Auditory processing and the development of language and literacy

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This paper considers evidence for basic auditory processing impairments associated with dyslexia and specific language impairment, against a back-drop of findings from studies of the normal development of auditory and phonological processing. A broad range of auditory impairments have been implicated in the aetiology of these language-learning disorders, including deficits in discriminating the temporal order of rapid sequences of auditory signals, elevated thresholds for frequency discrimination and for detection of amplitude and frequency modulation, impaired binaural processing and increased susceptibility to backward masking. Current evidence is inconsistent, but suggests that not all children with language difficulties have non-verbal auditory processing impairments, and for those that do, the impact on language development is poorly understood. Some implications for clinical practice are discussed.

Although children make use of visual cues when learning language, audition is of primary importance for language acquisition. The fact that language development can be severely compromised as a consequence of audiometrically-defined hearing impairment is prima facie evidence for the role of auditory processing in language development. Here we review claims that a range of more subtle impairments of auditory processing may be associated with, and possibly causally linked to, specific deficiencies in language and literacy. Space limitations prohibit discussion of claims concerning co-occurring subtle sensory impairments in vision and touch.

The language learning impairments that have received most attention in this context are dyslexia and specific language impairment (SLI). A commonly accepted definition of dyslexia is that it is a specific learning difficulty, primarily affecting the acquisition of reading and spelling, such that these skills are below the level to be expected for a given age and general cognitive ability. Some dyslexic children have concomitant language problems, but in ‘discrepancy defined’ samples of children with at least average IQ, oral language deficits are not wide-spread. In contrast, the term specific language impairment is applied typically when the non-verbal IQ score is at least 80, and performance on at least
two oral language tasks is significantly below the level predicted from IQ. However, it is important to note that there is no consensus about the IQ criterion that should be applied, and there is considerable heterogeneity within language-impaired samples².

Some investigators have assumed a common substrate for dyslexia and SLI (in effect that dyslexia is a mild form of SLI), but this assumption is likely only to be justified for children whose SLI is characterised by expressive language difficulties and phonological processing problems, rather than for those who exhibit pragmatic language abnormalities, involving difficulties with use of language in interaction. The distinctions between different forms of language difficulty have sometimes been obscured by the use of the term ‘language learning impaired’, but it is important to note that SLI children have more extensive language problems than dyslexic children, encompassing poor vocabulary, grammatical deficits and problems with the comprehension and production of sentence structure.

**Normal development of auditory processing in relation to speech perception**

The perception of speech requires a capacity to determine spectral shape, to detect and discriminate amplitude modulation and modulation of fundamental and spectral frequency, and to do so with temporal resolution that encompasses both the relatively slow changes that extend over an entire utterance and the relatively fast changes that occur as a result of rapid consonantal articulations. Moreover, given that speech is rarely heard in isolation from other sounds, the listener must segregate the signal of interest from background sounds (including other speech sounds), and attend appropriately to the auditory patterns in the segregated speech.

At least some of these capabilities are present in utero. The cardiac orienting reflex has been used to demonstrate that late gestational age fetuses respond more to pulsed than continuous sounds³, suggesting a sensitivity to amplitude modulation, and have a limited ability to discriminate complex tones differing in pitch⁴. It is presumably capabilities of these kinds that make it possible for neonates to discriminate low-pass filtered maternal from non-maternal speech⁵.

The auditory capabilities of normally-developing children are probably sufficient early in infancy to support discrimination of the linguistically-relevant contrasts in speech. By 6 months of age, infants’ frequency selectivity is similar to that of adults⁶, which suggests an ability to extract information about spectral shape, and temporal resolution is adequate for extraction of phonetically-relevant details in the amplitude envelope of
speech. However, there are some indications that infants do not have adult-like attentional capabilities; limitations on selective listening may constrain their ability to extract information from speech heard against a background of noise, particularly the speech of other talkers.

Sensitivity to the acoustic cues that carry supra-segmental information in speech has been demonstrated in neonates using habituation–dishabituation procedures; a change in language (from Dutch to Japanese) was detected, but only for speech waveforms played forwards, and not when the waveforms were reversed. A corresponding pattern of performance found for monkeys suggests that this language discrimination may depend on processes common to mammalian auditory systems generally. The extent to which similarities between the speech discrimination capabilities of humans and non-humans should be taken to argue against specialisation of human brains for speech perception remains controversial.

An influential view for many years has been that neonates are pre-programmed to perceive speech categorically, but sufficiently generally to afford the potential for learning any of the world’s languages. Sensitivity to phonetically relevant acoustic variation is then gradually shaped during the first year of life to home in on those phonetic contrasts that are relevant in the native language. However, Nittrouer, using a visually-reinforced conditioned head-turning procedure, reported that, of her 6–14-month-old participants, only 65% reached the criterion for discrimination of a vowel contrast and only 35% for a consonantal voicing contrast. It seems, therefore, that the speech perception capabilities of young infants may have been overstated. Nittrouer concluded that if lack of conditioning to the criterion in these procedures is due to a failure of discrimination, rather than due to infant temperament as has often been assumed, then the performance of young listeners is unreliable, but not randomly so.

According to Nittrouer and her colleagues, a child’s experience with their native language affects the perceptual weight assigned to individual acoustic properties of speech. They argue that children begin by relying on dynamic spectral properties, useful for recognising syllabic structure, whereas older children and adults tend to give more weight to steady-state acoustic properties, on which the development of fine-grained phonological representations depends. These developmental changes have only been demonstrated so far for a relatively limited set of phonetic contrasts, and it has been suggested that young children simply use the most acoustically salient cues; however, Nittrouer and Crowder found that 5- and 7-year-old children and adults did not differ in their relative sensitivity to steady state and dynamic acoustic cues, and argued that the developmental weighting shift is not the result of a change in sensitivity to the relevant acoustic parameters.

Thus the prevailing, but not settled, view on the normal development of speech perceptual abilities is that from birth, infants are sensitive to
the acoustic cues that signal phonetic contrasts, but that the cues they use will change with age in response to environmental input. An important issue is how any auditory processing deficits present at this stage might influence the establishment of the fine-grained phonological representations that underpin language development.

Auditory deficits associated with specific language impairment

According to one prominent theory, both oral and written language disorders in childhood can be traced to a non-verbal processing deficit that manifests itself when auditory information arrives at a rapid rate. This view was developed from an initial series of studies of children with SLI using a procedure often referred to as the Auditory Repetition Task (ART). In the ART, the child listens to two complex tones that differ clearly in pitch, separated by an inter-stimulus interval (ISI). Following training to the criterion on trials in which the tones are associated with different responses, the child has to copy the order of the tones in the order of their responses. Tallal and Piercy reported that their sample of 12 SLI children found this task more difficult than controls only when there was a relatively short ISI (<150 ms). Temporal order judgement tasks like this have been used widely as an indicator of the general efficacy of auditory temporal processing.

This rapid auditory processing deficit found with non-speech sounds is assumed within the theory to have a critical impact on the perception of consonants distinguished by rapid spectrotemporal changes; a further key assumption is that the relationship between auditory processing and language skill is a causal one mediated by phonological processing. Both of these assumptions are contentious. It has been claimed recently that training rapid auditory processing improves language skills, providing potentially powerful support for the validity of a causal theory linking the two abilities. Thus, it is important for theoretical and practical reasons that this theory be properly evaluated.

There have been rather few studies of temporal auditory processing in SLI. One of these used a version of the ART to investigate the auditory processing skills of 55 SLI children selected from twin pairs, and 76 control twins with normal language skills. The ART performance of the SLI group was significantly worse than that of controls but, contrary to Tallal and Piercy’s original findings, group differences tended to be larger at slow than at fast rates of presentation. The primary focus of the study was the heritability of auditory processing (performance on the ART) and phonological processing skills, assessed by a test of non-word
repetition. Although deficits on the non-word repetition task showed a significant degree of heritability, ART scores did not. These findings suggest that the relationship between non-verbal auditory processing and language skills is not mediated by phonological processing abilities. If ART deficits are principally determined by environmental factors, perhaps children with SLI experience difficulties in auditory processing tasks as a consequence of their language impairment.

Bishop and colleagues went on to explore in more detail the auditory processing capabilities of SLI and control children from the above sample\textsuperscript{21}. Backward masking thresholds correlated with performance in the ART measured 2 years earlier, attesting to the consistency of these measures, but did not predict language impairment. Moreover, there were no group differences in absolute threshold, thresholds for frequency modulation detection or pitch discrimination, or thresholds under forward or backward masking. The absence of a group difference in backward-masked thresholds is inconsistent with a previous report that children with SLI had elevated backward-masked thresholds compared to controls\textsuperscript{22}. A logical problem for the hypothesis that auditory processing deficits lead to language impairments is the finding that some control children had elevated backward masked thresholds and performed poorly on the ART but were not language impaired\textsuperscript{21}.

**Auditory deficits associated with dyslexia**

Many recent studies have investigated auditory processing skills in so-called ‘well-compensated’ dyslexic adults who may no longer have reading problems. There are grounds for caution in the interpretation of some of these studies. First, such participants are likely to differ from those in childhood samples that are recruited at the time they have reading problems. Second, a failure to find a difference between dyslexic adults and controls in an auditory processing task does not rule out the possibility that a deficit earlier in development compromised the development of phonological representations. Slow or delayed development of one process (albeit along normal lines) may alter the course of development of a related process in a sensitive period.

**Auditory temporal order judgements**

The auditory repetition task described above has been used in a variety of forms with reading-impaired participants. Tallal\textsuperscript{23} reported that ART performance was poor relative to that of controls for 9 of the 20 reading-impaired children in her study, and that ART scores were
correlated with performance on a phonological task, suggesting that impairments of reading, as well as impairments of oral language, can be the consequence of a reduced ability to process rapidly-occurring auditory stimuli. A recent report has suggested that a relationship between auditory temporal order judgements and phonological measures is also found for average and above-average readers\(^24\).

Contrasting results were obtained by Nittrouer\(^25\), who found that good and poor readers did not differ in performance of an ART-like task, nor did the poor readers show impairments in use of brief formant transitions to cue a phonemic contrast involving manner of articulation. Similarly, a study in our laboratory\(^26\) found no differences between dyslexic and control children in mean ART performance, although there was a small subgroup of dyslexics (24%) whose ART performance was outside the normal range. Marshall et al\(^26\) noted that children who were impaired on the ART also tended to take longer reaching the criterion in a tone identification and response mapping pre-test; this observation suggests that verbal labelling skill, rather than simply efficiency in rapid auditory processing, is important for ART performance. Indeed, the large individual differences in performance of ART-like tasks may be related to language skills, with low scores reported only for poor readers having concomitant weak language skills\(^27\).

Despite its superficial simplicity, the ART requires a range of non-auditory capabilities, including attentional and verbal labelling skills, as well as tone segregation, pitch perception and judgements of the temporal order of auditory events. The effects of reading and language impairments on these diverse aspects of the task remain unclear, as does the nature of any relationship between rapid auditory processing and phonological representations. In view of this, pragmatic caution should be exercised before implementing remediation programmes designed to improve language and reading performance by training rapid auditory processing skills.

Frequency discrimination

There have been several reports that dyslexic adults are impaired in tasks involving pure tone frequency discrimination, relative to normal-reading controls\(^28\)–\(^31\). McAnally and Stein\(^28\) proposed that the dyslexic participants’ elevated difference limens for frequency (DLF) could be understood in terms of an impairment in the ability to extract information about the temporal fine structure of auditory stimuli from the phase locking of auditory nerve firing patterns. This hypothesis predicts that any differences between dyslexic and control listeners should be more evident for tones at low frequencies, where phase locking information is available, than at
frequencies above 4–5 kHz, where it is not. However, the demonstration by Hill et al\(^32\) that DLFs were similar for dyslexic and control listeners for pure tones at both 1 kHz and 6 kHz is not consistent with the prediction.

The magnitude of threshold elevation for DLFs reported for dyslexic listeners across different studies shows considerable variation, possibly as a result of differences in the severity of dyslexia in the participant sample, and also of differences in aspects of the psychophysical procedures, such as the trial structure and the availability of feedback. A recent report has confirmed an influence of trial structure (2-interval versus 7-interval) on the magnitude of DLF differences between dyslexic and control listeners\(^33\). Such results question the extent to which differences between good and poor readers’ psychophysical thresholds directly reflect fundamental limitations in low-level sensory processing. Even highly constrained psychophysical tasks require attentional and memory processes, and little is known yet about the impact of dyslexia on such processes in the context of threshold estimates. As with most measures of poor readers’ performance, there are large individual differences in frequency discrimination\(^34\), and DLF estimates for dyslexic and control listeners typically show considerable overlap.

Poor readers have been reported to have elevated thresholds for detection of frequency modulation (FM), but only at slow modulation rates (2 Hz); detection of FM at fast rates (240 Hz) - which is dependent on resolution of spectral side-bands rather than on detection of FM per se - was not impaired\(^35\). A modest, but significant, relationship between phonological skill and auditory sensitivity to low rates of FM has been demonstrated in a class of normal primary-school children\(^36\). Thresholds for amplitude modulation are also reported to be elevated for dyslexic listeners, and, in contrast to FM thresholds, across a relatively wide range of modulation frequencies (10–320 Hz)\(^37\).

Given the importance of frequency and amplitude modulations in carrying information in speech, a reduction in sensitivity to frequency and amplitude variation, present when infants are refining their phonological representations on the basis of the speech they hear, might be expected to result in weak or inappropriate phonological representations that could affect subsequent language and literacy development. To be convincing, this position requires that the thresholds typically reported for dyslexic participants are high relative to the magnitude of modulations typically found in speech. Such comparisons are necessarily crude, but may be informative. For example, the stop consonants in the syllables \[ba\] and \[ga\] are differentiated primarily by the characteristics of the initial second-formant transitions, which typically differ in onset frequency by at least 500 Hz\(^38\). Although there are few normative data on which to base an estimate, 100 Hz is probably a reasonable rough approximation to the difference limen for formant frequency transition onset frequency\(^38\). The
mean threshold for detection of slow FM reported by Witton et al\textsuperscript{35} for dyslexic adults was approximately 50% larger than that of controls. If such estimates from dyslexic adults using tonal stimuli are indicative of the magnitude of threshold elevation for formant discrimination by infants at risk of dyslexia, it is not obvious why the threshold elevation alone would be sufficient to cause significant problems with speech perception.

Binaural processing

The binaural masking level difference provides an elegant approach to measuring the use dyslexic listeners can make of the fine-grain temporal structure of sounds. It has been reported that the masking level difference – in this case the difference between the masked thresholds for binaural tones that were in phase at the two ears and for binaural tones that were 180° out of phase at the two ears, presented in binaural-identical noise – was significantly smaller for dyslexic than for control listeners\textsuperscript{28} (although see Hill et al\textsuperscript{32}). There is also evidence that dyslexic children were impaired in a dichotic pitch identification task, where pitch sensations depended on interaural timing mismatches\textsuperscript{39}.

Backward masking

If dyslexics are impaired in their processing of rapid sound sequences, this may be because they are particularly susceptible to masking of a sound by temporally adjacent sounds. In one study, masked thresholds for dyslexic children were normal under forward masking, but (for 5 of the 8 participants) elevated under backward masking\textsuperscript{40}. In addition to this demonstration of abnormal backward detection masking, deficits have been reported in backward recognition masking, but only for poor readers with concomitant oral language problems\textsuperscript{41}.

The asymmetries in backward and forward masking led Rosen and Manganari\textsuperscript{40} to hypothesise that the acoustic cues to initial consonants might be backward-masked by the energy in the following vowel. In fact the dyslexic children in their study were not impaired on discrimination of syllable-initial relative to syllable-final formant transitions. This was true for synthetic speech syllables and for non-speech sounds with analogous spectral properties (isolated second formants); dyslexic children’s performance was slightly worse overall for synthetic speech syllables than for the non-speech isolated formants, but it is not clear whether this difference is attributable to the perceptual status of the sounds as speech or non-speech, or to the differences in acoustic complexity between synthetic syllables and isolated formants.
Tasks involving speech and non-speech sounds

In contrast to the proposal that impairments in basic auditory processes play a causal role in SLI and dyslexia\textsuperscript{16}, it has been suggested that the deficit is not a general auditory impairment but is specific to the processing of speech sounds. Consistent with this is the finding that poor readers, whose performance discriminating acoustically-similar speech syllables was impaired relative to that of control children, were not reliably impaired in discriminating non-speech ‘sine-wave’ analogues of the syllables, in which the formant frequency pattern was simulated with frequency-modulated pure tones\textsuperscript{42}.

Similar sine-wave analogues of consonant-vowel syllables have been used in an experiment comparing discrimination performance of dyslexic and control children in two conditions - first where the sounds were described to the listeners as electronic whistles, and second where the sounds were described as speech-like\textsuperscript{43}. Discrimination performance did not differ significantly between participant groups when the stimuli were described as whistles, but when described as speech-like, dyslexic children’s performance indicated a reduced tendency to categorise the sounds phonemically.

The extent to which any perceptual deficits in poor readers are speech-specific or associated with general auditory processing problems is the subject of continuing debate\textsuperscript{44–46}. A hindrance to resolving the issue experimentally is the difficulty in designing appropriate non-speech auditory stimuli so that performance with speech and non-speech sounds can be meaningfully compared. Sine-wave speech has the virtue that it can be made to mimic some of the spectrotemporal properties of formant patterns, and is typically heard, initially at least, as whistles without phonemic value; however, for some listeners it can evoke phonemic percepts on first presentation, and it differs greatly from speech in its acoustic complexity.

**Key points and conclusions**

- Advances in the understanding of the role of auditory processing in the genesis of language difficulties have been hampered theoretically by a lack of agreement about the relationship between basic auditory skills, speech perception and phonological processing abilities, and also methodologically by frequent uncontrolled group differences in experimental studies.

- It should be clear from this review that by no means all children with language learning impairments demonstrate non-verbal auditory processing problems. It has been suggested that, where present, auditory processing deficits may be a ‘synergistic risk factor’ for language impairment\textsuperscript{20}, that
exerts a moderating influence when children are already at genetic risk of language disorder, but they are neither necessary nor sufficient to explain language difficulties.

- Children with oral language impairments require comprehensive assessment of their cognitive strengths and difficulties to specify more accurately the nature of their difficulties. It is premature given the present state of knowledge to advocate training in auditory skills for these children.47,48. While this might bring about some benefit for their auditory attention and listening skills, the large-scale adoption of such training programmes is counter-indicated until the causal relationships among auditory, phonological and language impairments are clarified.

- Children with oral language impairments beyond the pre-school years require intensive programmes of speech and language therapy and there is good evidence of the benefits of phonological awareness training for dyslexia.

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New developments in hearing and balance