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The auditory basis of language impairments: temporal processing versus processing efficiency hypotheses

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Abstract

Claims have been made that language-impaired children have deficits processing rapidly presented or brief sensory information. These claims, known as the 'temporal processing hypothesis', are supported by demonstrations that language-impaired children have excess backward masking (BM). One explanation for these results is that BM is developmentally delayed in these children. However, little was known about how BM normally develops. Recently, we assessed BM in normally developing 6- and 8-year-old children and adults. Results showed that BM thresholds continue to improve over a comparatively protracted period (>10 years old). We also analysed reported deficits in BM in language-impaired and younger children in terms of a model of temporal resolution. This analysis suggests that poor processing efficiency, rather than deficits in temporal resolution, can account for these results. This 'processing efficiency hypothesis' was recently tested in our laboratory. This experiment measured BM as a function of delays between the tone and the noise in children and adults. Results supported the processing efficiency hypothesis, and suggested that reduced processing efficiency alone could account for differences between adults and children. These findings provide a new perspective on the mechanisms underlying communication disorders, and imply that remediation strategies should be directed towards improving processing efficiency, not temporal resolution.

Keywords: Specific language impairment; Temporal resolution; Auditory processing; Development

1. Introduction

Three to ten percent of children who are otherwise unimpaired have difficulty learning language [1]. This condition is known as Specific Language Impairment (SLI).

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In 1978, Zangwill [2] defined this condition as "slow, limited or otherwise faulty development of language in children who do not otherwise give evidence of gross neurological or psychiatric disability, and where the language difficulty is not secondary to deafness." The aetiology of this condition is largely unknown. However, by definition, children with SLI have normal detection of pure tones, which is the conventional clinical assessment of hearing loss. Even so, a child may pass conventional audiological assessment but nevertheless process more complex sounds abnormally. Indeed, some authors have suggested that auditory processing deficits may cause SLI [3]. These claims have been termed the 'temporal processing hypothesis' [3]. Despite mounting evidence suggesting a link between SLI and auditory processing impairments, their role in the genesis of developmental language disorders remains controversial.

2. Language impairments and the auditory repetition task

Claims that language impairments are associated with deficits in auditory processing have been reported as early as 1965 [4]. However, the idea that auditory processing deficits cause SLI is most associated with Tallal et al. [5,3]. An early study by Tallal and Piercy [5] investigated auditory processing in children with language impairments using the so-called 'Auditory Repetition Task'. The task involved listening to two brief tones. One tone was 100 Hz and the other was 305 Hz. The two tones were played one after the other with varying silent intervals between them. The children were trained to identify the order of the two tones by pressing keys on a keypad that corresponded to the low and high tones. The crucial finding was that language-impaired children had no difficulty in identifying the order of the tones when the silent interval between them was long (>300 ms); however, when the interval between the tones was short (<300 ms), performance worsened considerably. Control children, with normally developing language, performed well even with the shortest intervals between the tones. Tallal concluded from this study that language-impaired children have deficits in processing brief or rapidly presented sounds, and suggested that these deficits may cause their language disorder.

3. SLI and tone-in-noise masking

More recently, Wright et al. [6] supported Tallal's claims through a demonstration that children with SLI have difficulty detecting a much simpler stimulus, brief tones presented with a masking noise ('tone-in-noise masking'). Wright found what appeared to be an even more robust effect than Tallal's using more refined psychoacoustic techniques. In Wright's experiment, 8-year-old children sat in a soundproof room and tones and noises were played to the right ear only over headphones. Two identical narrowband noises (0.6–1.2 kHz, 300 ms duration, 40 dB SPL spectrum level) were presented in two intervals, one after the other. A 20 ms, 1 kHz tone was also presented in one of the intervals. The subject had to indicate which interval contained the tone. The level of the tone was then adaptively

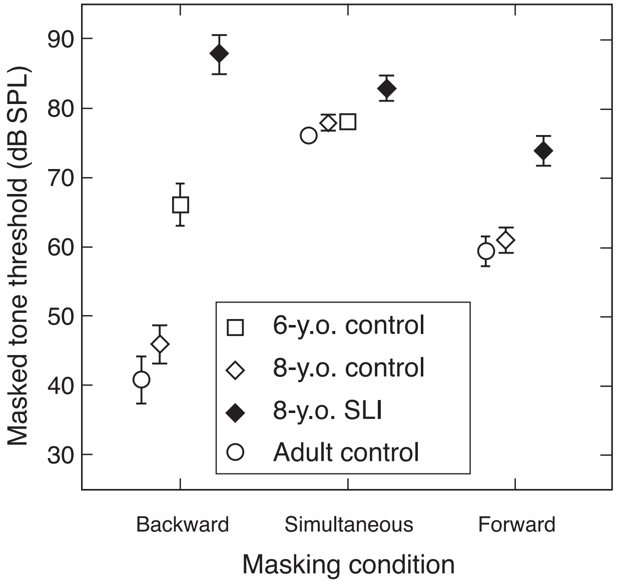

Fig. 1. Mean tone thresholds for the three masking conditions for normally hearing 6-year-old (n=16) and 8-year-old children (n=8) and adults (n=7). Thresholds are also plotted for 8-year-old children with SLI (n=8). Error bars show ±1 standard error. Control data from Hartley et al. [9] and SLI data from Wright et al. [6].

varied using the 'maximum-likelihood' technique [7] to estimate the listener's tone threshold. In one version of the task, the tone was presented immediately before the noise (Backward condition), in another the tone was presented during the noise (Simultaneous condition), and in a third version, the tone was presented after the noise (Forward condition).

The most striking result was that children with SLI had about 45 dB higher thresholds for the backward condition compared with controls (Fig. 1). Children with SLI also had, on average, 15 dB higher thresholds for the forward condition. However, SLI children only had small deficits in the simultaneous condition. It was concluded in the studies by Wright et al. that language impairments are associated with poor temporal resolution.

4. Development of tone-in-noise masking

Temporal resolution has been defined as the minimum time interval within which different acoustic events can be distinguished [8]. One possible explanation for Wright's results was that temporal resolution was developmentally delayed in children with SLI. However, until recently, little was known about the normal development of this aspect of auditory processing. In 2001, we investigated the development of temporal processing abilities in 6- and 8-year-old children and adults [9] using identical masking tasks and procedures to those used by Wright et al. [6]. We found that tone thresholds improved with

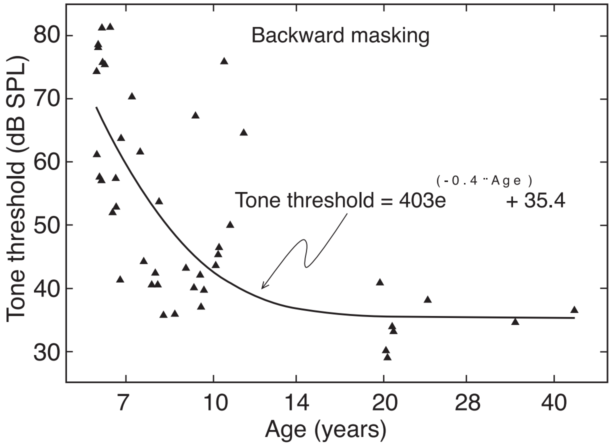

Fig. 2. Tone thresholds for a brief tone presented immediately before a masking noise (backward masking) as a function of age, with best fitting exponential function. Data from Hartley et al. [9].

age in both the backward and simultaneous masking conditions (Fig. 1). However, the improvements in the backward condition were much greater than in the simultaneous masking condition. Specifically, 6-year-old children had, on average, about 34 dB higher backward masking (BM) thresholds than adults. Whereas 6-year-old children had on average just 6 dB higher thresholds on the simultaneous masking task 8-year-old children had, on average, 12 and 3 dB higher thresholds than adults on the backward and simultaneous conditions, respectively. A negative exponential decay function fitted to data from all age groups indicated that backward masking only reaches adult-like performance between 11 and 15 years old (Fig. 2).

5. Development of the auditory system

A wealth of anatomical, physiological and behavioural data suggest that aspects of the auditory system are immature at birth [10]. The difference between adult and children's auditory processing abilities appears to arise from both structural and functional immaturities in the auditory periphery (peripheral to the auditory nerve), and from more central limitations on auditory perception [10,11]. A few aspects of hearing, particularly those that depend almost exclusively upon cochlear function, appear to reach adult-like performance in infancy. For example, detection thresholds for pure tones, especially for higher frequencies (>1 kHz), appear largely to reach adult-like performance by 2 years old [12]. More complex auditory processing tasks are present in infancy, but appear to continue to develop later into childhood before asymptotic performance is reached. Therefore, compared with pure-tone sensitivity, which appears to reach adult-like performance in infancy, backward masking thresholds appear to develop over a comparatively protracted period. Wright interpreted poor backward masking thresholds as deficits in temporal resolution.

6. A model of temporal resolution

Although neural mechanisms underlying temporal resolution are not fully understood, they are thought to represent more central processing within the auditory system [13]. To understand further the nature of auditory processing deficits associated with language impairments in younger children, we analysed these data [14] in terms of a model of temporal resolution [15]. The model of temporal resolution, originally developed by Moore et al. [15], consists of four stages (Fig. 3A):

(i) First, a tone and a noise are passed through a filter, which represents one of a bank of filters present in the auditory periphery.
(ii) Next, the output of the filter is passed through a compressive non-linear device (Fig. 3B), which simulates the compressive input–output function of the basilar membrane. The input–output function of the basilar membrane has been derived from both physiological [16] and psychophysical measurements [17]. It is widely believed that the compression on the basilar membrane depends upon an active physiological mechanism mediated by the outer hair cells [18]. The compressive non-linear function can be roughly divided into three regions: for low and high stimulus levels, the input–output function is approximately linear, that is a 10 dB increase in the input level results in a 10 dB increase in the response. However, for moderate level signals, an

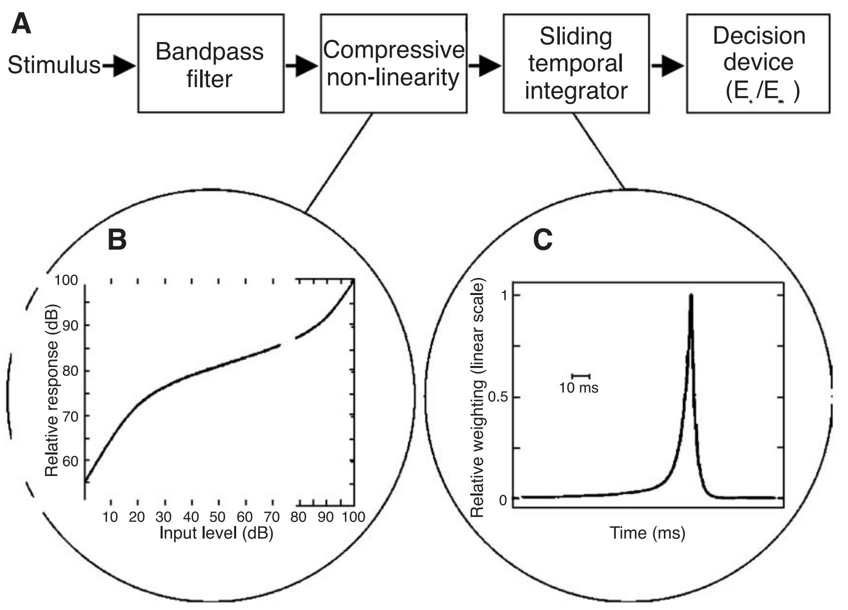

Fig. 3. (A) A block diagram of the model proposed by Moore et al. [15] to describe auditory temporal resolution. (B) A schematic representation of the compressive input–output function of the basilar membrane to a pure-tone stimulus. The relative response is arbitrarily scaled so that an input of 100 dB gives an output of 100 dB. (C) The shape of the temporal window [19].

increase in the stimulus level of 10 dB increases the output by just 1.6 dB, i.e. it is highly compressive.

(iii) A temporal window follows the compressive function (Fig. 3C). The shape of the temporal window has been derived from psychoacoustic experiments using combined forward and backward masking tasks [19]. Indeed, it has been suggested that a neural mechanism for this phenomenon may be located within the central auditory system [13], although the exact mechanism is currently unknown. The function gives most weight to the output of the non-linear stage at times close to the centre of the window. Progressively less weight is given to outputs before and after the window's centre. Importantly, the build-up is steeper than the decay, which accounts for the asymmetry between forward and backward masking thresholds.

(iv) Lastly, the model incorporates a decision device. The assumption of the model is that detection occurs when the ratio of the internal effect of the signal at the output of the temporal window is a certain proportion of the internal effect of the masker, i.e. Es/Em is a constant, regardless of the masking task.

7. Analysis of psychophysical data in terms of the model

In terms of the model (Fig. 3), to suggest that a child with SLI has poor temporal resolution implies he has a widened temporal window. However, there is an alternative explanation for Wright's results [6]. Our analysis using the model suggests that poor processing efficiency can account for Wright's data, without changing the shape of the temporal window. Processing efficiency encompasses all factors, aside from temporal resolution, that may affect detection on a task, such as attention, cognition and motivational factors [20]. In terms of the model, to suggest that children with SLI have poor processing efficiency means that they require a higher signal-to-noise ratio in the decision devise to detect the tone (Fig. 3A). To demonstrate how poor processing efficiency can account for Wright's results, we will consider an example. Let us hypothesise that in the study by Wright et al. [6], control children required a signal-to-noise ratio of XdB for detection to occur, and children with SLI required the signal-to-noise ratio to be X+6dB to detect the signal. In this example, SLI children require the tone to be 6 dB higher at the output of the compressive function for detection to occur (Fig. 3A). For the simultaneous masking condition, because the tone and noise co-occur, they are subject to the same compression on the basilar membrane. To increase the output of the compressive devise by 6 dB, the input must also be increased by 6 dB. However, for the backward condition, where tone is presented before the noise, physiological data suggest that compression is fast acting [21], therefore the tone and noises are compressed independently. In the backward masking condition, because of the shape of the temporal window (Fig. 3C), tone thresholds are comparatively low (Fig. 1) and lie within the highly compressive region of the input–output function (Fig. 3A). To increase the internal effect of the tone by 6 dB, the input must be increased by nearly 40 dB. So, for the backward condition, the tone level at threshold would be about 40 dB higher for SLI children than for controls. These findings are consistent with experimental data.

The model can also explain excessive forward masking in children with SLI (Fig. 1). Tone thresholds for forward masking are higher than for backward masking (Fig. 1) and, subsequently, lie in a region of the input–output function on the BM that is more linear (Fig. 3B). Thus, children with SLI have larger deficits in backward masking than in forward masking.

The same explanation can be used to explain the comparatively protracted development of backward masking in normally hearing children (Fig. 1). Specifically, if we assume that, compared with normally hearing adults, young children have poor processing efficiency, and require the internal effect of the tone to be higher at threshold, then processing efficiency deficits will be magnified in the backward masking condition due to the compressive non-linear function of the basilar membrane. This is again consistent with experimental data [9].

Our analysis suggests that auditory processing deficits in children with SLI can be better explained by an 'auditory processing efficiency hypothesis'. Indeed, this processing efficiency hypothesis is not only of theoretical importance since it has enormous implications to treatment and rehabilitation strategies. In fact, there are reports that auditory training can result in improved language abilities [3]. Therefore, we suggest that rehabilitation strategies should be directed to improvement in processing efficiency rather than temporal resolution.

8. A test of the competing hypotheses

A recent study in our laboratory [22] tested the competing temporal processing and processing efficiency hypotheses by measuring backward masking as a function of delays between the tone and the noise in children and adults. Twelve adults and 12 children, with normal reading and language skills, were tested using similar methods used in Wright's experiment. However, in this experiment, there were four different backward masking tasks, in which a silent interval was introduced between the tone and the noise of 0, 10, 50 and 150 ms. This enabled the shape of the positive side of the temporal window (Fig. 3C) to be predicted. Results showed that children had significantly higher tone thresholds for the backward masking task at every silent interval between the tone and the noise compared with adults. Experimental results for children and adults were then analysed using the model of temporal resolution [15]. The modelling showed that both data sets could be fitted well using a single temporal window whose shape was based on previous data obtained from adult listeners [19]. These data and the model support the processing efficiency hypothesis, and suggest that differences in the results between adults and children could be accounted for by reduced processing efficiency alone. Further experiments are planned to assess the processing efficiency hypotheses in language- and reading-impaired individuals.

9. Conclusions

In this paper we have argued that a deficit in auditory processing efficiency more completely describes a range of experimental data on language-impaired children than does a deficit in auditory temporal processing. However, the causal relationship between processing efficiency and language abilities remains unclear. Tallal et al. [23] hypothesised that auditory processing deficits might degrade the ability to perceive the brief elements of speech, and putatively cause language impairments. However, Bishop et al. [24] suggested that auditory processing deficits may act as a moderating variable that is neither necessary nor sufficient for causing language impairments, but which exert an effect on language development only in individuals who are otherwise at risk. Another theory states that any link between auditory processing and language impairments is not causal. Specifically, Beitchman et al. [25] suggested that associations between auditory processing and language impairments might reflect co-morbid attentional deficits. Therefore, although our analysis suggests that individuals with language impairments have deficits in processing efficiency, the causal relationship between these factors remains controversial.

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