

Suprathreshold Processing Deficits due to Desynchronous Neural Activities in Auditory Neuropathy

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1. Introduction

It has been an important tradition in psychophysics to relate behavioral observations to underlying physiological mechanisms (e.g., the “inner psychophysics” in Fechner’s terms). Several classical studies explored the relationship between the perceived stimulus magnitude and the sensory receptor function (Stevens, 1970) and between forward masking and two-tone suppression in the auditory nerve (Houtgast, 1972). Recently, we have witnessed a renaissance in this line of research, particularly using the hearing-impaired population to reveal normal auditory processes. For example, Oxenham and Plack (1997) and Schlauch (1998) used cochlear-impaired listeners to derive basilar membrane compression in humans. Zeng and Shannon (1994; 1999) and Zeng et al. (1998) used auditory prostheses to infer a compression-expansion scheme for intensity coding. Scharf et al. (1997) and Zeng et al. (2000) used vestibular-neurectomy subjects to probe auditory efferent functions. These studies are important because they can establish the necessary link between physiological observations in animals and perceptual functions in humans.

This study intends to examine the role of neural synchronization in auditory perception. It has been known for a long time that auditory neurons can generate action potentials synchronized to external stimuli. There are several forms of synchronized neural activities including phase locking to the stimulus frequency (Johnson, 1980), the response to the onset of the stimuli (Smith, 1988; Starr and Zaaroor, 1990), and the frequency-following response to the temporal waveform envelope of the stimuli (Joris and Yin, 1992). These synchronous activities in auditory neurons have been suggested to encode basic auditory percepts such as loudness (Smith, 1988; Zeng and Shannon, 1994) and pitch (Srulovicz and Goldstein, 1983) and to extract complex sound features such as spectral peaks and waveform envelopes for speech recognition (Young and Sachs, 1979; Galbraith, 1995).

Here we test the hypothesis relating neural synchrony to perception in human subjects who had been diagnosed with auditory neuropathy. Auditory neuropathy was first noted about 2 decades ago when researchers found a paradoxical absence of auditory brainstem evoked potentials in patients whose pure-tone thresholds were slightly elevated (David and Hirsh, 1979; Worthington and Peters, 1980; Kraus et al., 1984). Later studies showed that these patients had normal cochlear outer hair cell functions, indicated by the presence of cochlear microphonics and otoacoustic emissions (Starr et al., 1991; 1996; Berlin et al., 1993). Thus, different from the conventional cochlear loss, auditory neuropathy preserves the outer hair cell function but disrupts the neural synchrony in the auditory nerve. At present, the exact pathology that disrupts the neural synchrony is not known and may include loss of

inner hair cells, abnormal synaptic function, and/or demyelination in the auditory nerve fiber.

In this paper, we show psychophysical and speech data to provide direct behavioral evidence linking disruption of neural synchronous activities to perceptual processing deficits in auditory neuropathy subjects. We first describe the subjects' audiological profile, and present preliminary data in intensity discrimination, frequency discrimination, and masking. We then summarize the temporal processing data reported in a previous study (Zeng et al., 1999), and analyze the relationship between temporal and speech processing deficits. We also discuss these results in terms of their theoretical significance and clinical applications in infant hearing screening and aural rehabilitation.

2. Methods

Since the detailed methods have been described elsewhere (Zeng et al., 1999), we provide only relevant information in this paper.

2.1 Subjects

Ten auditory neuropathy subjects, 5 females and 5 males, participated in this study. These subjects were aged from 10 to 53 years old with an average age of 28 years old. Their pure-tone averaged thresholds (500, 1000, and 2000 Hz) ranged from 15 to 82 dB with an average of 48 dB HL. Their speech recognition scores (NU-6 words) ranged from 0% to 66% correct with an average of 22% correct. All subjects, except for AN5, had measurable otoacoustic emissions (3 to 16 dB), but none of them had normal auditory brainstem evoked responses. In addition, the imaging results using MRI and CT were normal in all 5 subjects tested.

Figure 1 shows typical audiological results obtained in subject AN10. This subject had low frequency hearing loss (60, 45, 15, 10, 5, and 0 dB HL for 250, 500, 1000, 2000, 4000, and 8000 Hz, respectively), strong and reliable presence of otoacoustic emissions (left panel), but no identifiable waveforms in the auditory brainstem evoked responses (right panel).

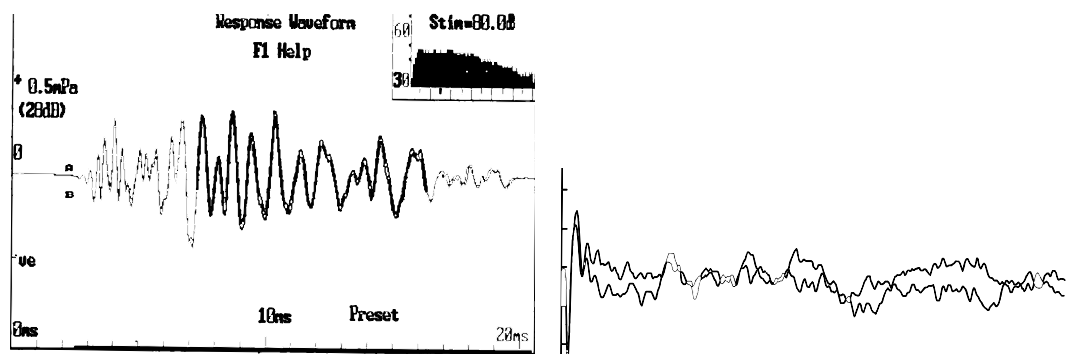


Figure 1. Audiological data in subject AN 10. The left panel shows strong and reproducible otoacoustic emissions in response to a 80-dB peak click (Otodynamics Ltd. – ILO88 OAE system: Response = 16.0 dB; Waveform reproducibility = 98%; Stimulus stability=98%). The right panel shows non-identifiable auditory brainstem responses (15 ms) to a 90-dB peak click, recorded on electrode 1 and 3 (Nicolet Otoneurologic System).

2.2 Stimuli

In intensity and frequency discrimination, tonal stimuli of 200 ms in duration were used. In forward and backward masking, the masker was a 100-ms, 1000-Hz tone and the probe was a 9-ms, 1000-Hz tone. In simultaneous masking, the masker was a 400-ms, broad-band (20-14,000 Hz) noise. The probe was either a 9-ms, 1000-Hz tone in the overshoot condition or a 400-ms tone in the gated condition. In temporal processing experiments, a broad-band (20-14,000 Hz) white noise was used. The noise had durations ranging from 5 to 500 ms in temporal integration and a 500-ms duration in the other experiments. In gap detection, a silent interval was produced in the center of the noise. In modulation detection, the noise was presented at a maximal comfortable level on an individual basis. All stimuli had 3-ms, cosine-squared ramps. They were generated digitally using TDT System II and presented to the subject through either an insert earphone (Etymotic ER2) or a headphone (Sennheiser 200).

2.3 Procedures

We used a 3-alternative, forced-choice, 2-down, 1-up, adaptive procedure in all psychophysical tests. This procedure produces a 70.7% correct response on the psychometric function.

3. Results

3.1 Intensity and frequency processing

Figure 2 shows normative data (shaded areas) and data from several neuropathy subjects (symbols) in intensity and frequency discrimination. When similar sensation levels were used, neuropathy subjects performed generally with the normal range in intensity discrimination. However, their frequency discrimination showed an interesting abnormal pattern, which was about 1 order of magnitude worse than the normal for frequencies below 2000 Hz but was within the normal range at frequencies at 4000 Hz and above.

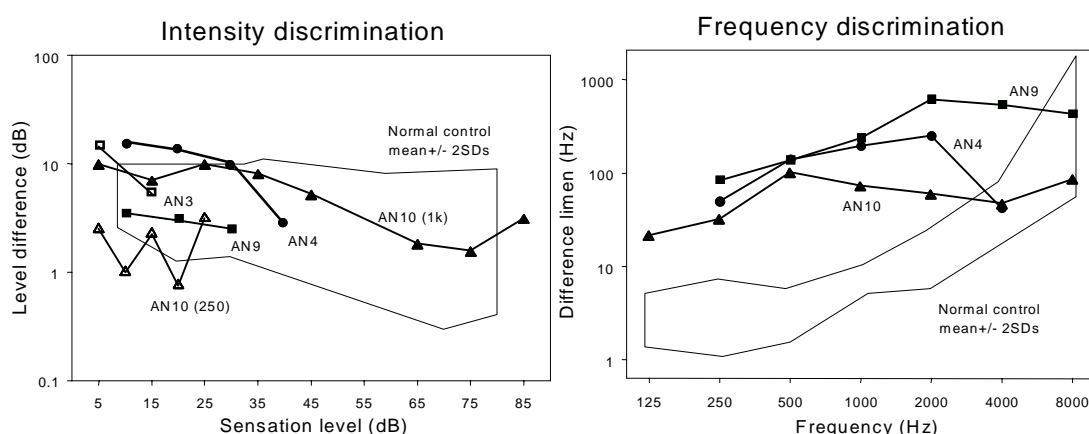


Figure 2. Intensity discrimination (left panel) and frequency discrimination (right panel). The shaded area represents the mean plus and minus 2 standard deviations from 4 normal-hearing subjects. Intensity discrimination data were collected with a 200-ms, 1000-Hz tone. Frequency discrimination data were collected with a 200-ms, 90-dB SPL tone. In subject AN10, intensity discrimination was measured at 250 and 1000 Hz.

3.2 Forward, backward, and simultaneous masking

Figure 3 shows normalized forward and backward masking functions in 3 neuropathy subjects and a normal-hearing control subject. The 100% point represents maximal masking at 1-ms delay, while the 0% point represents a total recovery to the quiet threshold (see figure legends for detailed thresholds in dB SPL). Overall, the neuropathy subjects show abnormally slower recovery from masking than the normal control, particularly in backward masking. In forward making, the neuropathy subjects, like the normal control, recover to the absolute threshold within 100 ms, but they show significantly more masking during the course of the recovery. We have also analyzed the recovery function using a linear normalization procedure (by intensity, rather than dB) and obtained even greater difference between the neuropathy subject and the normal control.

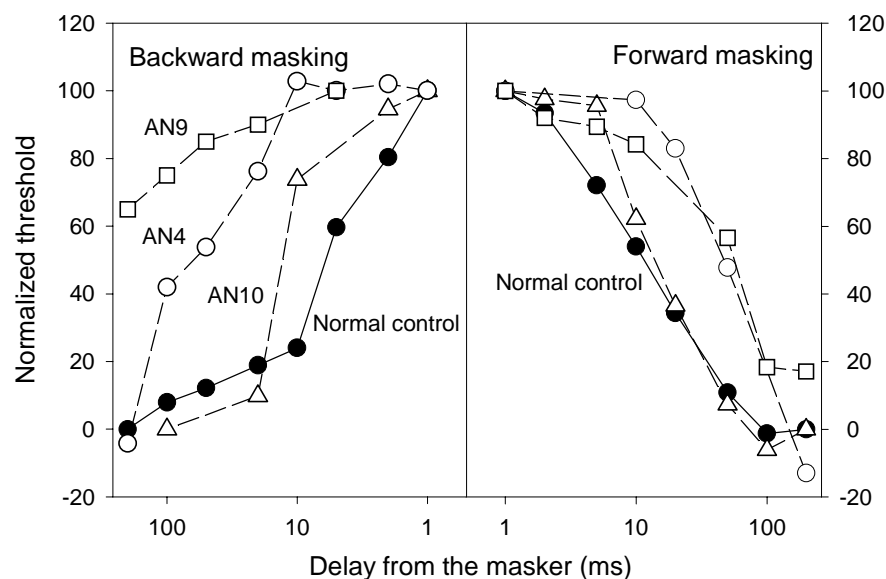


Figure 3. Normalized forward and backward masking functions. The normalized threshold is defined as: $100 \cdot (TH - TH_Q) / (TH_1 - TH_Q)$, where TH is the threshold in dB SPL at any delay, TH_1 is the threshold at 1-ms delay, and TH_Q is the threshold in quiet. For the normal control, the absolute threshold is 10.0 dB SPL, while the 1-ms threshold is 60.7 dB in forward masking and 33.8 dB in backward masking. For the neuropathy subjects, their absolute thresholds are 64.0, 78.8, 42.0 dB for AN4, AN9, and AN10, respectively, while their 1-ms thresholds are 96.5, 97.8, 84.8 dB in forward masking and 94.8, 100, 60.3 dB in backward masking.

Figure 4 shows three simultaneous masking functions in AN10 and the same normal-hearing control. The first two masking functions were obtained to estimate the overshoot effect for a 9-ms, 1000-Hz tone presented either at 3 ms (open triangles for AN10 and open circles for the normal) or 300 ms (filled symbols) delay from the onset of a 400-ms, broad-band noise. The third masking function was obtained for a 400-ms, 1000-Hz tone gated simultaneously with the noise. The normal control data are consistent with existing literature, showing a linear masking function for the long-duration tone and the short-duration tone presented in the steady-state portion of the noise and a non-linear function for the short-duration tone presented at the onset of the masker (e.g., Bacon, 1990). For the neuropathy subject, the long-duration tone masking function appears to be normal, but the short-duration tone masking is totally different from the normal control. First, overshoot, defined as the difference in thresholds between the onset and steady-state conditions, is essentially absent (1 dB

effect). Second, the slope of the masking function is doubled (2 dB:1 dB) compared with the normal linear masking function.

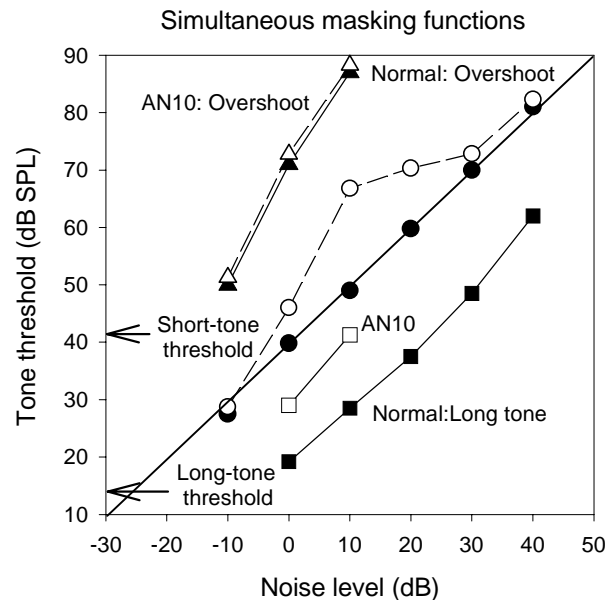


Figure 4. Simultaneous masking: Overshoot and gated conditions. The masker was a broadband noise (20-14000 Hz) with 400-ms duration and 3-ms cosine-squared ramps. Three probe conditions were used. The first probe was a 1000-Hz tone with 9-ms duration and 3-ms ramps and was presented 3 ms after the onset of the masker (open triangles for AN10 and open circles for the normal control). The second probe was the same short tone but was presented 300 ms after the onset of the masker (filled triangles for AN10 and filled circles for the control). The third probe was a 400-ms, 1000-Hz tone gated simultaneously with the noise masker (open squared for AN10 and filled squares for the control). The two arrows pointing to the y-axis represent the absolute threshold for the short (9-ms) tone and the long (400-ms) tone in the neuropathy subject. The diagonal line represents a linear masking function.

3.3 Temporal and speech processing deficits

Table 1 summarizes temporal processing measures from 10 neuropathy subjects and also presents the mean performance in the normal-hearing controls (bottom row).

Subjects	PTA (dB)	Integration (dB/octave)	Gap (ms)	TMTF (gain: dB)	TMTF (3-dB cut off)	Word recognition (% correct)
AN1	32	-4.0	6.0	-20.1	41.7	56
AN2	15	-3.2	10.5	-13.8	51.2	DNT
AN3	72	-8.0	36.6	-5.8	32.9	12
AN4	38	-5.0	11.2	-3.6	106.6	0
AN5	62	-5.2	20.8	-3.6	14.1	0
AN6	55	-3.8	12.1	-6.1	44.8	CNT
AN7	45	-3.0	7.7	-12.4	72.3	40
AN8	82	-3.2	15.4	-16.4	14.3	0
AN9	60	-4.5	13.3	-12.9	38.8	0
AN10	20	-4.2	4.5	-10.3	89.0	66
Average	48	-4.4	13.8	-10.5	50.6	22
Normal	5	-2.8	2.4	-20.4	237.8	100

The pure-tone-average (PTA) thresholds are presented in the second column. Temporal integration data are summarized as the slope of the integration function. Gap detection thresholds are those obtained at the highest sensation levels (30-40 dB SL). Also presented are the gain (dB) and the 3-dB cutoff frequency of a first-order Butterworth filter that was used to model the obtained temporal modulation transfer functions. Word recognition is the percent correct score of NU-6 words.

Linear regressions have been performed between word recognition and PTA thresholds ($r=0.86$, $p=0.003$), the slope of the integration function ($r=0.46$, $p=0.21$), gap detection thresholds ($r=0.63$, $p=0.07$), TMTF ($r=0.85$, $p=0.02$, $df=2$). A combination of PTA and TMTF can predict word recognition at a highly significant level [$\text{word\%}=49.5-0.99*\text{PTA}-2.02*\text{TMTF}(\text{dB})+0.04*\text{TMTF}(\text{Hz})$; $r=0.93$; $p=0.01$].

3.4 Simulation of auditory neuropathy

We have used an analysis-by-synthesis approach to simulate the auditory neuropathy in normal-hearing listeners (Drullman, 1994; Zeng et al., 1999). Briefly, speech sounds were divided into 1/3-octave bands and within each band, the fine-structure was extracted by a LPC-based method while the temporal envelope was extracted by a half-wave rectifier and a low-pass filter. To simulate different degrees of auditory neuropathy, the gain and the low-cutoff frequency of the envelope low-pass filter were manipulated according to the modulation detection functions in neuropathy subjects. For example, to simulate the severe neuropathy case, the modulation depth was reduced by 12 dB and the low-cutoff frequency was lowered to 25 Hz. We tested normal-hearing listeners with this simulation and found similar speech recognition deficits within the range produced by the neuropathy subjects (Zeng et al., 1999). Audio demonstrations of the simulation can be found on the web site (<http://www.bsos.umd.edu/hesp/zeng/>) and will be presented at the meeting.

4. Discussion

Our preliminary data show that intensity processing is not significantly affected by auditory neuropathy. Frequency discrimination is significantly affected at low frequencies but not at high frequencies, possibly reflecting the time versus place principle of pitch coding at these frequencies. Forward and backward masking data suggest a widened temporal window in auditory neuropathy subjects, consistent with their difficulties in gap detection and temporal modulation detection. In addition, the preliminary data show an absence of overshoot and abnormal growth of masking, two phenomena that may be related to the lack of auditory efferent functions in the neuropathy subjects (Berlin et al., 1993; Zeng et al., 2000).

The demonstrated temporal processing deficits in auditory neuropathy provide direct evidence for an important role of neural synchrony in auditory perception. The present data can also account for the speech recognition deficit that is disproportional to pure-tone hearing loss. They can further suggest new directions for aural rehabilitation of auditory neuropathy. According to the most recent report on young child hearing screening in Australia, about 10% of the children with permanent hearing loss had auditory neuropathy (Rance et al., 1999). Since the available hearing aids either do not change the temporal envelope (linear amplification) or reduce the modulation depth (compression circuits), they offer little help to patients with auditory neuropathy. New hearing aids that accentuate the temporal envelope or cochlear

implants that produce highly synchronous neural activity may be more effective than the conventional hearing aids in the clinical management of auditory neuropathy.

5. Acknowledgements

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