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Variability in auditory processing performance is associated with reading difficulties rather than with history of otitis media

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The nature and cause of auditory processing deficits in dyslexic individuals have been debated for decades. Auditory processing deficits were argued to be the first step in a causal chain of difficulties, leading to difficulties in speech perception and thereby phonological processing and literacy difficulties. More recently, it has been argued that auditory processing difficulties may not be causally related to language and literacy difficulties. This study compares two groups who have phonological processing impairments for different reasons: dyslexia and a history of otitis media (OM). We compared their discrimination thresholds and response variability to chronological age- and reading age-matched controls, across three auditory processing tasks: frequency discrimination, rise-time discrimination and speech perception. Dyslexic children showed raised frequency discrimination thresholds in comparison with age-matched controls but did not differ from reading age-matched controls or individuals with a history of OM. There were no group differences on speech perception or rise-time tasks. For the dyslexic children, there was an association between phonological awareness and frequency discrimination response variability, but no association with thresholds. These findings are not consistent with a 'causal chain' explanation but could be accounted for within a multiple deficits view of literacy difficulties.

KEYWORDS
auditory processing, dyslexia, frequency discrimination, otitis media, rise time

Practitioner Points

- Individuals with dyslexia show more variable threshold scores on a frequency discrimination task.
- Individuals with a history of otitis media do not show impairments in these measures of auditory processing.
- Measures of auditory processing are not necessarily useful as diagnostic indicators of dyslexia, even though some dyslexic individuals show difficulties in them.
- Response variability can reveal when discrimination thresholds may be unreliable due to task demands or attention.
- Auditory processing difficulties have important consequences, and signs of impairments in auditory processing should be explored.

1 | INTRODUCTION

Theories that literacy difficulties are underpinned by deficits in auditory processing have been debated for decades (Goswami, 2011; Tallal, 1980). It is well established that some, but not all children with literacy difficulties, demonstrate difficulties on a range of auditory processing tasks (Hämäläinen et al., 2013). However, at least three different potential explanations have been proposed for this association, including a direct causal relationship between auditory processing and phonological processing; a role for auditory processing as part of a multifactorial explanation of literacy difficulties; and an association between the skills, but no causal link—perhaps because a third variable such as sustained attention is associated with both reading and auditory processing performance. To test these theories, in this study, we compared the auditory processing skills of a group of dyslexic children with a group of children with a history of otitis media (OM: middle ear infection), along with chronological age- and reading age-matched typically developing children. Both children with dyslexia and children with a history of OM have previously been shown to have phonological processing difficulties (Carroll & Breadmore, 2018), but in the case of OM, the aetiology is known. Comparing the auditory processing performance of these two groups helps to distinguish between causal and multifactorial explanations of literacy difficulties.

1.1 | Theories that propose a relationship between auditory processing, language and literacy

There are now several theories that propose a direct causal relationship between deficits in auditory processing and language and literacy difficulties (e.g., Goswami et al., 2002; Stein, 2001; Tallal, 2004). While literacy difficulties (dyslexia) and language difficulties (developmental language disorder [DLD]) are separable disorders, there is a large overlap between them, with around 50% of individuals with DLD showing literacy difficulties (McArthur et al., 2000). Auditory processing theories often assume that DLD and dyslexia have shared underlying deficits. The link between auditory processing deficits and literacy is commonly assumed to be mediated by difficulties in speech perception and thereby language—specifically phonological processing (e.g., Goswami et al., 2002; Stein, 2001; Tallal, 2004).

One of the first theories of this kind was proposed by Tallal and colleagues, who argued that children with DLD (Tallal & Piercy, 1973a, 1973b), as well as those with dyslexia (Tallal et al., 1993), had deficits in their processing of brief, or rapidly presented, auditory information. According to the 'rate-processing constraint hypothesis', these deficits lead to difficulties in processing the rapid changes in frequency that occur within formants, which are critical for the identification and discrimination of speech sounds such as stop consonants. Similarly, the 'magnocellular theory' proposes that individuals with dyslexia exhibit—in addition to visual deficits—deficits in processing the rapid changes in spectrum that occur within formants; that is, changes in frequency, content and amplitude over time (e.g., Stein, 2018). More recently, the 'temporal sampling framework' proposes that dyslexia is caused by a deficit in the timing of neural oscillations that encode incoming auditory information, including speech (Goswami, 2011). Note that these theories vary according to the specific auditory processes that are proposed to be impaired in dyslexic groups. However, for all theories, the general premise is the same: that deficits in one or more auditory processes lead to difficulties in speech perception and thereby phonological processing and, in turn, reading and spelling.

A wide range of different tasks and stimuli have been used to test theories about the relationship between auditory processing, language and literacy. For example, studies testing the rate-processing constraint hypothesis have examined the performance of dyslexic and/or DLD groups on tasks including duration discrimination, forward and backward masking and the detection of gaps in sounds (e.g., Boets et al., 2007; Halliday & Bishop, 2006). Those assessing magnocellular theory have assessed frequency and amplitude modulation (FM and AM) detection (e.g., McAnally & Stein, 1996; Menell et al., 1999). Meanwhile, studies assessing the temporal sampling framework have used measures such as rise-time discrimination (i.e., the discrimination of changes in the amplitude onset of sounds), as well as prosody, rhythm and beat perception (Goswami et al., 2002; Hämäläinen et al., 2008). In addition, a number of studies have reported evidence for the poorer performance of both children and adults with dyslexia and/or DLD on auditory tasks that use static (i.e., non-fluctuating) stimuli such as frequency discrimination (Banai & Ahissar, 2004). The wide range of tasks and methods used has led to a lack of clarity in findings in the field. Nevertheless, a recent systematic review concluded that group differences between individuals with dyslexia and controls indicated deficits in rise time, frequency, and duration discrimination, as well as AM and FM detection (Hämäläinen et al., 2013).

1.2 | Alternate explanations

To add to the complexity, some researchers have argued that the auditory processing deficits observed in individuals with dyslexia (and/or DLD) may in fact be due to higher-level deficits in cognitive processes such as working memory, sustained attention or other executive function rather than deficits in auditory perception per se. For instance, simulations run by Roach et al. (2004) showed that the inclusion of trials where the simulated 'participant' acted in an inattentive way generated a pattern of variability in their models which was similar to that observed in dyslexic groups. More recently, a longitudinal study of 245 children found that those with language difficulties (but not those with a family history of dyslexia) had poorer frequency discrimination skills than controls at 5.5 years, but frequency discrimination did not predict reading or language skills over time. Rather, frequency discrimination thresholds were predicted by executive function skills in this group (Snowling et al., 2018). In addition, a recent meta-analysis of studies of frequency discrimination in dyslexic samples concluded that variability in both the participant characteristics and the psychophysical tasks contributed to the variability in effect sizes between studies (Witton et al., 2020). These findings are compelling, in that they suggest that the observed association between auditory processing deficits and developmental disorders of language and literacy may be just an association. Thus, according to these researchers, individuals with dyslexia and/or DLD may be more likely to have deficits in working memory, sustained attention, or other executive functions that underlie or mediate the relationship between their language and auditory processing difficulties, without a causal relationship between the two.

A useful way to investigate the extent to which performance on auditory processing tasks is affected by sustained attention or other executive function difficulties is to examine response variability. The threshold estimation tasks use an adaptive staircase procedure. The difference between the different stimuli starts large—making the detection task fairly easy initially. The differences between stimuli become progressively smaller until a learner makes an error, at which point the differences start to become progressively larger until a correct answer is given.

Once a correct answer is given, the differences start reducing again and so on. This procedure is useful in estimating thresholds as it focuses on stimuli close to an individual's threshold, and over the session, the reversals should draw closer together as the true perceptual threshold is determined. However, if an individual is inconsistent in their responses and makes errors at random, the procedure is less likely to arrive at the genuine perceptual threshold in the number of trials available. This would be observed as high levels of response variability. Response variability is typically measured by examining the standard deviation (SD) of the reversals used to calculate the thresholds.

Previous research has argued that high variability in performance on auditory processing tasks results from issues with attention in non-dyslexic populations. For example, Moore et al. (2008) found that high response variability due to poor sustained attention provided an explanation for elevated frequency discrimination thresholds in significant numbers of audiometrically typical children. They argued that the timing of the drifts in performance suggest an issue of sustained attention. Tomlin et al. (2015) directly measured this relationship in children referred for auditory processing assessment (and controls). They concluded that deficits in sustained attention influence (or are at least correlated with) auditory processing ability. Although the direction of causality is unclear, Tomlin et al. (2015) argued that many children referred for auditory processing assessment show cognitive deficits which are likely to cause the perceived difficulty and/or affect test results. It is therefore important to examine response variability in the present study, in addition to auditory processing thresholds.

Finally, aside from auditory processing theories, other researchers have argued that the deficits in phonological processing that are core to both reading and language disorders (Bishop & Snowling, 2004) instead arise as a result of specific difficulties with speech perception. Specifically, the 'allophonic theory' of dyslexia (Serniclaes, 2018; Serniclaes et al., 2004) proposes that individuals with dyslexia are *more* sensitive to differences between speech sounds that occur within a particular phonemic category (i.e., allophonic features), relative to normally reading controls. So, the theory goes, whereas normal readers learn to ignore subtle acoustic differences between speech sounds that have no relevance at the level of the phoneme, poor readers do not, as evidenced by their enhanced discrimination of allophonic boundaries (Bogliotti et al., 2008; Noordenbos et al., 2012a, 2012b, c.f. Messaoud-Galusi et al., 2011). In turn, this leads to a delay in accessing phonemic representations that are critical in learning to read (Blomert, 2011). Consistent with this idea, several studies have now shown that the phonological representations of adults with dyslexia are not imprecise at all, as auditory processing theories might predict, but instead are more difficult to access (e.g., Boets et al., 2013; Ramus & Szenkovits, 2008). Therefore, according to the allophonic theory, we might expect poor readers to show greater sensitivity to acoustic differences within speech categories compared to their normally reading peers.

1.3 | Empirical investigation

There are a few ways to investigate the disparities between different theoretical models of auditory processing deficits empirically. One is to use a standardised task procedure with low external task demands, across a wide range of different auditory stimuli, and explore which (if any) task(s) children with literacy or language difficulties have particular difficulties with. Another is to examine children with different underlying deficits, to investigate the putative causal pathway between literacy and auditory processing. If auditory processing deficits cause language and literacy difficulties via their influence on speech perception, one might expect to see these difficulties in children with speech perception difficulties such as those with mild-to-moderate hearing loss (MMHL). Halliday et al. (2017) combined these approaches. They examined profiles of auditory processing deficits using a standardized task format with a wide range of different auditory stimuli in a large sample of children with MMHL. They found, in that sample, that deficits on a general auditory processing factor were *necessary*, but not *sufficient* for language difficulties. In other words, almost all individuals with poor language also showed poor auditory processing, while some individuals showed poor auditory processing but good language skills. These findings were therefore in line with a multiple cause model of the association between auditory processing and language difficulties. Two tasks which did not load on the general auditory processing factor—AM detection (e.g., Goswami, 2011) and categorical speech discrimination—showed different patterns of association. Whereas poor performance on AM detection was rare and therefore not necessary for language deficits, it was typically sufficient, consistent with a causal model in which auditory processing difficulties are one of multiple potential causes. In contrast, performance on the speech discrimination task was not closely associated with language difficulties in this group. In summary, the evidence did not support a straightforward causal chain between auditory processing difficulties and language via speech processing. Instead, it suggested auditory processing difficulties might form one or more parts of a multiple cause model.

The approach taken by Halliday et al. (2017) is useful because it selects a sample of children at high risk of auditory processing difficulties and examines the language skills of these children. However, the study had some limitations. First, Halliday et al. (2017) did not include a direct comparison between children with MMHL and children selected on the basis of language and literacy difficulties, meaning it was not possible to know how similar these two groups would have been. Halliday et al. (2017) also included children with widely varying ages, and while they did use a pairwise-matched chronological age control group, they did not include an ability matched group of younger, typically developing controls. This is a useful approach in examining causal hypotheses around developmental disorders, which allows us to consider whether the observed level of auditory functioning only supports reading to this level or beyond. The use of reading level matches is a widespread practice in the field of dyslexia research but relatively underused in auditory processing studies (Goswami, 2015). The classical argument used is that comparing individuals with dyslexia with younger, reading age-matched controls allows one to understand whether they show a pattern of deficit (i.e., abnormal progress) in a particular area, or whether they show developmental delay—that is, a profile similar to younger, typical readers (Bradley & Bryant, 1983). A pattern of deficit is taken to imply that this deficit may be a potential cause of dyslexia, though this interpretation is not universally agreed (Zoccolotti, 2020). Meta-analyses have shown that as a group, dyslexic children tend to show poorer performance than reading level controls on phonological processing tasks (Melby-Lervåg et al., 2012), but not on auditory processing (Parrila et al., 2020). Reading-level matches have not been used before to examine the auditory processing skills of individuals with OM, to our knowledge, but it allows us to know whether their profile is in line with the level expected given their reading achievement.

Direct comparisons of children with two different disorder profiles can be very illuminating, particularly in understanding how shared underlying deficits combine to create different developmental disorder profiles (Hayiou-Thomas et al., 2017; Snowling et al., 2019). Direct comparisons across disorders can also highlight when deficits seem similar but actually differ in key underlying ways. For example, Carroll and Breadmore (2018) showed that while children with dyslexia and children with a history of OM both showed phonological awareness deficits, the profile of performance across the different phonological awareness tasks differed for the two groups. Individuals with dyslexia had particular difficulties on the meta-linguistic tasks such as phoneme deletion, while the individuals with a history of OM showed difficulties in segmenting and blending tasks, alongside relatively good meta-linguistic knowledge. If auditory processing deficits underlie phonological processing difficulties, as is widely claimed, one might expect to see differences in the profile of auditory processing skills between these two groups. However, a direct comparison has not previously been carried out.

1.4 | Auditory processing following otitis media with effusion

Most children suffer from middle ear infections at some point during the pre-school years, but a minority show significant recurrent OME. OME causes fluctuating levels of hearing loss during an episode and has been associated with changes in auditory perception that are both transient (i.e., resolve once the hearing loss has gone) and persistent (i.e., remain after the OME has resolved). For instance, animal models have shown that unilateral OME leads to deficits in the processing of sound localization cues (e.g., Lupo et al., 2011), whereas bilateral OME during a sensitive period leads to deficits in the use of AM and FM cues which outlast the hearing loss (Buran et al., 2014; Caras &

Sanes, 2015; Von Trapp et al., 2017). In humans, children with a history of OME have been shown to display deficits in binaural processing (Hall & Grose, 1993, 1994; Hogan & Moore, 2003; Moore et al., 1991), spectro-temporal processing (Hall & Grose, 1994) and AM detection (McKenna Benoit et al., 2019), which outlast the ear fluid. Whilst the majority of these deficits appear to resolve over time and/or after surgery (i.e., in the form of grommets), some show a relatively prolonged period of recovery. For instance, deficits in binaural processing (Hall et al., 1995; Tomlin & Rance, 2014), speech perception in noise (Schilder et al., 1994; Zumach et al., 2009), frequency discrimination (Cranford et al., 1997) and AM detection (McKenna Benoit et al., 2019) have all been shown in children with a history of OME several years after the hearing loss has resolved. In addition, OME during the first 3 years of life has been associated with high-frequency hearing loss and differences in the acoustic middle ear muscle reflex and auditory brainstem response at 8 years of age (Gravel et al., 2006). Some research has indicated that early OM is a risk factor for later central auditory processing disorder (CAPD), in which children show deficits in auditory processing despite normal hearing (Khavarghazalani et al., 2016). Research on CAPD and learning difficulties such as dyslexia have largely separate literatures, despite potential overlap (Dawes & Bishop, 2009). Nonetheless, there are good grounds to suspect that children with OM would have difficulties on the types of auditory processing tasks described in the studies above. We therefore predict that children with a history of OM, like those with dyslexia, would be at greater risk of showing deficits in auditory processing relative to their normally hearing or normally reading peers, but for different reasons.

These changes in auditory perception, combined with diminished audibility during an OME episode, may over time lead to reduced access and exposure to speech sounds, in the years in which language is acquired most rapidly. Consistent with this idea, individuals with a history of OME have been found to show relative weaknesses in phonological processing (Nittrouer & Burton, 2005) and literacy tasks (Kindig & Richards, 2000; Winskel, 2006), though some studies have indicated effects are small (Peters et al., 1994). In addition, several large-scale prospective studies have shown that children who experience recurrent OME during the first 2–3 years of life have poorer language outcomes at age 1–5 years (Friel-Patti & Finitzo, 1990; Roberts et al., 2002; Schilder et al., 1993; Teele et al., 1990, c.f. Paradise et al., 2007; Roberts et al., 1991). However, these group differences tend to resolve by 7–8 years of age (Roberts et al., 2002; Schilder et al., 1993; Zumach et al., 2010, c.f. Teele et al., 1990). On that basis, a meta-analysis concluded that there was little or no evidence for a long-term negative impact of early OME on children's acquisition of oral language, whilst acknowledging a number of shortcomings in the designs of early studies (Roberts et al., 2004).

There are at least two reasons for questioning whether this conclusion about the limited impact of OM on language development extends to literacy development in middle childhood. The first is that there is some evidence of weaknesses on literacy tasks despite normal oral language in a sample of children with a history of OM (Carroll & Breadmore, 2018; Winskel, 2006). This suggests that aspects of literacy might be particularly susceptible to deficits caused by early OME. The second is that recent work has suggested that specific language deficits may emerge later in childhood, not earlier, for some individuals with OME (Brennan-Jones et al., 2020).

Nittrouer and Burton (2005) examined the profile of speech perception, phonological processing and auditory temporal processing impairments in individuals with a history of OME. While significant weaknesses in speech perception, verbal short-term memory and phonological awareness were found, there were no specific impairments in auditory temporal processing. The authors conclude that auditory temporal processing is not part of the causal pathway from OME to phonological difficulties. However, the temporal processing task used had high task demands in terms of memory and verbal labelling, resulting in over a third of the OME group not passing the training phase. It therefore is not an ideal measure of auditory temporal processing and may be influenced by executive functions, as described previously in relation to studies of auditory processing.

2 | THE PRESENT STUDY

The current study examined the relationship between auditory processing and reading acquisition by comparing the performance of five groups of children on three auditory processing tests. Children with dyslexia and children with a history of OM matched on age were compared with (i) one another, (ii) chronological age-matched controls (CA) and (iii) reading-age-matched controls (RA) on measures of (a) frequency discrimination, (b) rise-time discrimination and (c) speech discrimination. These three measures represent the three different factors of auditory processing found by Halliday et al. (2017), which reported a general auditory processing factor and separate factors for rise-time discrimination and speech perception respectively. Further, these tasks measure elements of auditory processing associated with different theoretical accounts of dyslexia (Goswami, 2011; Stein, 2018; Tallal et al., 1993). Goswami and Tallal theorize that auditory processing impairments lead to deficits in speech processing and thereby phonological processing. However, that assumption seems to contradict the allophonic theory of dyslexia, which instead suggests that the phonological processing deficits might be caused by superior speech discrimination (Serniclaes, 2018; Serniclaes et al., 2004). To measure these auditory processing skills, we selected established odd-one-out tasks which have been applied in studies of typical development (Bishop et al., 2011), as well as in children with DLD (Bishop et al., 2010) and mild-to-moderate sensorineural hearing loss (Halliday et al., 2017, 2019).

We reasoned that if deficits in auditory perception are causally related to reading difficulties in children via difficulties in speech perception, then (1) as a group, both children with dyslexia and children with a history of OM should perform more poorly than chronological age-matched controls on some or all of the auditory processing tasks, and (2) the discrimination thresholds of children with dyslexia should resemble those of reading-age-matched controls.

If deficits in auditory perception are one of a number of factors contributing to the poorer reading outcomes, then one would predict that a subset of the dyslexic group would have difficulties. This could result in an overall group deficit in comparison with the CA controls. We would also expect a correlation between auditory processing discrimination thresholds and phonological awareness. By looking at these correlations, we can also explore evidence of a causal chain from frequency discrimination and/or rise-time discrimination, through speech discrimination to phonological awareness, bearing in mind that correlation is necessary, but not sufficient, for a causal relationship. Similarly, significant correlations would be a logical precursor to carrying out multiple regression. In addition, we can compare the patterns of performance in children with dyslexia with those with OM. If children with OM do not show the same deficits in the auditory processing tasks (as suggested by Nittrouer & Burton, 2005), this indicates that the documented phonological awareness difficulties that this group of children with OM show (Carroll & Breadmore, 2018) are not caused by difficulties in the types of auditory processing measured by these tasks.

Finally, if deficits in auditory perception are mediated by deficits in sustained attention, then children with dyslexia may demonstrate more response variability than CAs, due to the well-documented co-occurrence of dyslexia and attention difficulties (Willcutt & Pennington, 2000).

3 | METHOD

Children with dyslexia and a history of OM and reading-ability-matched and chronological age-matched children completed established frequency discrimination, rise-time and speech discrimination tasks.

3.1 | Participants

Children were recruited through opt-in parental consent, and attended schools across the Midlands, UK. All participants were monolingual native English speakers. In total, 114 children took part in the current study, falling into five participant groups: (i) children with dyslexia (dyslexia group), (ii) typically developing children matched to those with dyslexia for reading ability (RA dyslexia group), (iii) children with a history of OM (OM group), (iv) typically developing children matched to those with OM for reading ability (RA OM group) and (v) typically developing children matched for age to the dyslexia and OM groups (CA group). The typically developing children (RA dyslexia, RA OM, CA groups) had reading abilities in the normal range and their parents reported that they did not have any history of language, literacy or hearing difficulties. All children's hearing was assessed on the day of testing using an Amplivox 116 screening audiometer with Audiocups, to conduct pure-tone air-conduction audiometry without masking (at 500 Hz, 1, 2, 4 and 8 kHz) in accordance with the Recommended Procedure by the British Society of Audiology (2011). This confirmed that none of the children in typically developing groups were experiencing hearing loss. Details of the hearing of children in the dyslexic and OM groups are below.

Descriptive summaries of age, British Ability Scales word reading (Elliot & Smith, 2011), YARC passage reading accuracy, reading rate and reading comprehension (Snowling et al., 2009), as well as phonological awareness from the Clinical Evaluation of Language Fundamentals (CELF; Semel et al., 2006) are provided in Table 1.[1] Reading and phonological awareness tasks were administered and scored according to standardized instructions. The CELF phonological awareness measure is a composite score from 17 subsections that measure syllable, rhyme and phoneme awareness including identification, segmentation, blending and manipulation.

3.1.1 | Children with dyslexia and reading ability matched controls

Twenty-one participants were categorized as children with dyslexia (12 female and 9 male) and were aged 9.7–12.3 years (mean 10.10 years, SD 9 months). These children obtained a standard score on the British Ability Scales word reading test of 90 or below (mean 83, SD 4, range 75–90) and the mean reading age equivalence was 8.3 years. Independent sample *t*-tests confirmed that the dyslexia group had word reading age equivalents significantly below their chronological age-matched peers (CA group); $t(49) = -10.81$, $p < 0.001$. As one would expect for this population, standard scores indicate that passage reading accuracy and reading rate were below age expectations. Mean reading comprehension was in the average range for the dyslexic group but was significantly lower than CAs (see Table 1). *t*-tests comparing children with dyslexia with CAs confirmed significant differences in each measure, including phonological awareness; YARC ability scores accuracy $t(49) = -9.37$, $p < 0.001$; reading rate $t(49) = -6.82$, $p < 0.001$; reading comprehension $t(49) = -3.44$, $p = 0.001$; and CELF PA $t(49) = -3.15$, $p = 0.003$. Children were excluded from the dyslexia group if their parents reported a history of multiple ear infections or hearing loss/impairment. Air-conduction pure tone audiometry revealed two participants who may have undiagnosed mild hearing loss, just crossing the threshold (>25 dB and ≤ 40 dB HL). One of these participants presented with undiagnosed mild bilateral hearing loss (right average 27.5 dB HL, left average 25 dB HL), and one presented with unilateral mild hearing loss (right average 26 dB HL, left average 4 dB HL). These children were included in the sample.

The RA dyslexia group was formed of 21 reading ability matched controls (12 female, 9 male) aged 6.10–10.7 years (mean 8.6 years, SD 13 months), who were group-wise matched to the dyslexia group for word reading ability. Independent samples *t*-tests confirmed that the dyslexia and RA dyslexia controls did not differ in word reading age equivalence $t(40) = -1.30$, $p = 0.201$.

3.1.2 | Children with OM and reading ability-matched controls

Twenty-one children were categorized as having a history of OM (4 female, 17 male) and were aged 9.8–12.2 years (mean 10.9 years, SD 9 months). The parents of these children reported a history of multiple ear infections (more than seven before the age of three) or medical diagnosis of otitis media with effusion or glue ear (see Carroll & Breadmore, 2018 for further details of inclusionary criteria in this group). Children with dyslexia and OM did not differ in chronological age $t(40) = 0.42$, $p = 0.674$. The OM group had highly variable reading abilities (see Table 1). As a group, children with OM had word reading ages that were significantly below their age-matched peers (CA group); $t(49) = -2.86$, $p = 0.006$ but higher than those with dyslexia; $t(40) = -5.54$, $p < 0.001$. Air-conduction pure tone audiometry revealed that, at the time of testing, one child had bilateral MMHL (right 37 dB HL, left 52 dB HL), one

TABLE 1 Summary information about participants in dyslexia, RA dyslexia, OM, RA dyslexia and CA groups (chronological age, reading ability and phonological awareness).

Mean (SD)	*N*	Chronological age	BAS word reading	BAS word reading	YARC accuracy	YARC reading rate	YARC comprehension	CELF phonological awareness
			Standard score	Reading age equivalence	Standard score	Standard score	Standard score	Raw score
Dyslexia	21	10.10 (0.9)	83.0 (3.9)	8.3 (0.10)	88.1 (6.8)	89.4 (9.4)	99.1 (8.1)	73.9 (6.5)
RA dyslexia	21	8.6 (1.1)	108.9 (14.8)	8.7 (0.9)	106.2 (9.1)	108.6 (11.6)	108.0 (7.9)	72.9 (5.7)
OM	21	10.9 (0.9)	99.7 (10.2)	10.8 (1.9)	103.6 (8.4)	104.2 (9.6)	105.3 (10.7)	75.6 (4.8)
RA OM	21	10.4 (1.5)	105.7 (10.7)	10.9 (1.8)	104.6 (7.8)	107.8 (11.5)	108.2 (11.6)	77.4 (3.7)
CA	30	10.9 (0.8)	107.4 (6.0)	11.11 (1.5)	108.3 (6.4)	109.0 (8.9)	110.7 (12.1)	78.5 (4.0)

Note: Ages/age equivalents are presented years and months. CELF phonological awareness raw score reported because standard scores are not available.
Abbreviations: BAS, British Ability Scales; CA, chronological age; CELF, Clinical Evaluation of Language Fundamentals; OM, otitis media; RA, reading age; YARC, York Assessment of Reading Comprehension.

child had bilateral mild hearing loss (right 29 dB HL, left 27 dB HL) and two children had unilateral mild hearing loss (right 30 dB HL, left 15 dB HL and right 21 dB HL, left 26 dB HL respectively). This was consistent with the known hearing loss reported by these four children's parents. These children were included in the sample.

The RA OM group was formed of 21 reading ability matched controls (7 female, 14 male) aged 7.10–12.4 years (mean 10.4, SD 1.5 years) who were group-wise matched to children with OM for reading ability. Independent samples t-tests confirmed that they did not differ on word reading age equivalence $t(40) = -0.14$, $p = 0.893$.

3.1.3 | Chronological age-matched controls

The CA group was formed of 30 typically developing children (15 female, 15 male) aged 9.8–12.0 years (mean 10.9, SD 8 months) group-wise matched to the dyslexia group and the OM group. Independent samples *t*-tests confirmed that neither the dyslexic nor the OM group differed from the CA group on chronological age $t(49) = 0.49$, $p = 0.630$ and $t(49) = -0.00$, $p = 0.997$, respectively.

3.2 | Auditory processing tasks

Participants undertook a short battery of three auditory processing tasks, which formed part of a larger test battery that has been described in detail elsewhere (Bishop et al., 2010, 2011; Halliday et al., 2017, 2019). Testing was undertaken on an Intel i5–2430M CPU at 2.40 GHz Toshiba Satellite Pro R850–19 H laptop computer using custom software utilizing a computer-game-like format. Before each task, a series of five easy practice trials was presented to ensure that participants understood what the task entailed and what contrast(s) they were listening for. All children obtained at least four out of five correct responses on the practice trials, so we were confident that they understood what was required of them. Tasks were presented in counter-balanced order, and stimuli were delivered via Sennheiser HD215 headphones, with the volume set to a comfortable listening level. Audibility was confirmed during the practice trials.

For each task, a three-interval, three-alternative forced-choice (odd-one-out) paradigm was used. On each trial, participants heard three sounds, each separated by an inter-stimulus interval of 500 ms and represented on screen by cartoon character. Two of the characters ‘made’ an identical (standard) sound, and the third, randomly determined character, made a different (target) sound. Participants were instructed to select (by clicking with the mouse) the character that ‘made the different sound’. Feedback was provided to signal correct/incorrect responses.

At the start of each task, a one-down, one-up adaptive procedure was used to vary the difficulty level and to rapidly converge upon threshold (Baker & Rosen, 2001). This changed to a three-down, one-up procedure after the first reversal, targeting 79.4% correct performance (Levitt, 1971). Step size decreased over the first three reversals and remained constant thereafter. Tasks terminated after 50 trials, or once four reversals had occurred at the final step size (whichever came first). Discrimination thresholds were calculated as the arithmetic mean of the target stimuli over the last four reversals. For tasks where logarithmic step sizes were used, this was equivalent to the geometric mean. For all tasks, a higher discrimination threshold corresponded to poorer performance; that is, participants required a bigger difference between the standard and target stimuli in order to detect a difference. In addition, the SD of the target stimuli over the final four reversals was calculated as a measure of response variability.

3.2.1 | Frequency discrimination

For the frequency discrimination task, stimuli were 500-ms sinusoids, ramped on and off with 15-ms linear ramps. The standard was fixed at 1 kHz, and the highest (initial) target stimulus was 1.5 kHz. The frequency difference between the standard and target stimuli was initially reduced by a factor of two, which decreased over the first three reversals to a factor of √2. Discrimination thresholds are reported as the difference, in Hz, between the standard and target stimuli.

3.2.2 | Rise time

Rise-time discrimination was assessed using a 500-ms 1 kHz sinusoid, with a fixed fall time of 50 ms. The standard had a rise time of 15 ms and a steady state of 435 ms, and the initial target stimulus had a rise time of 435- and 0-ms steady states. Stimuli were RMS-normalized to ensure that there were no differences in overall amplitude between stimuli even when the steady state was short. The difference between the standard and the target stimuli varied in logarithmic steps, and step size decreased over the first three reversals. Discrimination thresholds are reported as the duration, in ms, of the rise time of the target stimulus.

3.2.3 | Speech discrimination

Speech discrimination was assessed using a /bɑ/–/dɑ/ consonant-discrimination task. The standard was a 175-ms digitized /bɑ/ originally spoken by a female speaker, and the initial target stimulus was a 175-ms digitized /dɑ/ spoken by the same speaker (see Bishop et al., 2010). A continuum of 98 intermediary stimulus was created between the standard and the initial target stimuli, using the speech-morphing programme TANDEM-STRAIGHT (Kawahara et al., 2008). The difference between the standard and the target stimulus was initially 15 places along the continuum, reducing to five over the first three reversals. Discrimination thresholds are reported as the place along the continuum, in %, of the target stimulus, with higher percentages corresponding to a more /dɑ/–like stimulus.

4 | RESULTS

In the first set of analyses, we compared performance on the auditory processing tasks by using the discrimination thresholds as the dependent variable. In the second set of analyses, we compared response variability across the auditory processing tasks by using the SD of the target stimuli over the final included reversals. To balance the risk of making Type I and Type II errors (given limited power due to sample size and number of groups), in both cases, we made a priori contrasts without adjusting the alpha level for multiple comparisons. First, we compared the children matched by age (dyslexia, OM, CA group), and then we compared dyslexia and OM groups to their reading-ability matched controls (RA dyslexia, RA OM). Given the hypotheses about the expected task differences, we carried out an overall MANOVA across all tasks, and additional separate ANOVAs for each task in turn. Bonferroni adjusted post hoc tests were only carried out to examine significant effects. Finally, we explored the relationship between auditory processing and phonological awareness in partial correlations (controlling for age) within each of the age-matched groups (dyslexia, OM, CA group).

4.1 | Auditory processing performance: Discrimination threshold analyses

Figure 1 illustrates the differences in performance on the auditory processing tasks as a function of participant group. Large discrimination thresholds indicate that participants required stimuli to differ by a large amount to reliably identify the odd-one-out—they correspond to poorer performance. A MANOVA with the between-subjects factor participant group (dyslexia, OM, CA groups) and log-transformed dependent variables frequency discrimination, rise-time and speech discrimination thresholds indicated no overall differences in auditory processing between groups $F(6,134) = 1.60$, $p = 0.152$, wilks' $\lambda = 0.87$, partial $\eta^2 = 0.07$. Nonetheless, the task specific ANOVAs of between-subjects effects revealed significant differences in frequency discrimination $F(2,69) = 4.72$, $p = 0.012$, partial $\eta^2 = 0.12$, but not in rise time $F(2,69) = 0.84$, $p = 0.435$, partial $\eta^2 = 0.02$ or speech discrimination $F(2,69) = 0.48$, $p = 0.624$, partial $\eta^2 = 0.01$. Bonferroni post hoc tests indicated that the main effect in frequency discrimination was due to significant differences between children with dyslexia and CAs ($p = 0.011$), with the children with dyslexia exhibiting higher thresholds and therefore poorer performance. The OM group differed neither from those with dyslexia ($p = 0.822$) nor CAs ($p = 0.224$).

Comparisons between children with dyslexia and RA dyslexia revealed a non-significant trend for overall differences in auditory processing discrimination thresholds $F(3,38) = 2.66$, $p = 0.062$, wilks' $\lambda = 0.83$, partial $\eta^2 = 0.17$. However, tests of between-subjects effects on each task revealed no significant differences in frequency discrimination $F(1,40) = 0.24$, $p = 0.629$, partial $\eta^2 = 0.01$, rise time $F(1,40) = 3.34$, $p = 0.075$, partial $\eta^2 = 0.08$ or speech discrimination $F(1,40) = 0.33$, $p = 0.569$, partial $\eta^2 = 0.01$. Note that on the rise-time task, where the effect approaches significance, the RA controls show higher discrimination thresholds (weaker performance) than the dyslexics.

Comparisons between children with OM and RA OM also revealed no significant overall differences in auditory processing $F(3,38) = 0.71$, $p = 0.554$, wilks' $\lambda = 0.95$, partial $\eta^2 = 0.05$. Tests of between-subjects effects on each task revealed no significant differences in frequency discrimination thresholds $F(1,40) = 0.61$, $p = 0.443$, partial $\eta^2 = 0.02$, rise time $F(1,40) = 0.64$, $p = 0.430$, partial $\eta^2 = 0.016$ or speech discrimination $F(1,40) = 1.59$, $p = 0.215$, partial $\eta^2 = 0.04$.

4.2 | Auditory processing response variability: SD analyses

Figure 2 illustrates differences in variability in performance on the auditory processing tasks, by depicting the SD of the reversals used to calculate the thresholds. A large SD indicates greater variability in performance. A MANOVA with the between-subjects factor participant group (dyslexia, OM, CA groups) and log-transformed dependent variables

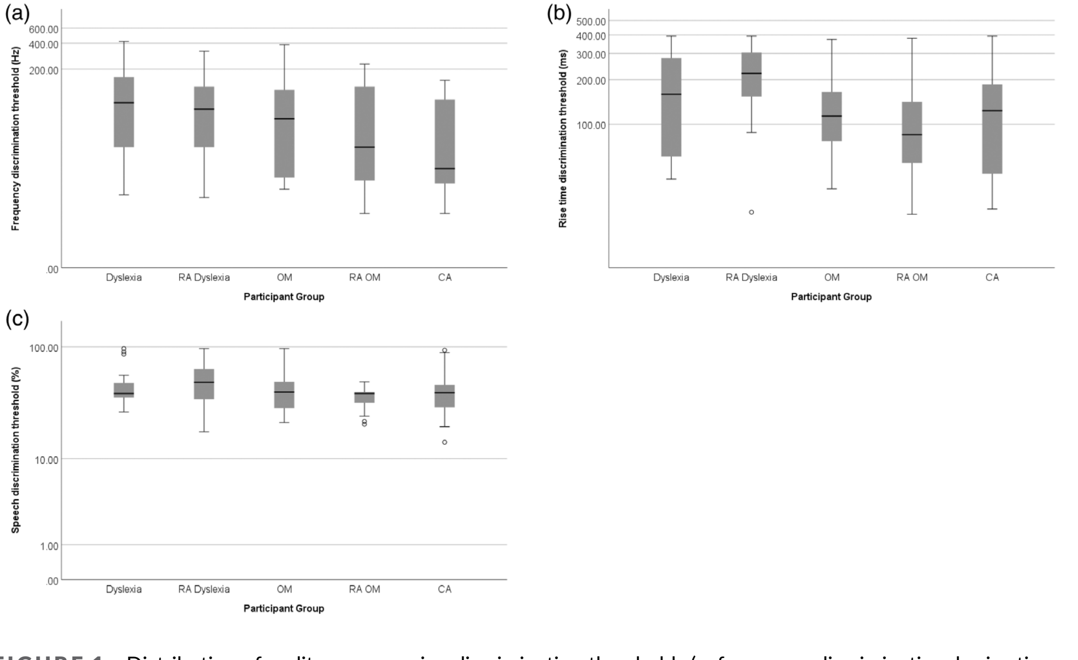

FIGURE 1 Distribution of auditory processing discrimination thresholds (a: frequency discrimination, b: rise time, c: speech discrimination) by participant group (dyslexia, RA dyslexia, OM, RA OM and CA). CA, chronological age; OM, otitis media; RA, reading age.

frequency discrimination, rise-time and speech discrimination SD of reversals indicated no overall differences in auditory processing response variability $F(6,134) = 0.93$, $p = 0.475$, wilks' $\lambda = 0.92$, partial $\eta^2 = 0.04$. Tests of between-subjects effects on each task revealed no significant differences in frequency discrimination $F(2,69) = 0.92$, $p = 0.404$, partial $\eta^2 = 0.03$, rise time $F(2,69) = 0.22$, $p = 0.800$, partial $\eta^2 = 0.01$ or speech discrimination $F(2,69) = 1.47$, $p = 0.238$, partial $\eta^2 = 0.04$.

Comparisons between children with dyslexia and RA dyslexia revealed no significant differences in auditory processing variability $F(3,38) = 1.33$, $p = 0.280$, wilks' $\lambda = 0.91$, partial $\eta^2 = 0.10$. Tests of between-subjects effects on each task revealed marginal differences in frequency discrimination response variability, driven by the slightly greater variability of children with dyslexia relative to RA dyslexia $F(1,40) = 4.04$, $p = 0.051$, partial $\eta^2 = 0.09$. However, there were no significant differences in variability in rise time $F(1,40) = 0.02$, $p = 0.896$, partial $\eta^2 = 0.00$ or speech discrimination variability $F(1,40) = 0.00$, $p = 0.959$, partial $\eta^2 = 0.00$.

Comparisons between children with OM and RA OM revealed no significant overall differences in auditory processing variability $F(3,38) = 0.51$, $p = 0.675$, wilks' $\lambda = 0.96$, partial $\eta^2 = 0.04$. Tests of between-subjects effects on each dependent variable revealed no significant differences in frequency discrimination $F(1,40) = 1.61$, $p = 0.212$, partial $\eta^2 = 0.04$, rise time $F(1,40) = 0.04$, $p = 0.846$, partial $\eta^2 = 0.00$ or speech discrimination response variability $F(1,40) = 0.00$, $p = 0.982$, partial $\eta^2 = 0.00$.

4.3 | Correlations

Table 2 records Pearson's partial correlations (controlled for age) between the auditory processing tasks and phonological awareness scores for the dyslexic, OM and CA groups separately. Given the small sample sizes, these should

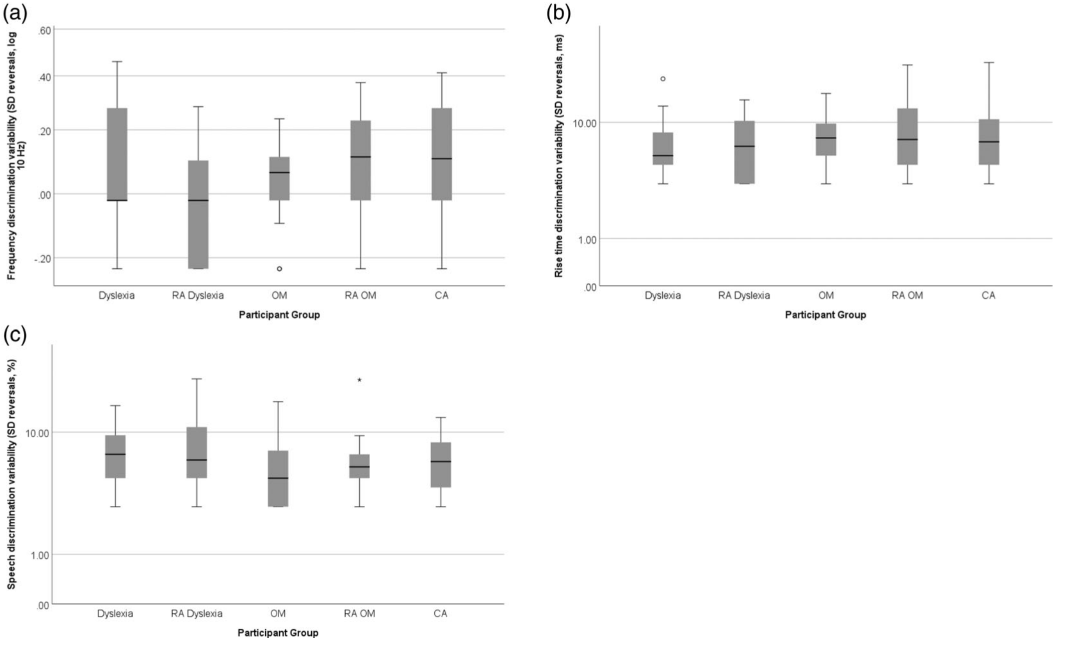

FIGURE 2 Distribution of response variability—SD of the reversals used to calculate auditory processing thresholds (a: frequency discrimination, b: rise time, c: speech discrimination) by participant group (children with dyslexia and their reading ability matched peers, children with OM and their reading ability-matched peers, chronological age-matched peers). OM, otitis media.

TABLE 2 Pearson's partial correlations (having controlled for age).

		Dyslexia[a]	OM	CA
Correlations with phonological awareness				
Frequency discrimination threshold (log 10 Hz)		$r(17) = -0.21$, $p = 0.200$	$r(18) = -0.17$, $p = 0.237$	$r(27) = -0.04$, $p = 0.416$
Rise-time discrimination threshold (log 10 ms)		$r(17) = -0.41$, $p = 0.040$*	$r(18) = -0.21$, $p = 0.189$	$r(27) = 0.17$, $p = 0.189$
Speech discrimination threshold (log 10%)		$r(17) = -0.31$, $p = .102$[b]	$r(18) = -0.23$, $p = 0.161$	$r(27) = 0.10$, $p = 0.307$
Frequency discrimination variability (SD reversals, log 10 Hz)		$r(17) = 0.61$, $p = 0.003$**	$r(18) = 0.28$, $p = 0.120$	$r(27) = 0.27$, $p = 0.076$
Rise-time discrimination variability (SD reversals, log 10 ms)		$r(17) = 0.01$, $p = 0.484$	$r(18) = -0.02$, $p = 0.474$	$r(27) = 0.20$, $p = 0.148$
Speech discrimination variability (SD reversals, log 10%)		$r(17) = 0.18$, $p = 0.230$	$r(18) = -0.07$, $p = 0.390$	$r(27) = 0.38$, $p = 0.022$*
Correlations between auditory processing measures				
Frequency discrimination threshold (log 10 Hz)	Rise-time discrimination threshold (log 10 ms)	$r(17) = 0.72$, $p < 0.001$**	$r(18) = 0.32$, $p = 0.09$	$r(27) = 0.36$, $p = 0.028$*
Frequency discrimination threshold (log 10 Hz)	Speech discrimination threshold (log 10%)	$r(17) = 0.65$, $p = 0.001$**	$r(18) = 0.08$, $p = 0.38$	$r(27) = -0.15$, $p = 0.22$
Speech discrimination threshold (log 10%)	Rise-time discrimination threshold (log 10 ms)	$r(17) = 0.54$, $p = 0.009$**	$r(18) = 0.31$, $p = 0.09$	$r(27) = -0.07$, $p = 0.37$
Frequency discrimination variability (SD reversals, log 10 Hz)	Rise-time discrimination variability (SD reversals, log 10 ms)	$r(17) = 0.11$, $p = 0.33$	$r(18) = 0.27$, $p = 0.12$	$r(27) = 0.45$, $p = 0.007$
Frequency discrimination variability (SD reversals, log 10 Hz)	Speech discrimination variability (SD reversals, log 10%)	$r(17) = 0.20$, $p = 0.21$	$r(18) = -0.25$, $p = 0.15$	$r(27) = 0.28$, $p = 0.07$
Speech discrimination variability (SD reversals, log 10%)	Rise-time discrimination variability (SD reversals, log 10 ms)	$r(17) = 0.34$, $p = 0.08$	$r(18) = 0.33$, $p = 0.08$	$r(27) = -0.23$, $p = 0.45$

Abbreviations: CA, chronological age; OM, otitis media; PA, phonological awareness.
[a]After removing the one outlier with very low PA (raw score 54).
[b]This relationship was significant when the outlier was included $r(18) = -0.49$, $p = 0.014$.
*$p < 0.05$; **$p < 0.01$.

be interpreted with caution. One individual in the dyslexic group who was an outlier for phonological awareness was excluded to avoid undue influence on the results. There is no significant association between frequency discrimination threshold and PA for any of the groups. Rise-time threshold shows a significant correlation with phonological awareness in the dyslexic group, but not in the CA or OM groups (see Figure 3). Fisher's z-transformations were used to test for significant differences between the effect sizes. This confirmed a significant difference between the

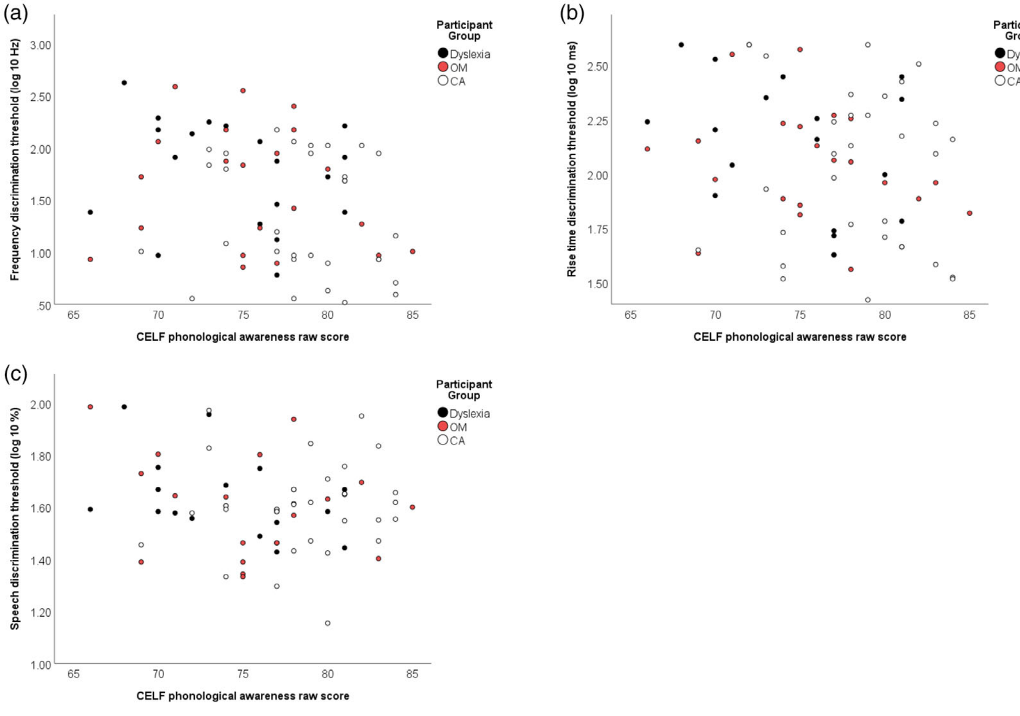

FIGURE 3 Scatterplots depicting the relationship between auditory processing discrimination thresholds (a: frequency discrimination, b: rise time, c: speech discrimination) and CELF phonological awareness for children with dyslexia, OM and CA controls. CA, chronological age; CELF, Clinical Evaluation of Language Fundamentals; OM, otitis media.

correlations between phonological awareness and rise time for the dyslexic group compared with the CA group ($z = -1.86$, $p = 0.031$), but the difference between the dyslexic and OM groups was not significant ($z = -0.62$, $p = 0.27$). The response variability measures are included as a measure of focus and consistency on the task. Variability in frequency discrimination correlates with PA in the dyslexic group, while variability in speech discrimination correlates with phonological awareness in the CA group. No other correlations with response variability reached significance (Figure 4).

4.4 | Results summary

In summary, children with dyslexia had impaired frequency discrimination thresholds compared with their CA-matched peers, but in line with RA controls (Figure 1a). Children with dyslexia also showed marginally greater frequency discrimination response variability than their RA-matched peers (Figure 2a), and their frequency discrimination response variability was significantly associated with phonological awareness (Table 2). The dyslexic children did not differ from CA or RA controls on rise time or speech discrimination thresholds. However, children with dyslexia did show a significant association between rise-time threshold and phonological awareness, which was not observed for CA controls (nor children with OM). Most noticeable in the rise-time results was the indication that the RA-dyslexic group had a difficulty with rise-time discrimination, even though this effect was not statistically significant. Since these participants were much younger than that other participant groups, this is likely to be a developmental effect. There was no evidence that speech discrimination abilities differed between participant groups.

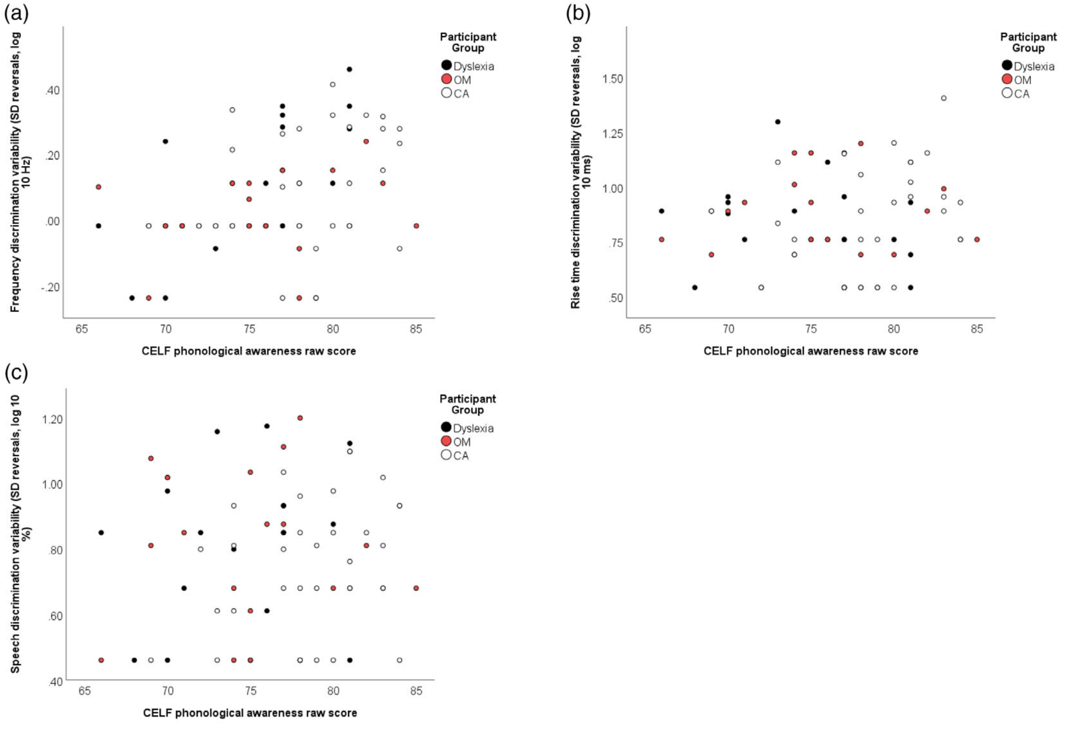

FIGURE 4 Scatterplots depicting the relationship between auditory processing response variability—SD of the reversals used to calculate auditory processing discrimination thresholds (a: frequency discrimination, b: rise time, c: speech discrimination) and CELF phonological awareness for children with dyslexia, OM and CA controls. CA, chronological age; CELF, Clinical Evaluation of Language Fundamentals; OM, otitis media.

Children with OM did not differ from the CA or RA controls on any measure. However, they did not differ from the dyslexics either, suggesting that their performance was intermediate between controls and dyslexics.

5 | DISCUSSION

To explore the nature of the relationship between auditory processing and reading acquisition, we compared children with dyslexia and children with a history of OM to RA-matched and CA-matched controls. Examining performance on each auditory processing task revealed some circumscribed difficulties in the frequency discrimination task (but not rise-time or speech discrimination) for the dyslexic group. However, further examination of response variability revealed that these effects might be artefacts of other deficits interfering with task performance.

Children with dyslexia did show weaknesses in frequency discrimination thresholds compared with CA controls, requiring a greater difference between sounds to be able to distinguish the odd-one-out. This is in line with previous research and consistent with any of our hypotheses concerning the relationship between auditory processing and dyslexia. However, frequency discrimination thresholds did not correlate with phonological awareness for any group of children. This lack of correlation contradicts the 'causal chain' hypothesis, as does the lack of deficits shown in the OM group. Instead, this lends weight to the view that increased frequency discrimination thresholds are part of a combination of a range of deficits that can be associated with dyslexia.

The findings relating to response variability are particularly illuminating. Frequency discrimination response *variability* correlated with phonological awareness for dyslexic children (only) and dyslexic children had greater response variability on this task compared with reading age-matched controls. These are important findings, as together they suggest that dyslexic children's frequency discrimination thresholds may be more likely influenced by factors separate to auditory processing. Given our own and prior research findings (e.g., Moore et al., 2008; Tomlin et al., 2015), we suggest that sustained attention is a likely cause of response variability. As has been argued elsewhere, this would mean that these difficulties with auditory perception or processing may be caused by deficits in these other cognitive skills (e.g., Roach et al., 2004; Snowling et al., 2018; Witton et al., 2020). Future research needs to explicitly measure the extent to which these cognitive skills account for variation in response variability, using multiple regressions to consider the impact of multiple predictors.

Our research contrasts with previous work showing auditory processing deficits in children with OM (Borges et al., 2020). However, it is aligned with previous research indicating no particular deficits in auditory processing in children with a history of OM (e.g., Nittrouer & Burton, 2005). Nonetheless, the findings should be interpreted with caution given the variability inherent in samples of children with a history of otitis media (Hartley & Moore, 2005).

This paper was novel in that it included individual reading level-matched controls for both the dyslexic and the OM groups. Overall, there were no significant differences between either of the impaired groups and their reading level-matched controls. On rise time, the only measure on which the differences approached significance, the dyslexic group slightly outperformed their reading level controls. There is therefore no evidence from the reading level comparison that auditory processing deficits play a causal role in literacy deficits.

In this paper, we propose that deficits in sustained attention may provide an explanation for the increased response variability in our dyslexic sample. Attention deficits and dyslexia are closely associated with one another (Carroll et al., 2005; Willcutt & Pennington, 2000). Children with a history of OM also show increased risks of attention difficulties (Bennett et al., 2001; Niclasen et al., 2016). However, the putative causal pathway is different in the two cases. Literacy deficits and attention deficits have been shown to share genetic risk factors (Willcutt et al., 2007), while OM is an environmental risk factor for later attention difficulties (Bennett et al., 2001). As such, one might expect the behavioural and cognitive characteristics of attention difficulties to differ in children with OM and those with dyslexia. A limitation of our research is that we did not measure sustained attention directly, and so we cannot be certain of the attention skills of the different groups who took part.

Even though rise time was the only auditory processing discrimination threshold measure to correlate significantly with phonological awareness, we did not find evidence of a rise-time processing deficit nor a speech discrimination deficit for dyslexic children, which contrasted with previous research (Goswami et al., 2002). However, our tasks differed from those studies in that we used an 'odd-one-out' paradigm rather than a categorization paradigm. Arguably, the odd-one-out paradigm places lower demands on perceptual memory. In addition, not all previous research shows difficulties on behavioural measures of rise-time discrimination thresholds (e.g., Hämäläinen et al., 2009). Future research should explore whether these results hold true with a wider range of paradigms and stimuli. For example, construct validity might be improved by using a latent measure of speech discrimination across a range of contrasts, or by varying the duration of stimulus presentation when measuring frequency discrimination.

Several limitations of the present study are worthy of mention. Firstly, while sample sizes are comparable with similar studies in the field, from a statistical perspective this might have limited power to detect small or inconsistent differences between groups. This limits our ability to draw strong conclusions from null results. Even so, the use of multiple control groups which are very well matched in terms of sample size and demographics strengthens our argument.

Another limitation relates to our definition of impairment in the OM groups, which was based on retrospective parental report. Previous research has highlighted that parent report lacks sensitivity for clinical and diagnostic purposes. However, this lack of sensitivity is mainly caused by parents failing to appropriately recognize the presence of OM and hearing impairment (false negatives). Rates of false positives, where parents incorrectly believe their child to have OM and/or hearing impairment, are much rarer (Anteunis et al., 1999). As a result, the inclusion criteria adopted here (parental report of either more than seven before the age of three, or medical diagnosis of otitis media with effusion or glue ear) should be considered conservative, meaning that we can be quite confident that children in the OM group had experienced significant OM in the early years. The fluctuating nature of OM presents a challenge for research in this field, with the definition used impacting on group membership for both the OM and control groups. Future research should further explore these findings with a more circumspect definition of history of OM, and it might be fruitful to explore the impact of related factors such as duration or timing of the last episode of OM, as well as interactions with socio-economic status. Previous research has indicated that low socio-economic status is associated with similar patterns of phonological impairment as a history of OM, arguably due to diminished language experience in both groups (Nittrouer & Burton, 2005).

5.1 | Conclusion

Overall, our findings are in line with previous research that indicates that auditory processing deficits do not cause dyslexia via deficits in speech perception and phonological awareness. Instead, the circumscribed auditory processing deficit we detected in this group of children with dyslexia seems to be caused by weaknesses in executive function or cognitive processing. This view is supported both by the fact that children with a history of OM do not show auditory processing deficits and by the increased response variability in the children with dyslexia. Further research is needed to directly explore the relationship between executive function and auditory processing in dyslexia.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTE

[1] Note that these participants were part of a longitudinal study. Data that was collected 18 months earlier has been published elsewhere Breadmore and Carroll (2016a, 2016b); Carroll and Breadmore (2018). Not all participants took part in this later phase of data collection, and there is no overlap between the data presented here and elsewhere.

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