sensory processing in developmental dyslexia encompassing other acoustic measures in addition to rise time, for example frequency, duration, and intensity discrimination (Hämäläinen et al., 2013), identified amplitude envelope rise time and sound duration as the auditory measures showing the largest average sample-size weighted effect sizes (0.8 for rise time, 0.9 for duration). These two acoustic measures also showed considerable consistency across studies (e.g., rise time discrimination was linked to reading/spelling in all 11 studies of rise time sensitivity reviewed by Hämäläinen et al., 2013). In the current study, we focus on amplitude rise time, duration, and sublexical phonological development. Other low-level acoustic measures may also be related to the development of phonological awareness, for example voice onset time detection may be related to phoneme awareness (Serniclaes & Seck, 2018), but they are not explored here. Using longitudinal data, we investigate the possibility that the causal direction during development may be the opposite of that proposed by Temporal Sampling theory, namely from phonological difficulties to rise time perceptual difficulties. We provide a stringent test of the direction of causality by using exploratory analyses that include an autoregressor.

The design of the current study also allowed us to assess whether IQ impacts the psychoacoustic

threshold measures used in developmental studies. It is often suggested that inattention and/or general nonsensory difficulties may underlie the poorer thresholds in psychoacoustic tasks that are typically obtained by children with language learning difficulties (e.g., Roach, Edwards, & Hogben, 2004). A proxy measure for general nonsensory difficulties is IQ. Regarding the IQ issue, impaired auditory sensory processing of rise time is for example found in “low IQ poor readers” (previously termed “garden variety” poor readers), children who show poor reading, poor phonological awareness, and who have full-scale IQs below 76 standard points (Kuppen, Huss, Fosker, Mead, & Goswami, 2011). It is possible that low IQ children obtain poorer sensory thresholds because their low IQ impacts task performance. However, children in Kuppen et al.’s (2011) study with equally low IQ who were good readers showed preserved auditory processing of amplitude rise time and preserved (age-typical) phonological awareness. Furthermore, individual variability in auditory processing skills within low IQ samples predicts the longitudinal growth of reading and phonology (Kuppen, Huss, & Goswami, 2014). Indeed, when the data from Kuppen et al. (2011) were analyzed using a developmental trajectories design (see Kuppen & Goswami, 2016), low IQ poor readers and children with developmental dyslexia showed convergent developmental trajectories for amplitude rise time discrimination. Both groups showed atypical rather than developmentally delayed trajectories. By contrast, for sound duration discrimination, children with developmental dyslexia exhibited developmental delay, while low IQ poor readers exhibited atypical trajectories. Accordingly, the emerging database on auditory processing and reading across languages suggests that auditory sensory processing abilities are related to phonological development for children who show a range of cognitive and linguistic abilities (Lallier et al., 2017).

Nevertheless, to date high IQ *good readers*, children who have full-scale IQ scores > 120 and/or who are reading far in advance of their age norms, have not been included in studies relating basic auditory sensory processing to reading development. During recruitment for the current study, the children nominated by their teachers as typically developing were found to include some children with very high IQ and/or with exceptional reading skills. The highest full scale intelligence quotient (FSIQ) score was 148, over 3 *SD* from the population mean of 100, and the largest discrepancy between age and reading age was 74 months—one

child aged 8 years 7 months had a reading age of 14 years 8 months. Rather than lose these children from our study, we decided to compare the longitudinal progress of children with dyslexia with that of age-matched children who were either typically developing or were of above-average reading and IQ. As the chronological age (CA)-matched children with high reading/IQ showed superior reading and phonological skills when the study began, we had a good range of reading as well as phonological performance in our sample, enabling us to document the longitudinal connections between auditory sensory processing, phonological development, and reading. We used six measures of potential low-level auditory deficits, three different measures of rise time sensitivity and measures of sensitivity to sound duration, sound intensity, and acoustic rhythm. The longitudinal acoustic and behavioral data were then analyzed using exploratory multiple regression. Multiple regression equations were created using a fixed order of steps, in which both age and IQ were entered first, before assessing the relations between auditory processing at Time 1 and phonological development 3 years later. In order to estimate the independent effect of a longitudinal predictor on growth in a cognitive measure, the autoregressive effect of previous cognitive skills (like phonological awareness) must be controlled (Boets et al., 2011). Accordingly, following the first set of exploratory longitudinal analyses, we ran a second set of exploratory multiple regression equations including either auditory processing at Time 1 or phonological awareness at Time 1 as the autoregressor. As our sample was relatively old at time 4, we measured awareness of sublexical phonology—onset-rimes and phonemes.

Our hypothesis was that a childhood difficulty in auditory discrimination, particularly regarding amplitude rise times, should (by the Temporal Sampling framework) affect the construction of a well-specified phonological lexicon continuously throughout development, affecting lexical phonological representations at all linguistic levels (phrasal, foot, syllable, onset-rime, phoneme; see Goswami, 2011, 2015, for detail). By Temporal Sampling theory, amplitude rise time discrimination rather than IQ should determine the developmental trajectories for phonology and reading. Consequently, amplitude rise time discrimination abilities (and other potential auditory processing difficulties) should be the significant predictors of the development of phonological awareness. In addition, these longitudinal relations should not be affected by whether IQ is high or in the normal range. Further

changes in auditory sensory processing over time should be unaffected by IQ. Although high IQ may confer early benefits for cognitive development, for example, superior phonological awareness, these benefits may plateau later in development as reading skills begin to affect the further development of phonological awareness (Perfetti, Beck, Bell, & Hughes, 1987). This possibility has yet (to our knowledge) to be explored in the literature.

## Method

### *Participants*

Eighty-six children (41 boys) aged on average 8 years when the study began (2005) participated in this research. Data collection preceded the introduction of a National Literacy Strategy for the United Kingdom, which could explain the large variability in reading development observed for the typically developing participants. Children were recruited via learning support teachers, and only children who had no additional learning difficulties (e.g., dyspraxia, attention deficit hyperactivity disorder, autistic spectrum disorder, specific language impairment), a nonverbal IQ above 85, and English as the first language spoken at home were included. The absence of additional learning difficulties was based on school and parental reports and our own testing. All participants and their guardians gave informed consent in accordance with the Declaration of Helsinki, and the study was approved by the Psychology Research Ethics Committee of the University of Cambridge, U.K. SES data were not formally collected, but participants were attending state schools (equivalent to US public schools) situated in a range of towns and villages near a University town in the United Kingdom. Most families were Caucasian and of lower class or middle class regarding income. The families were very enthusiastic about the project, and we experienced very little attrition. All children received a short hearing screen using an audiometer. Sounds were presented in both the left or right ear at a range of frequencies (250, 500, 1000, 2000, 4000, 8000 Hz), and all children were sensitive to sounds within the 20 dB HL range. The children included in this report are all the age-matched children out of a larger cohort initially tested (total  $N = 98$ , during the 4 years of the study six dyslexics, three CA children and three high reading/IQ children moved away) who had contributed data for the tasks being reported by test Year 4.

Forty-three of the children (27 male; mean age at first test point = 8 years 6 months) either had a statement of developmental dyslexia from their local education authority, or showed severe literacy and phonological deficits according to our own test battery. Children were assessed experimentally using the British Ability Scales (BAS) standardized tests of reading and spelling, and the Test of Word Reading Efficiency nonword scale (TOWRE phonemic decoding efficiency [PDE]), and were included in the study if they scored at least 1 *SD* less than the test norm of 100 on at least one of the two reading measures. Forty-three age-matched control children (CA control group) were also recruited. Following recruitment, it was found that these control children as a group had significantly higher cognitive ability (mean full-scale IQ = 126.9) than the dyslexic group (mean full-scale IQ = 105.4), as well as reading skills above the expected level for their age (mean reading standard score, 110.5, population mean = 100; average reading age 13 months ahead of chronological age). Inspection of individual data revealed that the highest FSIQ score was 148 and the second highest was 139, while the largest discrepancies between age and reading age were 74 and 67 months respectively. Accordingly, it was decided to divide the CA controls into typically developing and high reading/IQ groups. These groups are hereafter referred to as the CA group ( $N = 27$ , mean age at first test point = 8 years 5 months) and the high reading/IQ group ( $N = 16$ , mean age at first test point, 8 years 2 months). Children were assigned to the high reading/IQ group if they had a FSIQ of at least 120, or if they were 3 or more years advanced in reading age given their age, or both. Only two of the children had an IQ < 120, a child with a FSIQ of 106 and a reading advance of 56 months, and a child with a FSIQ of 119 and a reading advance of 45 months. As will be seen, in terms of the measures of auditory sensitivity taken during the study, IQ did not discriminate between the age-matched children. The high reading/IQ group differed by over 3.5 years in average reading age from the children with dyslexia, while the CA controls differed by 21 standard points and by nearly 2 years in average reading age from the children with dyslexia. Further details on the sample are provided in Table 1. Inspection of Table 1 demonstrates that the high reading/IQ group showed significantly superior reading and phonological skills to the CA group when the study began, as well as significantly better vocabulary skills.

Table 1  
Participant Details at the First Test Point (Year 1), with SDs in Parentheses

Group	Dyslexic	CA controls	High reading/IQ	$F(2, 85)^a$	$\eta_p^2$
Age (months)	101.9 (11.6)	101.4 (10.0)	97.6 (9.7)	1.0	.023
Reading age (months) <sup>b</sup>	83.9 (14.5)	106.8 (15.1)	122.3 (31.3)	28.3***	.405
WISC IQ <sup>c</sup>	105.4 (14.4)	106.0 (10.3)	126.9 (9.5)	19.1***	.315
Reading SS <sup>b</sup>	85.1 (9.5)	106.3 (11.3)	117.6 (13.0)	65.1***	.611
Spelling SS <sup>d</sup>	85.5 (8.7)	106.7 (9.6)	111.2 (11.7)	62.0***	.599
TOWRE PDE <sup>d</sup>	86.7 (9.4)	105.4 (13.7)	111.9 (15.5)	34.2***	.452
BPVS SS <sup>c</sup>	102.6 (12.2)	104.3 (10.3)	110.8 (7.2)	3.3*	.074
Phonological awareness (% correct) <sup>b</sup>	61.0 (15.1)	72.8 (14.8)	85.0 (14.9)	16.0***	.279
RAN (time in second) <sup>d</sup>	48.0 (14.6)	40.8 (11.5)	37.5 (5.6)	5.3**	.114
PSTM (% items correct) <sup>d</sup>	59.7 (13.7)	67.1 (14.7)	70.8 (11.3)	4.7*	.103

Note. CA = chronological age; WISC = Wechsler Intelligence Scale for Children; SS = standard score; TOWRE = Test of Word Reading Efficiency; PDE = phonemic decoding efficiency; BPVS = British Picture Vocabulary Scale; RAN = rapid automatized naming; PSTM = phonological short-term memory.

<sup>a</sup>Some tasks show Brown-Forsythe statistic. <sup>b</sup>DYS < CA < high reading/IQ. <sup>c</sup>DYS = CA < high reading/IQ. <sup>d</sup>DYS < CA = high reading/IQ. \* $p < .05$ . \*\* $p < .01$ . \*\*\* $p = .000$

### Procedures

At the beginning of the study, during the school year that ran from September 2005 to July 2006 (hereafter designated Year 1), children were given reading, spelling, vocabulary and IQ tests, experimental phonological awareness, rapid naming and phonological short-term memory (PSTM) tasks (see next), and psychoacoustic tasks assessing auditory thresholds for sound rise time, duration, rhythm, and intensity (see next). Three years later (during the school year that ran from September 2008 to July 2009, hereafter test Year 4), they received similar tests of reading, spelling, vocabulary, phonological awareness, sound rise time and duration. Longitudinal relations were assessed for the whole sample.

### Standardized Tests of Reading, Spelling, Vocabulary and IQ

The psychometric tests comprised the BAS (single word reading and spelling, Elliott, Smith, & McCulloch, 1996); the PDE measure of nonword reading from the TOWRE (Torgesen, Wagner, & Rashotte, 1999); the British Picture Vocabulary Scales (BPVS receptive vocabulary, Dunn, Dunn, Whetton, & Pintilie, 1982); and four subtests of the Wechsler Intelligence Scale for Children, 3rd ed.: block design, picture arrangement, similarities, and vocabulary. Full-scale IQ scores in Year 1 were prorated following the procedure adopted by Sattler (1982). In Year 4, IQ was assessed by one of the nonverbal subtests (picture arrangement).

### Psychoacoustic Tasks

In order to establish auditory sensitivity to the parameters of rhythm, duration, intensity, and amplitude rise time, a series of psychoacoustic tasks were created based on a cartoon "Dinosaur" threshold estimation interface originally created by Dorothy Bishop (Oxford University). Children listened to sounds associated with cartoon dinosaurs or other animals, and chose the animal that made a different sound to the standard sound by pointing or speaking. A standard adaptive psychoacoustic staircase procedure (Levitt, 1971) was employed, using a combined 2-steps-down 1-step-up and 3-steps-down 1-step-up procedure to reach the just noticeable difference. A test run terminated after eight response reversals or the maximum possible 40 trials. The threshold was calculated using the measures from the last four reversals. This indicated the smallest difference between stimuli at which the participant could still discriminate with a 79.4% accuracy rate. The children were assessed individually in a quiet room within their school or at home, with five practice trials for each task prior to the presentation of the experimental stimuli.

The psychoacoustic stimuli were presented binaurally through headphones at 75 dB SPL. Delivery was either AXB or 2IFC (2-interval forced choice). Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard & Sachs, 1975) and all testing laptops and headphones were equally calibrated. Children's responses were recorded on the computer keyboard by the experimenter. Most tasks have been

described in our previous publications (Goswami, Fosker, Huss, Mead, & Szűcs, 2011; Goswami, Wang, et al., 2011; Huss, Verney, Fosker, Mead, & Goswami, 2011; Kuppen et al., 2011), hence are described relatively briefly here. There were three measures of sensitivity to rise time, the 1 Rise task (which was given twice, to increase threshold reliability, see Boets et al., 2011), the 2 Rise task, and a 1 Rise task with intensity roving (Rise Rove). Three additional auditory measures, a duration detection task, a rhythm detection task (perception of rhythmic timing should be impaired if rise time sensitivity is impaired), and an intensity task (Intensity ABABA task) were also administered. For ease of comparison, the auditory parameters used in each task are presented in Table S1.

*1 Rise task.* Three 500 Hz tones of 800 ms duration were presented in each trial, with 500 ms ISIs. The two (standard) tones had a 15 ms linear rise time envelope, 735 ms steady state portion, and a 50 ms linear fall time. The target tone varied the linear onset rise time, with the longest rise time being 300 ms. Children were introduced to three cartoon dinosaurs. It was explained that each dinosaur in turn would make a sound and that their task was to decide which dinosaur's sound was different from the other two and had a softer rising sound (i.e., longer rise time, this target was either sound A or B).

*2 Rise task.* This task used a long stimulus with amplitude modulations within it. Given the long stimuli, presentation format was 2IFC. Forty stimuli of 3,573 ms (2.5 cycles of amplitude modulation) in duration were created using a sinusoidal carrier at 500 Hz amplitude modulated at the rate of 0.7 Hz (depth of 50%). A square wave was the basis of the underlying envelope modulation. Rise time was varied from 15 to 300 ms with a fixed linear fall time of 350 ms. The longest rise time was the standard. The child was asked to choose the dinosaur making the sharper beat (the shorter rise time).

*Rise Rove task.* This was identical to the 1 Rise task, except that the intensity of the sounds varied randomly between 65 and 75 dB, so that intensity was not a complementary cue to rise time. Note that overall brief rise time standards (15 ms) appear to be more useful than long standards (300 ms) for identifying children with difficulties (Kuppen et al., 2011).

*Duration task.* This task was based on sets of three tones, like the rise time tasks, but associated with cartoon sheep. The duration of the standard tone, presented second, was 400 ms. The first or

third tone could be identical to this standard, and either the third or first tone was longer than the standard, ranging up to 600 ms. Each tone was presented at 500 Hz with a 50 ms rise and fall. Children chose the cartoon sheep which made the longest sound.

*Intensity ABABA task.* This task employed two tone sequences and cartoon monkeys. In each sequence five 200 ms sine tones were presented with 50 ms rise time, 50 ms fall time and interstimuli intervals of 50ms. In one sequence, the tones were all of constant intensity 75 dB ("AAAAA") whilst in the other sequence, alternate tones had reduced intensity ("ABABA"). The task used a continuum of 40 stimuli which decreased in intensity at constant 1.7% steps from the standard 75 dB tone. The children were told that each cartoon monkey would make a series of sounds and that they had to decide which monkey made the mixture of loud and soft sounds.

*Rhythm task.* This was a novel task that has not been published previously, which also employed two tone sequences and stationary cartoon penguins. In one sequence a 500 Hz sinusoid 200 ms in duration with 50 ms rise and fall time was presented five times with equal 150 ms ISIs (gaps AAAA, 150 ms, 150 ms, 150 ms, 150 ms), thereby creating an isochronous rhythm. The second sequence had a linearly modified interval between the third and fourth tones ranging from 150 ms (largest gap) to 15 ms (smallest gap), thereby disrupting the isochronous rhythm (gaps AABB, e.g., 150 ms, 150 ms, 15 ms, 285 ms). Children were told that one penguin walked in a steady rhythm while one was unsteady and occasionally had a skip in its step. This was supported by the experimenter tapping examples of each walk on the desk. Children were asked to identify the penguin who did not make a steady rhythm. As rise time difficulties are theoretically linked to difficulties in perceiving rhythmic timing (see Colling et al., 2017; Goswami, 2011), this task was also expected to be related to poor phonology and hence poor reading.

### *Phonological Awareness Tasks*

*Onset oddity (Year 1).* The children listened over headphones to sets of three words and had to select the word that began with a different sound (e.g., *cone, pole, comb*). The position of the odd word varied randomly across the trials. Three different counterbalanced orders were used and practice trials were given. There were 20 experimental trials overall and a score of 1 was given for each correct

answer. The task used digitized speech created from a native female speaker of standard Southern British English. The stimuli are provided as Supporting Information (Table S2).

*Rime oddity (Year 4).* This task also used digitized speech created from the same native female speaker of standard Southern British English. The children listened to sets of three words or non-words through headphones, and had to select the one that did not rhyme (e.g., *hold, fold, post; rizz, nizz, kiv*). The position of the odd word varied randomly across the trials, practice trials were given, and three different counterbalanced orders were used. The task comprised 20 trials, 10 with real words, 10 with nonwords, and a score of 1 was given for each correct answer. The stimuli are provided as Supporting Information (Table S3).

*Phoneme deletion (Year 4).* Digitized speech from the same native female speaker of standard Southern British English was used to present 18 pseudowords (including three practice words), followed by a target phoneme contained in the pseudoword. Participants were asked to produce the pseudoword omitting the target phoneme (e.g., *Say "bice" without the "b"; Say "splow" without the "p"*). Phonemes were deleted from a variety of positions within the pseudoword (initial, medial, final). This task is from Pasquini, Corriveau, and Goswami (2007) and the stimuli are provided as Supporting Information (Table S4).

*Rapid Automatized Naming and PSTM Tasks*

*Rapid automatized naming (RAN).* The rapid automatized naming (RAN) tasks required children to name line drawings of objects. In Year 1, two sets of four objects were depicted, and in Year 4, two sets of five objects. Children were first introduced to the names of the pictures. They then received a page with a set of pictures repeated 40 times in random order and were asked to produce the names as quickly as possible. Performance was timed and scored for mean naming time across the two lists.

*Phonological short-term memory.* This task was based on digitized speech from the same female speaker who recorded the phonological awareness tasks, and consisted of 16 (Year 1) or 20 trials (Year 4) of four spoken monosyllables (all words at Year 1, e.g., *hem, dull, join, song*; all nonwords at Year 4, e.g., *rell, kide, tave, nug*). Children listened to each set of four items through headphones and repeated them back to the experimenter. Responses were analyzed in terms of the number of items recalled

correctly. Performance (% correct) is shown in the tables.

**Results**

Auditory discrimination data for the 86 participants when the study began (Year 1) are shown in Table 2. For each measure, the data were explored by group using box plots as well as measures of kurtosis and skew, to check that assumptions of normality were met. Any data points lying farther than three interquartile ranges from the nearer edge of the box were removed (there were four outliers for the Rhythm task [2 DYS; 2 CA], and two for the Intensity task [1 CA; 1 DYS]. It was not possible to retest 5 CA, 7 DYS, and 2 high reading/IQ children in the 1 Rise task in Year 1, hence their data points could not be averaged and are omitted from the analyses). Table 2 shows that the dyslexic children typically had higher group thresholds (poorer sensitivity) than both the CA controls and the high reading/IQ children for the auditory measures administered in Year 1. These differences were significant for the sensory measures of Rhythm and Intensity, and approached significance for the 1 Rise measure ( $p = .051$ ). In contrast, we did not find a difference in auditory sensory thresholds for the

Table 2  
*Auditory Thresholds by Group at the First Test Point (Year 1)*

Group	Dyslexic	CA	High reading/IQ	$F(2, 85)^{*,a}$	$\eta_p^2$
1 Rise (ms)	140.2	96.0	105.2	3.1 <sup>+</sup>	.083
(SD)	(69.0)	(61.3)	(45.5)		
Rise Rove (ms)	187.7	163.0	151.6	1.3	.031
(SD)	(73.4)	(83.2)	(80.5)		
2 Rise (ms)	270.1	258.7	254.0	1.7	.039
(SD)	(140.0)	(150.4)	(146.4)		
Duration (ms)	109.0	91.0	86.2	2.0	.046
(SD)	(42.2)	(39.9)	(42.5)		
Rhythm <sup>a</sup> (ms)	54.8	39.6	41.9	5.1 <sup>**</sup>	.090
(SD)	(29.5)	(20.1)	(20.1)		
Intensity	4.4	3.5	3.4	4.5 <sup>*</sup>	.117
ABABA (dB) <sup>a,b</sup>					
(SD)	(1.0)	(1.2)	(1.5)		

Note. CA = chronological age. When there were outliers, the  $F$  given is for the correspondingly reduced  $df$ .  
<sup>a</sup>Some tasks show Brown-Forsythe statistic. <sup>b</sup>DYS worse than CA, high reading/IQ = CA. <sup>+</sup> $p = .051$ . <sup>\*</sup> $p < .05$ . <sup>\*\*</sup> $p < .01$ .

Table 3

Reading, Auditory Sensitivity and Phonology at the Final Test Point (Year 4), With Standard Deviations in Parentheses

Group	Dyslexic	CA	High reading/IQ	$F(2, 85)^a$	$\eta_p^2$
Age in months Year 4 ( <i>SD</i> )	138.0 (14.0)	137.0 (12.0)	132.2 (11.6)	1.2	.028
Reading age (months; BAS) <sup>b</sup>	106.7 (19.2)	152.3 (23.4)	165.4 (36.2)	46.7***	.532
Reading SS (BAS) <sup>b</sup>	83.9 (10.0)	110.3 (10.5)	120.9 (18.2)	71.0***	.634
Spelling SS (BAS) <sup>c</sup>	81.3 (10.2)	104.9 (9.0)	111.1 (10.5)	75.3***	.647
TOWRE PDE SS <sup>b</sup>	85.7 (10.3)	110.6 (12.2)	112.4 (14.2)	50.6***	.552
BPVS SS <sup>d</sup>	102.7 (11.9)	108.4 (8.9)	114.7 (8.6)	8.1**	.164
Rime oddity (% correct) <sup>b</sup>	69.5 (12.1)	81.7 (10.3)	85.7 (8.3)	17.2***	.295
Phoneme deletion (% correct) <sup>b</sup>	53.7 (18.3)	76.5 (15.9)	84.2 (12.9)	26.3***	.391
RAN (seconds) <sup>b</sup>	46.4 (10.3)	41.3 (5.7)	39.3 (5.9)	5.4**	.117
PSTM (% correct) <sup>b</sup>	42.8 (12.4)	59.4 (17.7)	62.0 (17.3)	14.0***	.257
1 Rise (threshold in ms) <sup>b</sup>	109.6 (74.4)	36.5 (11.9)	35.2 (11.6)	15.6***	.278
Duration	99.5 (42.3)	76.0 (41.7)	80.8 (30.3)	2.6	.058

Note. BAS = British Ability Scales; CA = chronological age; SS = standard score; TOWRE = Test of Word Reading Efficiency; PDE = phonemic decoding efficiency; BPVS = British Picture Vocabulary Scale; RAN = rapid automatized naming; PSTM = phonological short-term memory.

<sup>a</sup>When there were outliers, the  $F$  or Brown–Forsythe statistic given is for the correspondingly reduced  $df$ , see footnote 1. <sup>b</sup>DYS worse than CA = high reading/IQ. <sup>c</sup>DYS worse than CA worse than high reading/IQ. <sup>d</sup>DYS = CA worse than high reading/IQ. \*\* $p < .01$ . \*\*\* $p = .000$ .

typically developing children with average vs. high reading/IQ (CA group, high reading/IQ group). Table 3 shows performance by group 3 years later (Year 4) for phonology (rime oddity, phoneme deletion, RAN, PSTM), vocabulary (BPVS), reading and spelling (BAS single word reading and spelling, TOWRE PDE), and auditory processing of rise time and duration. The other rise time measures were not given in Year 4 of the study, due to a focus on links with musical processing (see Goswami, Huss, Mead, Fosker, & Verney, 2013, for the other auditory measures used in Year 4). If IQ governs developmental changes in phonology and auditory sensory processing, then the high reading/IQ age-matched children should continue to perform significantly better in comparison to the typical IQ age-matched children (CA group). This was not the case. For most measures (word reading, nonword reading, rhyme awareness, phoneme awareness, RAN, and PSTM), the high reading/IQ group showed performance levels that were not different to the CA group. Their earlier advantage in these cognitive measures was no longer present. This is unlikely to reflect regression to the mean, as in terms of tasks generating standard scores, the scores go up. No group differences were found when the amplitude rise time and sound duration auditory measures were re-administered 3 years later. For the auditory processing measures, therefore, the high reading/IQ group did not show a difference in average thresholds to the CA group in

either Year 4 or Year 1. By Year 4, the high reading/IQ group only showed superior performance to the CA group for two cognitive measures, spelling (which had been matched when the study began) and vocabulary (which had been superior for the high reading/IQ group when the study began). These data suggest that while high IQ confers some early linguistic benefits for children, particularly regarding vocabulary, the development of basic auditory processing and phonological awareness is not impacted by IQ.

Inspection of Table 3 also shows that the impairments in phonological processing that characterized the children with dyslexia in Year 1 were still present in Year 4. The children with dyslexia still showed significantly poorer performance in every phonological and reading-related task. Their impairments in amplitude rise time discrimination were now very marked. Although the typically developing controls had improved their thresholds for rise time processing over the 4 years of the study (by around 65 ms on average), the dyslexic children showed less improvement (around 30 ms). Accordingly, the developmental trajectories for rise time processing were very different for the children with dyslexia compared to the typically developing control children. Sensory processing for the dyslexic group continued to be impaired. Indeed, the mean dyslexic rise time threshold at age 11 years was higher (worse) than the mean threshold of the typically developing children 3 years earlier, when aged



8 years, indicating the severity of the sensory deficit. In contrast, no group differences were found in duration thresholds for all three groups of children, as also found in Year 1. This appears to rule out IQ (or attentional effects) as a basis for group differences in improvements in psychoacoustic task performance. Nevertheless, it is possible that reading itself was improving rise time thresholds for the typically developing groups. One-way analyses of variance were used to explore group differences and further details are given in the tables.

If poorer auditory discrimination in childhood causes poorly specified neural phonological representations of speech and related difficulties in achieving phonological awareness, then individual differences in sensitivity to rise time, duration, intensity, and rhythm measured in Year 1 should predict individual differences in phonological awareness 3 years later. Table 4 presents the time-lagged correlations between the auditory measures taken in Year 1 and the children's progress in phonological awareness 3 years later (scatterplots for rise time are provided as Figures S1–S3). Time-lagged correlations with reading and spelling development are also included in the table. Inspection of Table 4 shows that IQ was not correlated with the auditory processing measures, with the exception of the Rise Rove measure. The negative correlation suggests that for the roving measure (a cognitively more effortful task), lower IQ is related to poorer sensory thresholds (higher threshold values). As expected, all the auditory measures showed significant time-lagged correlations with children's phonological development, for both rhyme and phoneme measures. The auditory measures also showed

significant time-lagged correlations with the development of reading and spelling, with the largest significant correlations for reading being with the 1 Rise and Rhythm measures ( $r = .35$ ), and the largest correlation for spelling being with the Rhythm measure ( $r = .39$ ). Unexpectedly, the duration and intensity measures showed significant correlations with age. Accordingly, in order to explore the longitudinal relations between auditory processing and phonological development, exploratory multiple regression equations were run in which both age and IQ were entered first, before the relations between auditory processing and phonological development were assessed. Given our hypothesis that individual differences in sensory processing rather than IQ would govern longitudinal relations with phonological awareness, the interaction between IQ and each auditory variable was also computed.

Table 5 presents the results of these multiple regression analyses when rhyme oddity and phoneme deletion respectively were used as dependent variables. For each dependent variable, a set of 6 four-step fixed entry equations entering age at Step 1 and IQ at Step 2 were computed, followed by an auditory processing measure from Year 1 at Step 3 and the interaction between that measure and IQ at Step 4. As Table 5 shows, neither age nor IQ contributed significant variance to these equations. However, all the measures of auditory processing taken in Year 1 were longitudinal predictors of growth in phonological awareness. Indeed, the acoustic rhythm sensitivity measure accounted for the largest absolute amount of unique variance, contributing 22% of unique variance to individual

Table 4

*Pearson Correlations Between Auditory Sensitivity Thresholds in Year 1 and Age, IQ, Phonological Awareness, Reading, and Spelling in Year 4*

	Age Y4	WISC Y4	Rime Y4	Phon Y4	Read Y4	Spell Y4
1 Rise	-.23	-.19	-.39**	-.33**	-.35**	-.34**
2 Rise	-.16	-.17	-.34**	-.29**	-.28**	-.26*
Rise Rove	-.21	-.34**	-.41**	-.27*	-.25*	-.19
Rhythm	-.20	-.12	-.41***	-.46***	-.35**	-.39***
Duration	-.46**	-.13	-.26*	-.22*	-.25*	-.34**
Intensity	-.26**	.08	-.32**	-.31**	-.26*	-.36**
Rime Y4	.08	-.14	—	-.58***	.66***	.64***
Phon Y4	.58**	.09	.58***	—	.68***	.68***
Read Y4	-.05	.14	.66***	.68***	—	.87***
Spell Y4	-.08	.11	.64***	.68***	.87***	—

*Note.* Y4 = Year 4; WISC = Wechsler Intelligence Scale for Children Picture Arrangement score; Rime = rime oddity; Phon = phoneme awareness; Read = standardized reading score; Spell = standardized spelling score.

\* $p < .05$  \*\* $p < .01$  \*\*\* $p < .001$

Table 5

Unique Variance ( $R^2_{\text{change}}$ ) in Phonological Awareness at Year 4 Explained by Auditory Processing Measured at Year 1; (a) Rime Oddity is Shown in Columns 1 and 2, and (b) Phoneme Deletion in Columns 3 and 4

Step	(a) $\beta$ (rime)	(a) $R^2_{\text{change}}$ (rime)	(b) $\beta$ (pho- neme)	(b) $R^2_{\text{change}}$ (phoneme)
1. Age	0.082	.007	-0.045	.002
2. IQ	0.155	.024	0.089	.008
Step 3				
1 Rise	-0.381	.129**	-0.357	.114**
2 Rise	-0.315	.093**	-0.297	.083**
Rise Rove	-0.406	.135**	-0.306	.077*
Rhythm	-0.390	.142**	-0.485	.220***
Duration	-0.262	.052*	-0.304	.069*
Intensity	-0.324	.097**	-0.347	.112**
Step 4				
1 Rise $\times$ IQ	1.248	.07*	1.980	.176***
2 Rise $\times$ IQ	-0.138	.001	0.417	.006
Rove $\times$ IQ	-0.083	.000	-0.338	.000
Rhythm $\times$ IQ	0.386	.013	0.118	.001
Durn $\times$ IQ	-0.355	.007	-0.502	.014
Intens $\times$ IQ	-1.553	.063*	-0.721	.013

Note. Durn = duration; Intens = Intensity ABABA.  
\* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$

differences in phoneme awareness. Two of the interaction terms contributed significant extra variance to the equations. The interaction between 1 Rise and IQ contributed significant additional variance for both dependent variables. In each case the  $\beta$  coefficient was positive, indicating that the effect of IQ on phonological awareness increased as rise time discrimination got worse. The interaction between Intensity ABABA and IQ also contributed significant additional variance, here only to performance in the rime oddity task. In this case the  $\beta$  coefficient was negative, indicating that the effect of IQ on phonological awareness decreased as intensity discrimination got worse. Accordingly, having high IQ may protect the development of phonological awareness to some extent if rise time processing is very poor, particularly the development of phoneme awareness. Phoneme awareness is typically conceived theoretically as a product of reading instruction (Ziegler & Goswami, 2005).

In order to compute the effects of auditory processing in predicting growth in phonological awareness once the autoregressor was controlled, phonological awareness measured in Year 1 was next included in the multiple regression equations at Step 3 (Boets et al., 2011), before entering an auditory measure at Step 4. The results are shown

Table 6

Unique Variance ( $R^2_{\text{change}}$ ) in Phonological Awareness at Year 4 Explained by Auditory Processing Measured at Year 1, controlling for PA at Year 1 as the Autoregressor; (a) Rime Oddity is Shown in Columns 1 and 2, and (b) Phoneme Deletion in Columns 3 and 4

Step	(a) $\beta$ (rime)	(a) $R^2_{\text{change}}$ (rime)	(b) $\beta$ (phoneme)	(b) $R^2_{\text{change}}$ (phoneme)
1. Age	0.082	.007	-0.045	.002
2. IQ	0.155	.024	0.089	.008
3. PA Year 1	0.410	.160***	0.443	.187***
1 Rise	-0.306	.080**	-0.273	.064*
2 Rise	-0.271	.068**	-0.249	.058*
Rise Rove	-0.401	.132***	-0.300	.074**
Rhythm	-0.330	.099**	-0.422	.162***
Duration	-0.168	.020	-0.203	.029
Intensity	-0.233	.047*	-0.248	.054*

Note.  $\beta$  = standardized  $\beta$  coefficient;  $R^2_{\text{change}}$  = unique variance accounted for at each step of the four-step fixed entry multiple regression equations; PA = phonological awareness.  
\* $p < .05$ . \*\* $p < .01$ . \*\*\* $p = .001$ .

in Table 6. The table shows that all the measures of auditory sensitivity still accounted for significant unique variance in the development of phonological awareness when the autoregressor was controlled, for both rhyme awareness and phoneme awareness, with the exception of the duration measure. The Rise Rove measure, theoretically a purer measure of auditory sensitivity to rise time (as intensity, a perceptually related cue, is varied randomly) contributed the largest amount of unique variance to rhyme awareness, while the Rhythm measure contributed the largest absolute amount of independent variance to phoneme awareness. The analyses show that auditory sensory processing makes an independent and significant longitudinal contribution to growth in phonological awareness once the effects of the autoregressor are controlled.

However, as the children had already begun reading when the study began (which was necessary in order for those with developmental dyslexia to be identified), it could also be the case that individual differences in phonological awareness are causing individual differences in the development of auditory discrimination abilities. Accordingly, analyses including auditory processing as the autoregressor are also required. Both the 1 Rise and Duration measures were administered in Year 4 of the study, and so we were also able to explore this alternative causal pathway using multiple regression equations. The equations tested whether individual differences in sensitivity to phonological awareness measured in Year 1 would predict

individual differences in auditory sensitivity 3 years later when the autoregressor (auditory processing in Year 1) was controlled. Each equation entered age at Step 1 and IQ at Step 2, and then either 1 Rise or duration sensitivity measured in Year 1 at Step 3 as the autoregressor, followed by phonological awareness measured in Year 1 at Step 4. The dependent variable was either 1 Rise threshold at Year 4 or Duration threshold at Year 4. Neither equation showed that phonological awareness was a significant predictor of auditory sensory processing (1 Rise,  $R^2 = .03$ ,  $p = .11$ ; Duration,  $R^2 = .02$ ,  $p = .19$ ). Therefore, the current data suggest that the direction of the developmental relation is from individual differences in basic auditory processing to individual differences in phonological awareness.

### Discussion

This study reports the first longitudinal investigation of which we are aware of the development of auditory sensory processing in high IQ exceptional readers. Having recruited an age-matched sample which turned out to include some children with exceptional reading and/or very high IQ, we divided the age-matched controls into CA and high reading/IQ groups. The high reading/IQ group showed significant differences in performance compared to the CA group for the reading, phonology, and language measures given at age 8 years. However, we did not find group differences following increased time in school. By 11 years of age, only vocabulary and spelling development showed significant group differences. It is notable that the high IQ exceptional readers tested here showed significantly better reading and phonological awareness skills than the CA group in Year 1 despite not having different levels of acoustic sensitivity to rise time. The CA and high reading/IQ children in fact showed no group difference in any of the auditory discrimination tasks at either developmental time point. They also showed no group difference at both time points for the RAN and PSTM tasks, also classically considered predictors of later dyslexia. Accordingly, the benefits of having high IQ appear to be most substantial in the early years of schooling, and for linguistic measures rather than sensory measures. Nevertheless, longitudinal analyses with the whole sample suggested that high IQ may protect the development of phonological awareness to some extent when auditory sensory processing of amplitude rise time is very poor. It may thus follow that children at risk for dyslexia who have high IQ

may mask their risk if tested early in development, by performing relatively well in phonological awareness tasks. This possibility requires empirical research, as high IQ children with dyslexia were not tested. The data presented here complement the work of Kuppen and her colleagues with low IQ good and poor readers, suggesting that basic sensory processing is an important determinant of phonological skills irrespective of whether a child has high or low IQ (Kuppen & Goswami, 2016; Kuppen et al., 2011, 2014).

The data suggest that amplitude rise time discrimination rather than IQ appears to be most closely associated with growth in phonology. The children with developmental dyslexia, who were matched to the CA group for IQ, showed significantly poorer performance than both control groups in all the reading, phonology, and language measures at both assessment points (ages 8 and 11), with the sole exception of receptive vocabulary. Regarding basic auditory processing, the children with developmental dyslexia showed poor auditory discrimination skills at age 8 years, with significant differences compared to the typically developing children for the acoustic rhythm and intensity measures. Three years later, they showed significantly poorer discrimination of amplitude rise time (1 Rise measure). For receptive vocabulary, the children with dyslexia did not show a difference in comparison to the CA group at either time point. This is not surprising, as studies of children with developmental dyslexia typically report no vocabulary deficits when vocabulary is measured in school-age samples. Rather, vocabulary deficits in dyslexia are typically observed earlier in the developmental trajectory, before the age of around 4 years. For example, prospective studies of younger children at family (genetic) risk of dyslexia report deficits in expressive vocabulary at 17 months (Koster et al., 2005) and in receptive vocabulary at 40 months (Scarborough, 1990). Longitudinal studies of children at-risk for dyslexia have shown delayed growth patterns of both receptive and expressive vocabulary from 17 to 35 months (van Viersen et al., 2017), while longitudinal studies of infants at risk for dyslexia show that vocabulary size at age 3 years can be predicted by infant rise time discrimination skills (Kalashnikova, Goswami, & Burnham, 2019b). However, as there is little research on vocabulary development in dyslexia between the ages of 4 and 8 years, it cannot be concluded that there is a spurt in vocabulary development after age 4 years in dyslexia (although see case study reports by Nergard-Nilssen, 2006).

To assess whether the relation between auditory sensory processing and phonological development in children with and without dyslexia is a causal one, longitudinal analyses using Year 1 measures as autoregressors were conducted. The longitudinal analyses using phonological awareness as the autoregressor showed that all the measures of sensitivity to rise time taken at the beginning of the 4-year study (1 Rise, 2 Rise, Rise Rove) made independent longitudinal contributions to growth in children's phonological awareness by Year 4. Independent longitudinal contributions to growth in phonological awareness were also made by the novel rhythm sensitivity measure, and by the measure of sensitivity to intensity changes. However, when the autoregressor was included in the longitudinal analyses, the duration measure was not a significant predictor of phonological development. By contrast, analogous longitudinal analyses predicting rise time sensitivity from phonological awareness and using rise time in Year 1 as the autoregressor did not support the alternative possibility that growth in basic auditory processing depends on phonological awareness. Matched analyses for duration sensitivity controlling for duration in Year 1 as the autoregressor showed a similar pattern. These data suggest that, of the two auditory measures identified by Hämäläinen et al. (2013) as showing the largest effect sizes in dyslexia, rise time, and duration, perceptual sensitivity to amplitude rise time may make the key contribution to the developmental trajectory for phonological awareness. Nevertheless, it should be noted that as shown in Table 5, having higher IQ protected the development of phonological awareness when rise time sensitivity was very poor.

As noted earlier, theoretically rise time is important for phonological development in part because it is related to awareness of speech rhythm (Goswami, 2011). The predictive strength of the novel acoustic rhythm measure used at Time 1 supports this interpretation. As well as predicting later phonology, the rhythm measure also showed large and significant correlations with later reading and spelling performance for this sample (Table 4). This is consistent with a recent literature showing strong associations between nonspeech rhythm processing and reading development (e.g., Ozernov-Palchik, Wolf, & Patel, 2018). The rhythm measure was omitted at Time 4 as it took a long time to administer, however, similar acoustic rhythm measures could prove useful as clinical tools. Meanwhile, developmental trajectory analyses with low IQ samples suggest that duration discrimination is delayed

in children with developmental dyslexia, while rise time discrimination is atypical (Kuppen & Goswami, 2016). For the current high reading/IQ sample, duration discrimination was not different in the children with dyslexia compared to controls. Consequently, over developmental time, rise time would appear to be the more influential auditory processing measure regarding the development of phonological awareness. On the other hand, as Hämäläinen et al. (2013) summarized their findings as evidence for auditory difficulties in dyslexia with dynamic and speech prosody-related sound features, using prosodic outcome measures rather than the sublexical outcome measures used here may have revealed significant longitudinal relations between duration sensitivity and phonology. Children with Developmental Language Disorder (DLD) are known to show impaired discrimination of both rise time and duration, and for DLD samples both measures show links with prosodic phonology (see Cumming, Wilson, & Goswami, 2015; Richards & Goswami, 2015, 2019).

In summary, the current analyses suggest that the recovery of linguistic structure from the speech signal by children may be more dependent on auditory sensory processing of amplitude modulation and speech rhythm than previously recognized. By this acoustic account, rhythm and prosody are integral features of children's phonological representations for lexical items, and atypical representation of rhythmic and prosodic features will necessarily affect sublexical phonological awareness via the linguistic hierarchy (Goswami, 2018). The acoustic structure of amplitude modulation information in speech at slower rates determines the perceptual experience of "stress beats" (P-centres, see Goswami et al., 2002; Scott, 1998), which are related to speech rhythm. The sensory discrimination of stress beats is also important for neural speech encoding (Giraud & Poeppel, 2012). Animal models of neural encoding suggest that when rhythmic predictability is established for an acoustic stimulus, neural networks realign the phase of their oscillations (synchronize their cyclical firing) so that the networks are in a high excitability phase when a new event occurs (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008). This phase synchronization enhances (amplifies) the neuronal processing of that acoustic event, thereby improving signal processing. Neural phase entrainment is known to be important for speech processing by humans (Giraud & Poeppel, 2012; Luo & Poeppel, 2007), and is atypical in children with dyslexia (Molinaro et al., 2016; Power, Mead, Barnes, & Goswami, 2013). Accordingly,

children with dyslexia may have brains that fail to amplify neuronal processing of the most informative events in the speech signal via atypical phase synchronization related to poor rise time discrimination, thereby impairing the accurate representation of phonology (Power et al., 2013). Indeed, human neuroimaging studies demonstrate that there is automatic phase-resetting of auditory cortical networks to match amplitude modulation information at different rates in speech, and that automatic sensory detection of amplitude rise times triggers this automatic phase-resetting process (Doelling, Arnal, Ghitza, & Poeppel, 2014; Gross et al., 2013). These adult data help us to understand the developmental mechanisms underpinning the relations between amplitude rise time discrimination and phonological development in children revealed here, and are summarized in detail in recent reviews of Temporal Sampling theory (Goswami, 2018, 2019). Temporal Sampling theory offers a systematic mechanistic and theoretical framework for linking sensory, neural, and linguistic difficulties in children.

A limitation of the current approach is that the auditory data rely on psychophysical measures, which are difficult to use with young children. In adult psychophysics, it is usual to administer hundreds of trials to a handful of participants, and the absolute threshold is considered an objective measure of the just noticeable difference. With children, such intensive testing is not feasible, hence auditory performance is best interpreted within the range of thresholds achieved by a group of children (as done here). Factors such as task familiarity and engagement with the test may also affect children's performance (see Kuppen et al., 2011, for a discussion). Regarding biomarkers for dyslexia (Goswami, 2009), one prediction from Temporal Sampling theory is that neural encoding of the speech envelope should be atypical in developmental dyslexia. Neural encoding of speech envelope information is indeed atypical in dyslexia, providing an alternative biomarker (Abrams, Nicol, Zecker, & Kraus, 2009; Di Liberto et al., 2018; Power, Colling, Mead, Barnes, & Goswami, 2016). Another prediction is that children and adults with dyslexia should be impaired at perceiving noise-vocoded speech, where spectral content is removed but amplitude modulation is preserved; this is the case (Johnson, Pennington, Lowenstein, & Nitttrouer, 2011; Megnin-Viggars & Goswami, 2013; Power et al., 2016). Tasks for younger children based on noise-vocoded speech offer another potential avenue for developing child-friendly diagnostic measures of dyslexic

risk (e.g., using puppets who speak noise-vocoded speech). Systematic developmental investigation of the complementary roles of the speech envelope and amplitude modulation in speech perception may offer further opportunities for diagnosis and remediation (Rios-Lopez, Molnar, Lizarazu, & Lallier, 2017).

In conclusion, the current study showed independent effects of a range of measures of auditory sensitivity as longitudinal predictors of growth in phonological awareness. There was no complementary predictive independent effect of phonological awareness on the growth of auditory sensitivity. The data support the general theoretical claim made by Temporal Sampling theory that difficulties in processing the structure of amplitude modulation are an important developmental cause of the phonological difficulties that characterize children with developmental dyslexia across languages. Rise time difficulties are present with both speech (Goswami, Fosker, et al., 2011) and nonspeech stimuli (Goswami, Wang, et al., 2011; Goswami et al., 2002, 2010), the effect sizes are large (Hämäläinen et al., 2013), the sensory difficulties are not related to IQ or vocabulary differences (Kuppen & Goswami, 2016; Kuppen et al., 2011, 2014), and the causal direction appears to be from sensory difficulties to phonological and linguistic difficulties (Corriveau et al., 2010; Kalashnikova et al., 2019b; Law et al., 2017; Plakas et al., 2013; Vanvooren et al., 2017). Accurate processing of the amplitude envelope is critical for speech intelligibility (Giraud & Poeppel, 2012). Therefore, developmental difficulties in rise time discrimination will affect the development of the child's entire phonological system. The data analyzed here show that these multiple links between accurate amplitude rise time processing and recovering phonological structure from the speech signal appear to be relatively independent of IQ. Performance at younger ages in behavioral phonological awareness tasks may, however, be affected by IQ, and having higher IQ may protect the development of phonological awareness to some extent if rise time processing is very poor. However, consistent with a sensory framework, the atypical neural activation measured in fMRI studies when children with developmental dyslexia are performing phonological tasks also appears to be independent of IQ (Hancock, Gabrieli, & Hoefl, 2016; Tanaka et al., 2011). This would be expected on the basis of the data presented in the current study. We find that individual differences in auditory sensory processing are an important cause of the phonological deficits that characterize children with dyslexia,

and that individual differences in auditory sensory processing are largely independent of IQ.

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### Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

**Figure S1.** Scatterplot Showing 1 Rise Threshold in Year 1 Against Rime Oddity in Year 4 by Behavioural Group

**Figure S2.** Scatterplot Showing 2 Rise Threshold in Year 1 Against Rime Oddity in Year 4 by Behavioural Group

**Figure S3.** Scatterplot Showing Rise Rove Threshold in Year 1 Against Rime Oddity in Year 4 by Behavioural Group

**Table S1.** Auditory Stimulus Parameters

**Table S2.** Oddity Onset Task Year 1 Items

**Table S3.** Rime Oddity Task Year 4 Items

**Table S4.** Phoneme Deletion Task Year 4 Items