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15. ENCODING OF COMPLEX SOUNDS IN AN ANIMAL MODEL: IMPLICATIONS FOR UNDERSTANDING SPEECH PERCEPTION IN HUMANS

Brad Wible, Trent Nicol, Nina Kraus

INTRODUCTION

An understanding of the biological foundations of speech perception demands a corresponding appreciation of the neural encoding of complex sounds. Our interests span a range of topics in these interrelated fields of auditory perception and neurophysiology. Among them are the encoding of complex sounds in auditory midbrain, thalamus, and cortex. The evoked response approach permits measurement, with precise timing, of phasic and tonic aspects of the encoding of such sounds. Of particular interest is the aggregate neural response to speech. Many of these responses include both transient and sustained components, much like a speech signal itself. Inasmuch as it may be an oversimplification to equate features of speech, such as consonants and vowels, with transient and sustained evoked responses, there are certain parallels. Just as perception of consonant sounds is much more vulnerable to disruption with background noise, the analogous neural transient response is degraded by noise. Likewise, phase locked responses are hallmarks of subcortical auditory pathways and may be measured in scalp recordings from humans and direct intracranial recordings in an animal model. Temporal and spectral analyses of these responses have been shown to directly reflect some of the analogous characteristics of the corresponding stimuli, for example the fundamental frequency and some harmonic structures of a vowel.

In one particular population - learning-disabled children - abnormally poor perception of auditory signals has been demonstrated, with respect to normal-

learning peers, and these perceptual deficits have been linked to accompanying abnormalities in the encoding of sounds by both transient and sustained components of auditory evoked responses (Cunningham et al., 2001; Hayes et al., 2003; King et al., 2001; Kraus et al., 1996; Wible et al., 2002). Based on such findings, it has been proposed that, among such subsets of learning disabled children, poor sensory encoding of the subtle acoustic distinctions that distinguish speech signals results in pronounced ambiguity and uncertainty associated with the internal representations of utterances, which ultimately impairs the fidelity with which such representations of the phonemes, thus syllables and thus words, can be meaningfully related to linguistic, orthographic, conceptual and expressive processes.

The guinea pig model is useful for a number of reasons. Recording of evoked responses from electrodes placed within guinea pig auditory pathway allows observation of highly-localized patterns of activation within anatomical structures that are thought to be analogous to those contributing to the scalp recorded responses we measure in children. For example, the inferior colliculus is thought to be a major contributor to scalp recordings of transient and phasic brainstem activity (Jacobson, 1985). Across the frequency regions spanned by the stimuli in which we are interested, guinea pig hearing thresholds are comparable to those demonstrated by human listeners. Guinea pig communication calls contain acoustic structures analogous to those observed in human speech, such that the guinea pig auditory system can be assumed to incorporate mechanisms optimized for processing of such signals. We are specifically interested in low-level "automatic" coding of the acoustic structure of the signal (i.e., *not* interested in effects of "higher" processes such as those subserving attentional, linguistic, or other cognitive functions). In seeking to isolate mechanisms of basic auditory encoding, it can be safely assumed that human speech does not activate any processes in the guinea pig that are dedicated to representing the linguistic content of the signal. Likewise, it can be safely assumed that the use of anesthesia eliminates any remote potential for the guinea pig to "understand" or attend to the signals. In addition to understanding normal processing, the guinea pig model has been useful in providing insight into the sources of abnormal processing such as that observed in learning impaired children. Based on our own observations of human evoked responses and on further descriptions in the literature stimulus parameters are manipulated to emulate conditions under which auditory processing by the learning-impaired children might be thought to suffer.

Here we consider two lines of investigation. First, we describe how encoding of speech sounds is disrupted by background noise and by rapid stimulation. Second, we discuss how encoding and perception can be improved by incorporation of acoustically-enhanced speech cues. In parallel designs, we have been studying these issues in both animals and school-age children.

REPETITION RATE AND BACKGROUND NOISE

Increased talker rate and background noise are two conditions known to adversely affect accurate perception and recognition of speech. These detrimental effects have been shown to be especially pronounced in learning-impaired subjects. Wible and colleagues investigated cortical (Wible et al., 2002) and subcortical (Wible et al.. 2004) responses to rapidly repeated speech sounds, both in quiet and noisy backgrounds in children with learning problems (LP) and normal controls (NL). Ongoing studies are investigating these phenomena in guinea pig models of the normal mammalian auditory pathway. These studies are summarized herein.

Methods, Human

LP children (cortical experiment: n = 13, subcortical experiment: n = 11) performed poorer than NL children (n = 12, 9) on a measure of single word reading and spelling (Wilkinson, 1993), and on a test of discrimination of speech sounds *(/da/-/ga/;* Carrell et aI., 1999). Four-token stimulus trains were presented monaurally to the right ear by earphone. The 40 ms synthesized syllable */da/* was presented at 80 dB, separated within the trains by an interstimulus interval (ISI: time from offset of stimulus to onset of subsequent stimulus) of 360 ms (cortical experiment) or 12 ms (subcortical). Intertrain intervals (ITI: time separating the offset and onset of subsequent trains) of 1060 ms and 30 ms were used during cortical and subcortical experiments, respectively. A continuous white noise masker (+15 dB signal-to-noise ratio (SNR) was added to half of the trials. Evoked potentials in response to the first and fourth stimuli in a train were compared. Recordings of cortical activity were from an electrode placed over left temporal lobe (TL: midway between T4 and T6), used the nose as reference, had gain of 5000, and were band pass filtered from 0.05 to 50 Hz. Recordings of subcortical activity were from an electrode placed at the vertex (Cz), used right mastoid as reference, had gain of 5000, and were bandpass filtered from 100 to 2000 Hz. Forehead served as ground. Impedances were less than 5 kOhm. Correlation between initial and repeated cortical responses (over the range spanning 10-60 ms post-stimulus-onset) reflected relative change in timing of responses. The subcortically generated frequency-following response (FFR), measured from 11.4 to 46.4 ms post-stimulus-onset, was investigated by Fourier analysis. The FFR reflects the periodic structure of the stimulus (Sohmer et al., 1977), in this case the transition from the onset of the consonant to the vowel. This response was isolated by frequency into components corresponding to the stimulus' fundamental frequency (Fo, 125 Hz) and first formant (F_1, 220-720 Hz).

Methods, Animal

Evoked potentials were recorded from left primary auditory cortex (AI; 10 kOhm silver ball electrode) and central nucleus of the inferior colliculus (IC; stereotaxically positioned I MOhm tungsten needle), in 11 adult (-350 g), albino, ketamine/xyaline anesthetized guinea pigs. Responses were amplified 5000 times and band pass filtered from 5 to 3000 Hz. Stimulation was according to paradigms described above, with ISIs of 350, 50, 24, and 12 ms, and ITI of 600 ms. Correlations between Al responses to the first and fourth stimuli in a train were measured over the 10-50 ms latency range. FFRs from IC were measured from 17.20--42.75 ms, and analyzed according to frequency components described above.

Cortical Responses, Human

Similar to previous findings (Wible et al., 2002) describing long-latency responses recorded from the vertex (Cz) , these earlier responses from TL, reflecting initial activation of auditory cortex, demonstrated differences between NL and LP children. LP children demonstrated lower correlations between the initial and repeated responses in noise than in quiet (Fig. 15.1, Right). NL children demonstrated no differences between quiet and noise. Relatively high inter-response correlations were maintained by LP children in quiet, similar to NL children in both quiet and in noise, suggesting that the timing of response generators was maintained, and demonstrating that effects of repetition alone did not segregate LP from NL children. The marked decrease in correlations, likely reflecting diminished synchronization of response generators, was particular to the representation of repeated stimuli in noise in LP children.

Cortical Responses, Animal Model

Patterns of correlation of guinea pig responses recorded at 350 ms ISI provided a model for the responses demonstrated by NL children. Given the established literature reporting abnormal temporal processing as a basis for learning problems, increasing the temporal demands upon the normal system was thought to be a reasonable approach to model processing in the abnormal, LP-like system. In other words, we speculated that rather than representing entirely novel aspects of processing, perhaps the LP system represents a poor performing tail of the distribution of normal processing, such that a "normal" system could be made to demonstrate "LP-like" characteristics by forcing it to process under conditions falling toward a tail of the distribution of normal performance. Responses recorded at a decreased ISI of 50 ms were used to model the LP system. Overall magnitudes of inter-response correlations were larger in the animals than in humans, due to differences in recording techniques

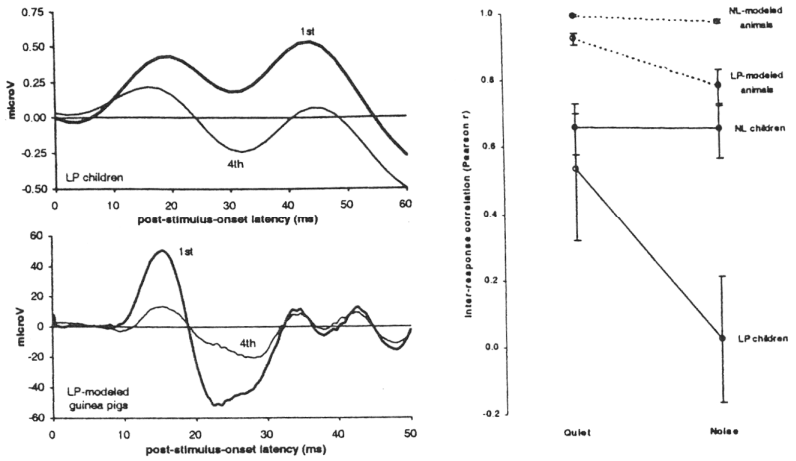

Fig. 15.1. Top left: Average responses to first and fourth stimuli in train, in quiet, recorded over temporal lobe in LP children. **Bottom left:** Average responses to first and fourth stimuli in train, in noise, recorded over guinea pig primary auditory cortex. with LP-modeled 50 ms ISI. **Right:** Correlations between cortical responses to first and fourth stimuli, presented in quiet and noise. in NL and LP children, and in NL- and LP-modeled guinea pigs. Error bars reflect standard errors of the means.

that provided larger response amplitudes with respect to background noise. Under ISI and SNR conditions similar to the human study, the guinea pig Al responses maintained similar inter-response correlations in noise with respect to quiet, much like the NL controls (Fig. 15.1, Right). At the shorter, LP-modeled ISI, inter-response correlations in noise were lower than in quiet, similar to the pattern observed in LP children. As also demonstrated by the human data, stimulus repetition alone, in quiet, did not dramatically degrade processing at the LP-modeled faster rate; correlations at the LP-modeled rate were relatively high in quiet, and were not profoundly dissimilar from the correlations at the NL-modeled rate in both quiet and noise. It was rapid repetition in combination with background noise that resulted in greatly diminished inter-response correlations at the faster LP-modeled rate. The processing of a faster rate by the normal system appears to have been a reasonable choice to model abnormal processing of a slower rate by the LP system.

Subcortical Responses, Human

The primary component of the /da/-evoked FFR corresponds in frequency to the stimulus' Fo. No differences in the magnitude of the Fo component of the FFR were observed between LP and NL children. However, at higher frequencies

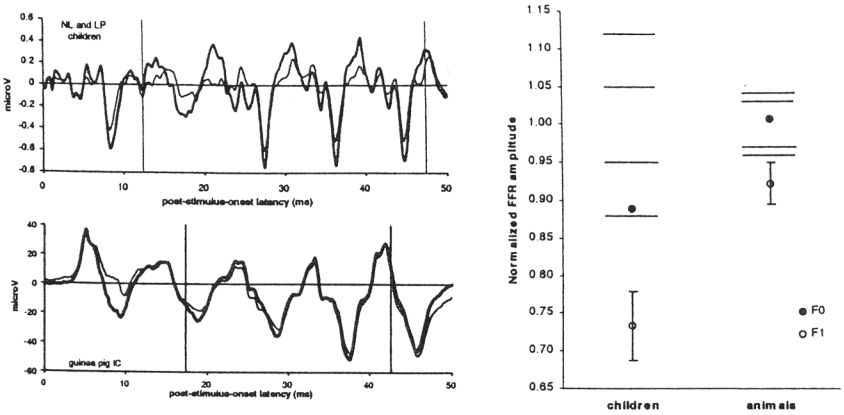

Fig. 15.2. Top left: Averaged brainstem responses to the first stimulus in the train, in NL (thick line) and LP (thin) children. The FFR was measured over the range indicated between the dashed lines. **Bottom left**: Averaged IC responses to the first (thick line) and second (thin) stimuli in the train, at ISI 24 ms, in guinea pig. The FFR was measured over the range indicated between the dashed lines. **Right (children)**: Mean FFR amplitudes for LP children, shown as percentage of NL response amplitude, over frequency ranges corresponding to /da/ stimulus Fo (solid circle) and F_1 (open circle). LP error bars reflect standard error of the mean. Normal ranges (+/- standard error of NL) are shown for Fo (solid line) and F_1 (dashed line). **Right (animals)**: Mean FFR amplitudes in response to second stimulus in train, at 24 ms ISI, shown as percentage of response to first stimulus, over frequency ranges corresponding to /da/ stimulus Fo (solid circle) and F_1 (open circle). F_1 error bars reflect standard error of the mean. Normal ranges (+/- standard error of first response) are shown for Fo (solid line) and F_1 (dashed line).

corresponding to F_1, LP children demonstrated diminished FFR activity (Fig. 15.2, Right: normalized to NL responses, LP responses are below the normal range for F_1, within the normal range for Fo). Responses in noise were not analyzed, due to excessive degradation of responses. These group differences were observed in response to the fourth stimulus, but also in response to the first stimulus in the train, prior to the within-train stress of repetition.

Subcortical Responses, Animal Model

Given the established literature implicating sensitivity to rapid stimulation as a basis for auditory processing deficits in LP children, we speculated that the response component that was shown to be abnormally represented in the LP response to the first stimulus in the train (F_1) would be likely to demonstrate noticeable effects of rapid stimulation in an animal model, while the Fo

component, which was not degraded in the LP response, would be similarly unaffected in animals.

In guinea pig IC, thought to be a generator of the human scalp-recorded FFR (Sohmer et al., 1977), comparison of the first two responses in a train, separated by 24 ms, provided a model of the normal effects of a similar interval, 30 ms, which was used to separate the final and initial stimuli in subsequent trains in the human study. As described for the guinea pig models of the human cortical response, a decreased ISI (in this case, 12 rns) was used to attempt to model the particular response patterns demonstrated by LP children. The Fo component of the guinea pig IC FFR was largely unchanged by rapid repetition of the stimulus at both 24 and 12 ms ISI. In contrast, the frequencies corresponding to F_1 were diminished by repetition at both rates (Fig. 15.2, Right: normalized to first responses, the responses to repeated stimuli appear below the normal range for F_1 within the normal range for Fo). The different ISIs (12, 24 rns) did not provide a differentiation between responses akin to the observed NL / LP differences. Still, it is informative and interesting that differences in processing between NL and LP children were observed on the component that demonstrated sensitivity to rapid stimulation (F_1), while similar processing among NL and LP groups was demonstrated on the component that did not reflect effects of rapid stimulation (Fo). In other words, were one to predict differences in processing between NL and LP children, based on the established temporal-deficit literature and on the present guinea pig data, the temporally-sensitive F_1 component of the FFR would present a more likely candidate than the Fo component, which is precisely the pattern that was observed in human data.

In combination, the human and guinea pig results suggest that the impairments seen in LP children may be due to an inability of their auditory systems to precisely respond under conditions of rapid stimulation that are relatively unchallenging to the NL children. This deficit was simulated in the guinea pig model by using exaggerated repetition rates and by investigating temporal sensitivity of different spectral components of the response. Both human and animal studies implicated degraded processing at subcortical as well as cortical levels as contributing to the auditory perceptual difficulties, and subsequent higher-level language problems, experienced by the LP children.

CUE-ENHANCEMENT

In adverse listening conditions such as noisy environments, as well as when addressing non-native or hearing-impaired listeners, talkers naturally alter their speech in order to make it clearer. Two cue enhancements involving stop consonants are increased stop-gap duration and increased amplitude of plosive consonants (Picheny et al., 1986). Cunningham and colleagues (Cunningham et al., 2001) measured syllable discrimination abilities in school-age children, using two synthesized continua containing conversational and cue-enhanced

(clear) variants of a speech sound, presented in quiet and in background noise. Both cortical and subcortical speech-evoked responses were recorded and comparisons were made between normal controls and LP children who performed poorly on the discrimination task (Figure 15.3, Left). A guinea pig physiology model was employed to help elucidate the underlying human cue-enhancement results (Cunningham et al., 2002).

Methods, Human

Behavioral just-noticeable-differences were assessed with four /ada/-to-/aga/ continua. A 'conversational' continuum had a stop-gap duration of 50 ms and a consonant-vowel (CV) intensity ratio of -18 dB. In a 'clear' continuum, the stop-gap and CV ratio were increased to 230 ms and -8 dB, respectively. Two more continua employed each of those cue enhancements separately. All continua were presented at 65 dB SPL binaurally under headphones (Sennheiser HD-540) in quiet and with a white noise masker presented at a signal-to-noise ratio of +5 dB It was found that for these subject groups and stimuli, the increased CV intensity ratio was much more effective than the increased stopgap duration. Therefore, the initial vowel /a/ was removed and 40-ms duration conversational and clear /da/ syllables, differing only in CV intensity ratio, were used for human evoked response recording.

Cortical and subcortical auditory evoked responses were differentially amplified and recorded from Cz, referenced to nose and earlobe, respectively. Stimuli were delivered monaurally to the right ear at 80 dB SPL both with and without a white noise background masker presented at a +5 dB signal-to-noise ratio. For subcortical responses, stimuli were delivered with a repetition rate of l1/s and responses were recorded for 60 ms post-stimulus. Responses were digitized at 20 kHz and online bandpass filtered from 0.1 to 2 kHz. Latency of the onset response was measured, and the sustained response was evaluated by Fourier analysis and stimulus-to-response correlation. Cortical responses were recorded separately using a repetition rate of 1.7 /s, a response window of 500 ms post-stimulus, and bandpass filters of 0.1 to 100 Hz. Latencies and amplitudes of the major cortical responses in the 50-250 ms latency range, in particular P2 and N2, were measured.

Methods, Animal

In guinea pigs, far-field auditory evoked responses were recorded from left primary auditory cortex, and near-field evoked responses were recorded from primary subdivisions of left medial geniculate nucleus and inferior colliculus. The conversational and clear /ada/ stimuli were delivered to the right ear at 85 dB SPL with and without a white-noise masker at a signal-to-noise ratio of +5 dB. Repetition rate was 1/s and the response window was 500 ms post-stimulus. Responses were online bandpass filtered from 0.05 to 1000 Hz. Amplitudes of the onset responses were measured at the three recording sites. Subcortical

sustained responses also were compared between stimulus conditions and among the anatomical levels by means of RMS amplitude, Fourier analysis and stimulus-to-response correlation.

Syllable Perception, Human

NL and LP children were similar in their abilities to discriminate conversational */ada/-/aga/* syllables when presented in quiet. The addition of background noise markedly degraded performance of LP children with respect to NL children. The inclusion of clear-speech cue enhancements in these syllables presented in background noise improved LP performance, which returned to levels demonstrated by NL children (Fig. 15.3, Left).

Cortical Response, Human

Cortical P2-to-N2 amplitudes for the two subject groups were equivalent in response to the conversational */da/* in quiet. The addition of background noise, however, led to a much more severe response degradation in the LP group. Maintaining the background noise, the cue-enhanced */da/* stimulus restored the response amplitude in LPs to the same level as that of the NL controls (Fig. 15.3, Right).

Subcortical Response, Human

Latencies of the onset response, occurring at about 8 ms post-stimulus-onset, demonstrated a pattern similar to that of the cortical response. That is, in response to the conversational */da/* presented in quiet, onset latencies were equivalent between subject groups, and the addition of background noise delayed the onset response in LPs relative to the normal controls. Onset latencies between the two groups again became equivalent in response to the clear */da/* in noise.

The frequency-following response, however, demonstrated a different pattern from that of the cortical and subcortical onset responses. The frequency composition of the sustained response was equivalent between the two groups to conversational */da/* in quiet. With background noise, the higher-frequency components (450-750 Hz) were diminished in the LP group, relative to the NL controls but this deficit was not restored by the clear */da/.* A similar pattern was seen using a stimulus-to-response correlation technique. This technique revealed a deficit in the LP group frequency following response observed in noise, but this deficit was not restored by cue enhancement.

Animal Model

In the guinea pig, because the full */ada/* stimulus was used there were two discrete onset/sustained responses. The initial */a/* portion of the stimulus was

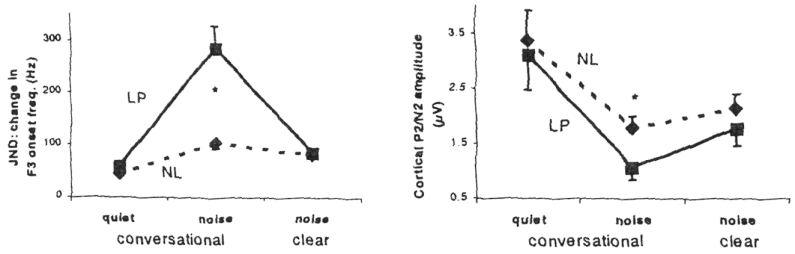

Fig. 15.3. Physiological and behavioral outcomes of noise and cue enhancement. **Left:** Syllable Discrimination: LP subjects discriminate as well as NL controls on a conversational /ada/ to /aga/ continuum when stimuli are presented in quiet. With the addition of background noise, LPs perform significantly worse. When cue-enhancement strategies are added to the stimuli, LP performance in the same background noise improved to match that of the NL controls. **Right:** The same pattern of results is demonstrated with cortical response amplitude. The LPs differ from the NL controls only in the conversational stimulus in noise condition. (Figures modified from Cunningham et al., 2001.)

unaltered between the conversational and clear stimuli, thus analyses were confined to the response evoked by the */da/*. The response to the conversational */da/* in quiet was considered the basis for comparison of the responses to the conversational and clear stimuli in noise.

Onset responses, Animal

When noise was added to the conversational stimulus, the onset responses were dramatically reduced at all three recording sites. However, there was a definite hierarchy of diminution among the levels. The inferior colliculus response amplitude was least affected and the cortex amplitude was most affected. Moreover, the cortical response amplitude benefited most from the clear stimulus manipulation (Fig. 15.4).

Sustained responses, Animal

The frequency-following response to the voiced portion of the */da/* stimulus was present only at the two subcortical recording sites. In general, RMS amplitude of the steady-state portion of the response was unaffected by the noise masker at both sites. More specifically, however, Fourier analysis of the inferior colliculus response revealed that while the lower-frequency components of the response were diminished by the noise masker, the higher-frequency components, corresponding to F_1 in the vowel, were stable. Though representation of lower-frequency components was diminished in amplitude by the addition of noise, the temporal precision of these components was preserved to a degree sufficient to

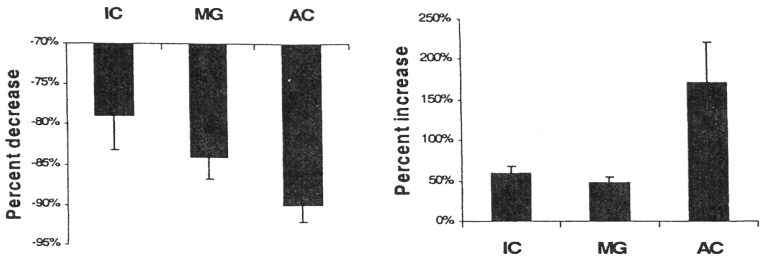

Fig. 15.4. Onset response amplitudes recorded from three levels along the auditory pathway (IC = inferior colliculus; MG = medial geniculate nucleus; AC = auditory cortex). **Left:** Effect of Noise: Background noise most affected the amplitude of the onset response at auditory cortex. **Right:** Effect of Cue Enhancement: The clear stimulus had the most impact at auditory cortex. (Figures modified from Cunningham et al., 2002.)

maintain similar levels of stimulus-to-response correlation across noise conditions. As observed in the children, the clear /da/ stimulus resulted in no improvements in the steady-state response at either recording location on any measure.

Both manipulations - the addition of background noise and the subsequent cue-enhancement of the speech token - impacted the cortical response most, in both children and in the guinea pig model. The subcortical response seen in human subjects, inferred by the scalp-recorded frequency-following response, was consistent with the subcortical responses recorded intracranially in the animal model: both were much less affected by noise when compared to cortex. Results in both subject groups provide evidence for the independence of the underlying neural processes that manifest themselves as transient onset and sustained frequency-following responses. Furthermore, the resilience of the subcortical sustained response in the LP group in adverse listening conditions, in contrast to the dramatic disruption of the cortical evoked responses, furnishes evidence that auditory-based learning problems in this group likely have an origin in the cortical encoding of acoustic transients in speech. Though not as pronounced as the effects in cortical encoding of acoustic transients, subcortical representation of the periodicity of the vowel component also indicated modest deficits in the LP children. Finally, the use of stimulus manipulation to promote restoration of normal-like responses, both behaviorally and physiologically, may help to inform effective remediation strategies.

DIFFERENTIATION OF PROCESSING, PATHWAYS, FUNCTION

Presentation of single, discrete stimuli has been observed to elicit multiple, independent patterns of neural activation, corresponding to different stimulus

features. An example of this phenomenon comes from the literature examining anatomical and functional differences in the neural processing of the identification and location of a stimulus, or distinguishing "what" from "where." While much of this research has been performed in the visual system (Ungerleider & Mishkin, 1982), anatomically distinct pathways have recently been shown to contribute to the differentiation of analogous features of auditory stimuli (Clarke et al., 2002; Rauschecker & Tian, 2000; Zatorre et al., 2002). Differentiation of processing has also been demonstrated with respect to the acoustic structure of the stimulus, for example selective activation in response to simple tones versus complex vocalizations, and phasic versus tonic encoding of stimulus structure (for review, see Popper & Fay, 1992). In all of these cases, functional organization is evident, hallmarked by the efficient distribution of processes among multiple centers and circuits, each optimized for a particular function, contributing to integration into a perceptual whole.

Independence of patterns seen in the onset and sustained responses has been a repeated finding in the research conducted in this lab, some examples of which have been detailed here. Certain stimulus manipulations, such as repetition, masking noise and cue enhancement, differentially affect the transient and periodic response elements. Given the above-described literature addressing differentiation of pathways, function and corresponding perceptual ramifications, perhaps the differences between transient and periodic encoding presented here can be understood to reflect similarly organized assemblies of pathways and functions, evolved to extract and process information dependent upon its acoustic structure and/or environmental and communicative importance. For example, much information about the identity, intent and emotional condition of the speaker is contained in the fundamental frequency and harmonic structure of the utterance, which would be robustly represented by the periodic encoding at subcortical levels Vast amounts of information about the phonetic content of the utterance, for example representation of fricatives and stops, are included in the transient portions of the response, reflected with remarkable precision in aggregate subcortical neural activity, and for which encoding in auditory cortex has been demonstrated to be ideally suited. While our hypotheses, and subsequent experimental designs, are not intended to specifically address such issues of differentiation, consideration of our findings within such a framework could prove insightful.

CONCLUSIONS

In the designs presented here, the human subject groups contained children with clinically diagnosed language-based learning problems. Several instances of abnormal processing of sounds have been described as likely contributing to the learning problems experienced by these children. These deficits were observed at multiple levels of the auditory pathway and affected different portions of the encoded signal. For example, the auditory encoding deficits seen in this group

are very apparent in the presence of substantial levels of masking noise. Not coincidentally, it is in such listening conditions, for example in noisy classrooms, where many such children experience the most perceptual difficulty.

As a model of the human auditory system, the guinea pig has proven to be a useful tool. Localized recording from discrete subcortical nuclei permits confirmation of inferences resulting from scalp recordings in humans. This model permits an approximation of the "normal" system. Given reasonable assumptions about the nature of the "impaired" system, stimulus manipulations and investigations of particular sensitivities of response components can also model, to a degree, mechanisms that may contribute to abnormal cortical and subcortical processing in humans.

An interesting finding from the study of effects of stimulus repetition and noise on cortical processing in NL and LP children, and supported by guinea pig models of normal and impaired processing, is that perhaps abnormal encoding of auditory stimuli does not reflect an altogether novel, degraded process, and thus entirely different underlying mechanisms, but that it instead reflects a tail end of exceedingly poor processing along the distribution of normal performance. Such a perspective has appeared elsewhere in the literature concerning learning problems. Rather than representing a distinctly "impaired" mode from a bimodal distribution of reading ability, dyslexia can be described as reflecting a poor-performing tail of unimodal normal distribution of reading ability (Shaywitz et al., 1992). Likewise, our data could support such a notion, that the "abnormal" encoding demonstrated by LP children is in fact similar to "normal" encoding that would be demonstrated by NL children under exaggerated conditions, when normal processing was stressed over a more extreme range of performance.

Also of particular interest are our multiple descriptions of deficits in subcortical processing that were observed in the LP children. While not entirely unheard of previously, the literature describing brainstem processing in relation to learning disabilities pales in comparison to studies of cortical phenomena. That differences are observed at such an early, primary level of encoding is vastly interesting. In many respects, such investigations may have been overlooked, as low-level encoding has long been described as so relatively robust that it may not have been considered as fraught with potential abnormalities as more sensitive, complex processing in cortex. Disruptions in such low levels of encoding speak to the distinctly auditory-perceptual nature of these problems, as opposed to effects observed in cortical auditory responses, that are often confounded by longer-latency, simultaneously-evolving attentional, linguistic, and cognitive responses.

ACKNOWLEDGMENTS

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REFERENCES

Carrell, T.D., Bradlow, A.R., Nicol, T.G., Koch, D.B., & Kraus, N. (1999). Interactive software for evaluating auditory discrimination. Ear & Hearing, 20, 175-176.

Clarke, S., Bellman Thiran, A., Maeder, P., Adriani, M., Vernet, O., Regli, L.. Cuisenaire, O., & Thiran, 1.P. (2002). What and where in human audition: Selective deficits following focal hemispheric lesions. Experimental Brain Research, 147, 8-15.

Cunningham, J., Nicol, T., King, C.D., Zecker, S.G., & Kraus, N. (2002). Effects of noise and cue enhancement on neural responses to speech in the auditory midbrain, thalamus and cortex. Hearing Research, 169,97-111.

Cunningham, J., Nicol, T., Zecker, S.G., Bradlow, A., & Kraus, N. (2ool). Neurobiologic responses to speech in noise in children with learning problems: deficits and strategies for improvement. Clinical Neurophysiology, 112,758-767.

Hayes, E., Warrier, C.M., Nicol, T., Zecker, S.G., & Kraus, N. (2oo3). Neural plasticity following auditory training in children with learning problems. Clinical Neurophysiology, 114,673-684.

Jacobson, J.T. (1985). The Auditory Brainstem Response. San Diego, CA: College Hill.

King, C., Warrier, C.M., Hayes, E., & Kraus, N. (2ool). Deficits in auditory brainstem encoding of speech sounds in children with learning problems. Neuroscience Letters, 319,111-115.

Kraus, N., McGee, TJ., Carrell, T.D., Zecker, S.G., Nicol, T.G., & Koch, D.B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. Science, 273, 971-973.

Picheny, M.A., Durlach, N.I., & Braida, L.D. (1986). Speaking clearly for the hard of hearing. II: Acoustic characteristics of clear and conversational speech. Journal of Speech & Hearing Research, 29, 434-446.

Popper, A., & Fay, R. (1992). The Mammalian Auditory System, Vol. II. New York: Springer - Verlag.

Rauschecker, J.P., & Tian, B. (2ooo). Mechanisms and streams for processing of "what" and "where" in auditory cortex. Proceedings of the National Academy of Sciences USA,97, 11800-11806.

Shaywitz, S.E., Escobar, M.D., Shaywitz, B.A., Fletcher, J.M., & Makuch, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. New England Journal of Medicine, 326, 145-150.

Sohmer, H., Pratt, H., & Kinarti, R. (1977). Sources of frequency following responses (FFR) in man. Electroencephalography and Clinical Neurophysiology, 42, 656-664.

Ungerleider, L., & Mishkin, M. (1982). Two cortical visual systems. In D.Ingle, M. Goodale, & Mansfield R. (Eds.), Analysis of visual behavior (pp. 549-586). Cambridge, MA: MIT Press.

Wible, B., Nicol, T.G., & Kraus, N. (2002). Abnormal neural encoding of repeated speech stimuli in noise in children with learning problems. Clinical Neurophysiology, IB, 485-494.

Wible, B., Nicol, T., & Kraus, N. (2OO4). Atypical brainstem representation of onset and formant structure of speech sounds in children with language-based learning problems. Biological Psychology, 67,299-317.

Wilkinson, G. (1993). Wide range achievement test-3. Wilmington, DE: Jastak.

Zatorre, R. 1., Bouffard, M., Ahad, P., & Belin, P. (2oo2). Where is 'where' in the human auditory cortex? Nature Neuroscience,5, 905-909.