

Temporal processing in the primate auditory cortex

X. Wang, T. Lu and L. Liang

*Laboratory of Auditory Neurophysiology, Department of Biomedical Engineering
Johns Hopkins University, Baltimore, MD 21205, USA
xwang@bme.jhu.edu*

1. Introduction

Neural representations of time-varying features of acoustic signals in the cerebral cortex are of special interest to our understanding of complex sound processing at this level of the auditory system. Temporal features are fundamental components of communication sounds such as human speech and animal vocalizations. Both humans and animals are capable of perceiving time-varying features of complex sounds in a wide range of time scales from sub-millisecond to tens and hundreds of milliseconds. How the auditory cortex encodes this wide dynamic range of temporal feature is not well understood. The neural representation of temporal features begins at the auditory periphery where auditory-nerve fibers faithfully represent fine details of complex sounds in their temporal discharge patterns. At subsequent nuclei along the ascending auditory pathway, the precision of this temporal representation degrades gradually, due to biophysical properties of neurons along the ascending pathway and temporal integration of converging inputs from one station to the next. It has long been noticed that neurons in the auditory cortex do not faithfully follow rapidly changing stimulus components. A number of previous studies have showed that cortical neurons can only be synchronized to temporal variations of sounds at a rate far less than 100 Hz, compared with a limit of greater than 1 kHz at the auditory nerve (see review by Langner 1992). The functional significance of this apparently "slow" response rate at the auditory cortex is unclear. The lack of synchronized cortical responses to rapidly changing stimulus components has been puzzling. Previous studies in this area have been hampered by the use of anesthetic preparations that were known to alter temporal response properties of the auditory cortex (Goldstein et al. 1959). We have directly addressed these questions in single-unit recording studies of the auditory cortex in awake marmoset monkeys. This article summarizes our recent findings.

2. The limit on stimulus-synchronized discharges in unanesthetized auditory cortex

While rapidly modulated sounds are clearly perceived by both humans and animals, the neural basis for representing such stimulus components in the auditory cortex has not been well studied. The existing body of data, largely from anesthetized auditory cortex, shows limited stimulus-synchronized responses by individual cortical neurons. Because of confounding factors of anesthetics, it is important to examine these issues in unanesthetized auditory cortex. In our study, we systematically investigated responses of single neurons in the primary auditory cortex (A1) of awake marmoset monkeys to rapid sequences of clicks. Both wide- and narrow-band click trains with inter-click intervals

(ICI) ranging from 3 msec to 100 msec were studied. Narrow-band clicks were centered at each neuron's characteristic frequency (CF). In contrast to neurons studied in anesthetized auditory cortex which responded strongly to both wide- and narrow-band clicks (Lu and Wang 2000), the majority (>90%) of neurons examined in awake auditory cortex responded strongly to narrow-band clicks but were only weakly driven or, more often, unresponsive to wide-band (rectangular) clicks. One type of response to click trains is illustrated by Figure 1. This type of neuron generally exhibited significant stimulus-synchronized responses to the click stimuli at long ICIs (>25-30 msec). The discharges to click trains became non-synchronized at medium ICIs and diminished at short ICIs (apparently due to inhibition). The second type of neuron changed their firing rate almost linearly as a function of ICI when such intervals are shorter than 25-30 msec (data not shown). These two response types were observed in a large number of neurons we studied. Our findings suggest that the limit on stimulus-synchronized responses is on average 25-30 msec (median value of sampled population) in A1 under unanesthetized conditions. The observation of neurons sensitive to changes of short ICIs indicates that a discharge-rate-based mechanism may be in operation when ICIs are shorter than 25-30 msec.

Cortical Responses to Click-Trains (wide-band)

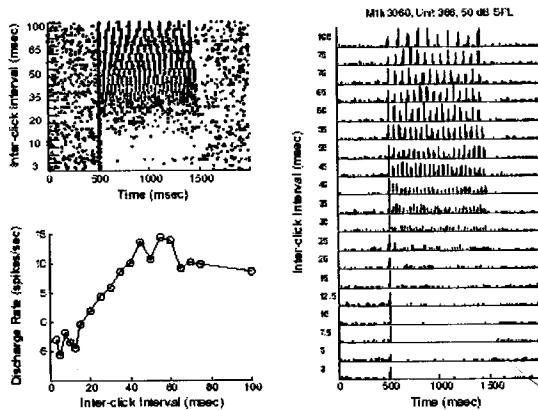


Figure 1. An example of single-unit response to wide-band (rectangular) click trains recorded from the primary auditory cortex (A1) of awake marmoset. Inter-click intervals (ICIs) ranged from 3 to 100 msec. Each click train was delivered in 10 repetitions in randomized manner (stimulus onset at 500 ms, duration 1000 ms).

3. Temporal integration window of the primary auditory cortex

The limited stimulus-synchronized responses observed in single cortical neurons suggest that a neuron integrates sequential or continuous stimuli over a brief time window that we define operationally here as the *temporal integration window*. Two sequential acoustic events falling within the temporal integration window are not distinguished as separate events at the output of a neuron. We further investigated this idea through another series of experiments in which we tested cortical neurons with a variety of temporal variations. In our experiments, temporal variations were introduced in two ways, sinusoidal amplitude-modulated tones (sAM) and frequency-modulated tones (sFM). These stimuli were centered at a neuron's CF. The majority of neurons in A1 responded maximally to modulated tones with sustained firings at a particular modulation frequency. Figure 2 (left) shows responses of a typical neuron to sAM stimuli at various modulating frequencies. At modulation frequency of 32 Hz, the

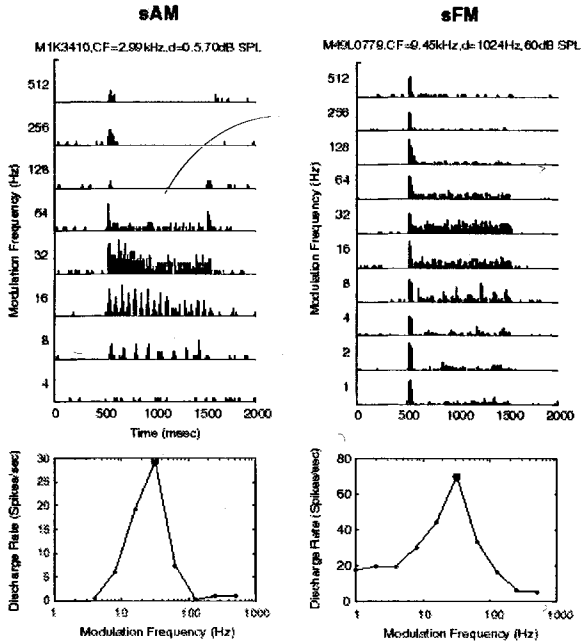


Figure 2. Examples of cortical responses to sAM and sFM stimuli. PSTHs are shown for all modulation frequencies tested. Average discharge rate was calculated over the duration of a stimulus (onset at 500 ms, duration 1000 ms).

discharge rate reached the maximum observed. This modulation frequency is conventionally referred to as the *best modulation frequency* (BMF). Note that this neuron discharged weakly at lower modulation frequencies and did not discharge at all (after onset discharges) at some higher modulation frequencies. The lack of responses at higher modulation frequencies appears to result from inhibition that is not activated at lower modulation frequencies in this and many other cases we observed. An example of representative responses to sFM stimuli is shown in Figure 2 (right). This neuron also discharged maximally at modulation frequency of 32 Hz. Overall, the most frequently encountered BMFs in A1 of awake marmoset monkey ranged from 16 to 64 Hz for both sAM and sFM stimuli. For the population of neurons we studied, the distribution of BMFs centered at approximately 30 Hz for both sAM and sFM stimuli. Furthermore, for many neurons we studied, there was a close match between BMF_{AM} and BMF_{FM} . Because amplitude and frequency modulations are produced along different stimulus dimensions, the matched BMF suggests a common intrinsic neural mechanism that processes these temporal variations. Together, these data showed that individual neurons in the auditory cortex of awake marmosets have a preferred *temporal modulation frequency* (~30 Hz) that is relatively independent of how stimulus modulation is introduced. The auditory cortex thus is maximally excited at this particular modulation frequency. This evidence supports the notion that neurons in the auditory cortex integrate sound streams over a time window of approximately 30 msec in length.

Does this preferred temporal modulation frequency bear any implications to the processing of natural sounds? As we know, speech and musical sounds contain prominent modulations in the envelopes of their waveform. Low-frequency (<30Hz) modulations are important for speech reception and melody recognition, whereas higher-

frequency modulations produce other types of sensations such as roughness. The primate species studied, the common marmoset, produces two types of vocalizations (*trill* and *trillphee*) that display prominent sinusoidal frequency modulations near this cortically preferred temporal modulation frequency. We calculated the frequency of the modulation in a call's spectrogram for a large number of samples in each call type (Agamaite and Wang 1997). The distribution of the modulation frequency in both calls is centered close to 30 Hz. The average value of this modulation frequency differed among individual marmosets, suggesting that this parameter may be used in caller identification. Behaviorally, trill and trillphee calls are considered contact calls that marmosets use during intra-species vocal exchanges. Having the calls' modulation frequencies close to this cortically preferred temporal modulation frequency should facilitate processing of these calls by marmoset's auditory cortex.

4. Cortical responses to stimulus transients within the temporal integration window

The experiments discussed above suggest that neurons in the auditory cortex integrate stimulus component within a time window of ~30 msec and treat components outside this window as separated acoustic events. Because humans and animals are known to discriminate changes in acoustic signals in time scales shorter than the proposed temporal integration window, cortical neurons must be able to signal such rapid changes in sounds. We investigated sensitivity of cortical neurons to rapid changes within the temporal integration window using a class of temporally modulated signals, *ramped and damped sinusoids* (Patterson 1994). A damped (ramped) sinusoid consists of a pure tone modulated by an exponential function. It has a fast (slow) onset followed by a slow (fast) offset. The rate of amplitude decay (or increase) is determined by the exponential half-life. Because ramped and damped sinusoids are the time-reversed

Responses to Ramped/Damped Sinusoids

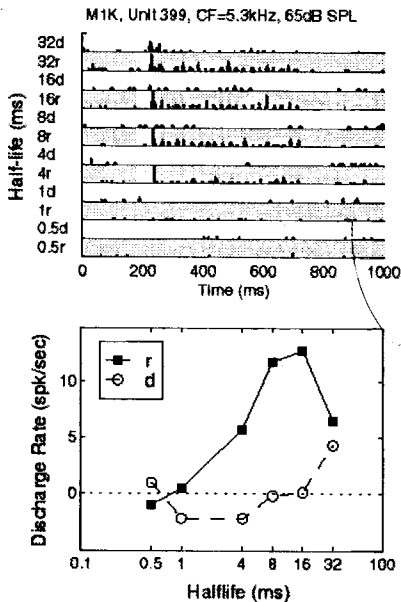


Figure 3. An example of cortical responses to ramped and damped sinusoidal stimuli recorded from A1 of awake marmoset (d-damped, r-ramped). This neuron preferred ramped sinusoids to damped sinusoids for half-life values of 4-32 msec.

signals of each other, they have identical long-term Fourier spectra. Our experimental stimuli consisted of ramped or damped sinusoid segments, 25 msec in duration, repeated consecutively to 500 msec. For each neuron, the carrier frequency was set at the characteristic frequency and half-life was varied from 0.5 to 32 msec. Most of cortical neurons we studied showed clear preference to either ramped or damped stimuli (i.e., they responded more vigorously to a single stimulus type) with a greater portion of units preferring ramped stimuli. Some units responded nearly exclusively to one stimulus type. A representative example is shown in Figure 3. Generally, preference to stimulus type was consistent between different half-lives. These observations demonstrate that temporal characteristics within the temporal integration window can profoundly modulate a cortical neuron's responsiveness. In addition, a response measure based on neuronal populations suggests a possible physiological correlate of the perceptual asymmetry between these two types of stimuli as demonstrated by Patterson and colleagues.

5. Summary

Based on our findings from the studies discussed above, we suggest a two-stage model for processing temporal information by the auditory cortex. In this model, the auditory cortex integrates continuous acoustic streams over a temporal integration window of approximately 30 msec. Temporal patterns that are separated by intervals longer than this integration window are explicitly coded by temporal discharge patterns of cortical neurons. Rapid time-varying components within the integration window are instead represented implicitly by a discharge-rate-based code. The combination of both temporal and rate codes should sufficiently encode a wide range of temporal dynamics of biologically important complex sounds.

The significant reduction in temporal limit on stimulus-synchronized discharges at the auditory cortex as compared with the periphery has an important functional implication. It suggests that cortical processing of sound streams operates on a "segment-to-segment" basis rather than on a more or less "moment-to-moment" basis at the auditory nerve. This is perhaps necessary for complex integration and comparison to take place at this level of the auditory system, as such higher level processing tasks require a broader view of acoustic events preceding and following a particular time.

6. Acknowledgements

This study has been supported by NIH-NIDCD Grant R01 DC-03180 and a grant from Whitaker Foundation (RG-96-0268). We thank Steve Eliades for technical support and Ashley Pistorio for assistance in animal training.

7. References

- Agamaite, J. A. and Wang, X. (1997). Quantitative Classification of the Vocal Repertoire of the Common Marmoset (*Callithrix Jacchus Jacchus*). Association for Research in Otolaryngology Abs. 20.
- Goldstein, M. H., Jr, Kiang, N. Y.-S., and Brown, R. M. (1959) Response of the auditory cortex to repetitive acoustic stimuli. *J. Acoust. Soc. Am.* 31, 356-364.
- Langner, G. (1992) Periodicity coding in the auditory system. *Hear. Res.* 60, 115-142.
- Lu, T. and Wang, X. (2000). Temporal discharge patterns evoked by rapid sequences of wide- and narrow-band clicks in the primary auditory cortex of cat. *J. Neurophysiology* (in press).
- Patterson, R.D. (1994) The sound of a sinusoid: Spectral models. *J. Acoust. Soc. Am.* 96, 1409-1418.

Comment by Viemeister

Might the similarity between the BMFs (and MTFs, Fig. 2) for sAM and sFM reflect FM to AM conversion produced by auditory filtering?

Reply

It is possible that auditory filtering contributes to the similarity between the BMFs for sAM and sFM we observed in the auditory cortex. However, several evidences would argue that the FM-to-AM conversion produced by auditory filtering could not be the only explanation. First, the modulation depths of the sFM stimuli we tested were sufficiently large so that a number of other central mechanisms become involved such as lateral inhibitions from frequency regions flanking a neuron's excitatory frequency response area. Both the cortical neurons we studied and subcortical neurons that provide their inputs are known to have lateral inhibitory areas. Second, while there were similarities in the BMFs based on mean firing rates, temporal discharge patterns resulting from sAM and sFM stimulation can be different (see comments below), suggesting that responses to the sFM stimuli were not completely converted to an sAM-equivalent representation.

Comment by Rees

Your conclusion that AM and FM might be detected by the same neural mechanisms is based on mean firing rate measures. With frequency modulation depths that exceed the bandwidth of the neuron's frequency response area one might expect to see a synchronised response that is at twice the modulation rate since the frequency sweeps through the response area twice during each cycle. Was there any difference in the synchronised responses to AM and FM?

Reply

We indeed observed in some cortical neurons synchronized discharges occurring at twice the modulation rate when the modulation depth of a sFM stimulus was larger than the bandwidth of the neuron's frequency response area. The synchronized response patterns were clearly different between sAM and sFM stimuli under these conditions. If modulation depths smaller than the bandwidth of the frequency response area were used, cortical neurons may exhibit discharges synchronized to each cycle of a sFM stimulus, as they usually do for sAM stimuli. Even in these cases, sAM and sFM stimuli may produce synchronized discharge patterns that differ in details. However, the upper limits of modulation rate (MTF cutoff frequency) for synchronized responses were similar between sAM and sFM stimuli in each neuron. In general, when a cortical neuron responded to sAM stimuli with synchronized discharges, it did so to sFM stimuli as well. A large number of cortical neurons, however, showed no synchronized discharges to sAM or sFM stimuli. For many cortical neurons, regardless of whether a neuron showed synchronized discharges, its responses to sAM and sFM stimuli exhibited similar BMFs when measured by mean firing rates.