logical changes that are latent until an agent such as lithium is administered (*17*). The failure to observe a change in renin activity in peripheral plasma suggests that a central mechanism may be responsible for the lead-induced increase in LIP. Thus, the observed lead-induced alteration may provide an excellent model for further study of developmental changes caused by lead, because LIP occurs consistently and is easily quantified. Further studies are needed to elucidate the mechanisms responsible for increased LIP in rats treated neonatally with lead, as well as to determine if these mechanisms are associated with pathological conditions linked to lead exposure, such as hypertension (*12*).

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16. To date (15 months of experimentation), these experiments have encompassed 20 pairs of lead-treated and control litters totaling 97 lead-treated rats and 95 controls given lithium at least once. In every experiment the lead-treated rats exhibited significantly greater LIP than did controls for days 7 through 9 after lithium administration.
17. R. B. Mailman, M. Krigman, R. A. Mueller, P. Mushak, G. R. Breese, in preparation. In these animals the amounts of lead in the brain and blood decreased rapidly after cessation of lead treatment. Brain levels decreased from a maximum of 0.60 to 0.80 μg of lead per gram of tissue to levels indistinguishable from controls (<0.10 μg/g) by 60 days after treatment, whereas the amount of lead in the blood decreased from greater than 100 μg/100 ml 24 hours after treatment to control levels (<10 μg/100 ml). This animal model has been examined for possible neurochemical or behavioral alterations induced by lead. For example, we found no significant changes in concentrations or turnover of catecholamines or serotonin, in basal food or water consumption, somatic growth, or in basal locomotor activity ("doughnut" cage). A decreased locomotor response after injections of L-dihydroxyphenylalanine (L-dopa), but not after injections of amphetamine or scopolamine, has been observed, but unlike the LIP, does not occur consistently from litter to litter.
18. The relative increase in water consumption of each rat (lead-treated and control) was plotted against the PRA when it was killed. No correlation was found for treated or control rats, alone or separately. This suggests that LIP is not mediated directly by circulating PRA. Measurements of circulating angiotensin II were made by direct radioimmunoassay of both fresh and stored plasma. Though no significant differences were again observed between lead-treated and control rats (both demonstrating similar increases in immunoreactivity after lithium administration) the technique of direct assay without removal of competing materials or separation from degrading enzymes probably necessitates reinvestigation [K. J. Kosunen, *Scand. J. Clin. Lab. Invest.* **36**, 467 (1976)] of the role of angiotensin II in this phenomenon. In one experiment in which we used an average of two animals from each of six different pairs of lead-treated and control animals, plasma lithium levels were determined when the animals were killed approximately 24 hours after the last LiCl injection. No significant differences were found between lead-treated and control rats.
19. We thank G. King, R. Ison, and D. Smith for assistance. A preliminary report of this work was presented at the annual meeting of the American Society of Pharmacology and Experimental Therapeutics [R. B. Mailman, M. Krigman, P. Mushak, R. A. Mueller, G. R. Breese, *Pharmacologist* **9**, 134 (1977)]. Supported by PHS grants ES 01104, HD 10570, and HD 03110.

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Human Auditory Frequency-Following Responses to a Missing Fundamental

Abstract. *Both a complex tone perceived as a 365-hertz "missing fundamental" and a 365-hertz pure tone evoked 365-hertz far-field frequency-following responses. Narrow-band masking noise centered at 365 hertz attenuated the responses to the pure tone but not to the complex tone. Results support the concept that perception of the missing fundamental is based on periodic neural activity.*

A complex tone composed of harmonics related to a low fundamental frequency can produce a sensation of pitch one octave or more below the lowest frequency present in the stimulus complex. The perception of a pitch in the absence of spectral energy at that frequency has been of interest to auditory researchers since the experiments of Seebeck in 1843 (*1*). Seebeck's findings challenged the prevailing concept that pitch perception was determined solely on the basis of a sinusoidal stimulus component corresponding to each pitch perceived (*2*). Subsequently, this phenomenon has been viewed as an example of an alternative form of pitch coding in which the auditory system responds to the inherent periodicity of a stimulus pressure wave in addition to its spectral composition. Perceptual phenomena related to those observed by Seebeck have been described more recently under several different labels. Among these are "the missing fundamental" (*3*), "residue pitch" (*4*), and "periodicity pitch" (*5*).

Although the stimulus conditions yielding missing fundamentals are widely known, the neural basis by which their pitch is perceived remains largely unexplored, save for a few studies of single units in animals. Such studies have shown that auditory neurons at various brainstem levels can phase-lock to low tones or, in some cases, to difference tones derived from higher partials, even when phase-locking to the partials themselves fails to occur (*6*). Electrophysiological data obtained with two other methods further suggest that low-frequency "volley coded" (*7*) pitch information might be carried in the ensemble characteristics of groups of phase-sensitive auditory neurons. One of these methods, the multiple-unit record (*8*), like single-unit recording, lends itself only to animal preparations. The other, the auditory frequency-following response (FFR), has recently been obtained from human subjects through the use of far-field procedures (*9*).

The FFR is a low-voltage neuroelectric wave whose period corresponds precisely to that of a low-frequency tonal stimulus. Such FFR activity, evoked by acoustical stimulation, is generally considered to be the aggregate envelope of the action potentials of a large group of phase-locking auditory neurons concentrated within major brainstem auditory nuclei (*10–12*). Although in the past the FFR has often been confused with

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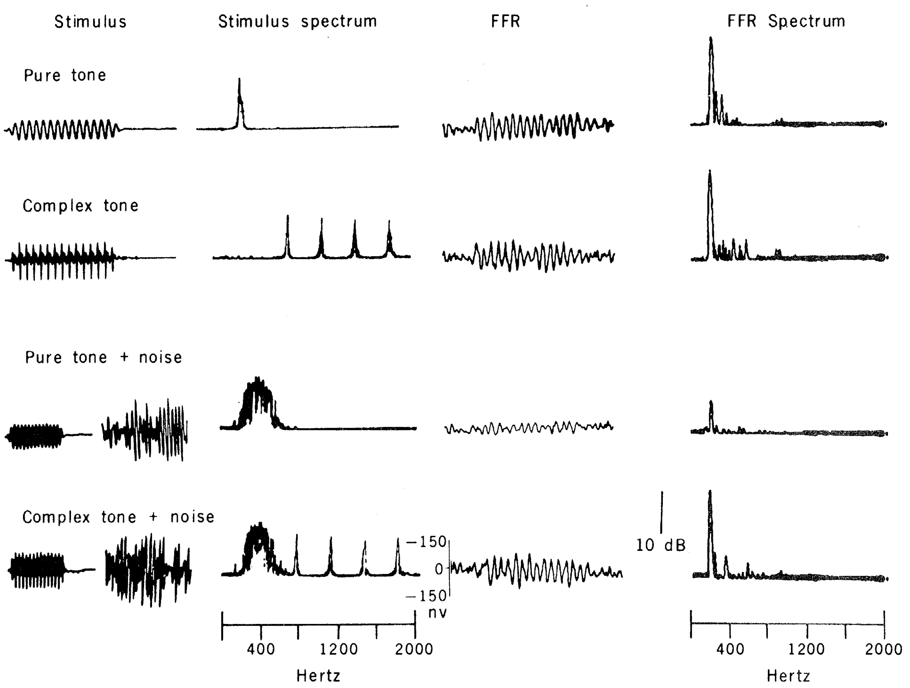

Fig. 1. The FFR to pure and complex tone stimuli alone and in the presence of a masking noise. Column 1 shows averaged microphone responses ($N = 30$) to the stimuli. The bottom two rows of this column show pure and complex noise plus a 365-Hz centered masking noise two critical bands wide, first as an average of 30 sweeps and then as a single sweep, each 62.4 msec long; the signal tone is effectively obscured by the noise masker. Column 2 shows analog spectral analysis of stimulus wave forms. Column 3 shows composite averaged FFR's from seven subjects. Each trace is 62.5 msec long. Column 4 is the analog spectral analysis of the adjacent composite FFR wave. The vertical reference for both sets of spectra is relative sound pressure level or voltage (*dB*).

the cochlear microphonic, it can easily be distinguished therefrom by its upper frequency limits (*12*, *13*), its latency or phase shift relative to the stimulus (*12*), and its nonlinear behavior in the presence of masking noise (*10*). Recent studies of the FFR recorded from the human vertex suggest that the response originates largely from the inferior colliculi. Since the FFR constitutes a relatively pure measure of neural periodicity, we used it to monitor periodic neural activity during perception of the missing fundamental.

Two tonal stimuli were used. One was a complex wave synthesized by the addition of four sinusoidal components (730, 1095, 1460, and 1825 Hz) of equal amplitude and sine starting phase. The second was a synthesized pure tone of 365 Hz, which corresponded to the frequency of the missing fundamental or the common first harmonic of the four components of the complex wave. The acoustic pressure waves resulting from both these stimuli have a period of 2.74 msec.

In order to confirm that the complex stimulus yielded a salient missing fundamental, subjects listened to the complex tone in one ear and a pure tone generated by a separate audio oscillator in the other while adjusting the oscillator to match the fundamental or lowest pitch of the complex wave. All subjects adjusted the oscillator to within 2 Hz of the 365-Hz missing fundamental.

Both the complex wave and the 365-Hz fundamental tone were digitally synthesized within the computer by means of a sine function with a resolution of 16,000 samples per second. For the purpose of collecting FFR data, both waveforms were converted to discrete tone bursts by applying digital linear ramp functions with a slope of 20 percent per millisecond to both the beginning and end of a 45-msec wave segment. These tone bursts were then scaled to yield 81 dB sound pressure level (SPL) when delivered through a 10-bit digital-to-analog converter. The spectral content of the stimuli was determined by analyzing with a low-frequency analog analyzer (modified Tektronix 1L5) the output of a condenser microphone (B & K) acoustically coupled to the subject's earphones.

Responses from seven subjects with normal hearing were collected under each of four stimulus conditions (Fig. 1). Condition 1 consisted of the 365-Hz fundamental tone. Condition 2 used the complex missing fundamental tone. Condition 3 used the pure tone of condition 1 to which was added a continuous masker composed of random noise, band-limited to two critical bands centered at 365 Hz. Condition 4 used the complex tone in the presence of the same noise masker. In conditions 3 and 4, the noise was adjusted to 86 dB SPL, 5 dB above the SPL of the tonal stimuli. The two left-hand columns of the figure show oscilloscope traces of microphone responses and real-time analog spectral analyses of the acoustic pressure waves produced by each of the four stimuli when measured at the subject's earphones.

Recordings were made with subjects seated in an acoustic chamber. Stimuli were delivered binaurally through a headset consisting of two shielded earphones. Vertex responses (earlobe reference) were amplified to a gain of 10^5 and band-pass filtered between 200 and 1000 Hz in order to eliminate the brainstem evoked response (*14*). Averaged FFR's were accumulated using the same computer system that generated the stimuli. A sampling rate of 16,000 samples per second yielded 1000 data points in a 62.5-msec epoch. Each average was based on either 2000 or 3000 responses (*15*).

The spectral content of averaged responses was determined by passing the accumulated average through a digital-to-analog converter into the low-frequency analog analyzer. Thus identical analyses were applied to the stimuli (Fig. 1, column 2) and the responses (Fig. 1, column 4). Quantitative confirmation of the relative amplitude relationship of the principal spectral peaks of column 4 were obtained with a narrow-band digital filter within the computer.

Analysis of the FFR records reveals that the complex stimulus consistently evoked an FFR wave form. In contrast to the stimulus pressure wave, however, this FFR exhibited the majority of its spectral energy at the missing fundamental frequency. The frequencies of the four component partials of the complex tone are not significantly represented within the FFR spectrum. The FFR to the missing fundamental is spectrally similar to, and in most cases, larger in amplitude than the FFR wave evoked by a pure tone of the same pitch. The first two rows of Fig. 1 illustrate this point. Although the pure-tone and complex-tone stimuli have different spectral compositions, the FFR wave forms evoked by each of them contain predominantly one frequency, 365 Hz, which conforms to the perceived pitch of both stimuli.

The bottom two rows of Fig. 1 show that narrow-band noise centered at 365 Hz has no effect on FFR to a missing fundamental, but drastically attenuates FFR to a pure tone at that frequency. This result is consistent with the psychophysical finding that the missing fundamental is difficult to mask perceptually (*16*). The bottom two panels of column 2 show that the energy in the noise masker is confined to the band surrounding the 365-Hz fundamental, but does not overlap any of the components of the complex stimulus.

The effects of noise on FFR to the two stimuli are seen in the FFR wave forms and spectra of columns 3 and 4. In the presence of masking noise, the amplitude of averaged FFR to the pure tone is reduced by a mean value of 8.04 dB. The same masker was effective in reducing FFR to the missing fundamental by a mean value of only 1.04 dB. Comparison of these mean masking decrements shows the FFR to the pure tone to be significantly masked [$t(1,6) = 2.26$, $P < .05$], while FFR to the complex tone is not [$t(1,6) = 0.44$] (*17*). These results support the hypothesis that the pitch of the missing fundamental (residue pitch) is based on the period of a stimulus wave rather than its spectral content.

Our observation that band-limited masking noise affected FFR to a pure tone, but failed to affect a similar FFR derived from the residue of a complex tone, argues against the hypothesis that the missing fundamental arises from distortions that excite the apical 365-Hz region of the cochlear partition. Were this the case, the noise masker should have had a significant attenuating effect on FFR to the complex tone, as it did on FFR. The masking results further suggest that the pitch of the pure tone is carried by elements most sensitive to low frequencies, whereas the pitch of the missing fundamental is mediated by elements sensitive to frequencies other than those within the band of the masking noise.

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14. The brainstem evoked response (BSER) [D. Jewett, H. N. Romano, J. S. Williston, *Science* **167**, 1517 (1970)] is a wave complex associated with stimulus onset, which can obscure the first 10 msec of FFR. High-pass filtering the incoming electroencephalographic signal with a 200-Hz cutoff before analog-to-digital conversion effectively removes BSER activity without significantly distorting the FFR.
15. In six subjects, a sample size of 2000 was used. In one subject, the signal-to-noise ratio was so low that a sample size of 3000 was required in order to produce a reliable averaged FFR. When responses from this subject were entered into the composite waves shown in column 3 of Fig. 1, they were reduced in amplitude by 1/3 in order to preserve scale consistency.
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17. Both analog spectral analysis and digital filter analysis of the composite FFR records, combined across seven subjects, show the decrement in pure-tone response to be approximately 11 dB in the presence of the noise masker (Fig. 1, column 4). When the attenuation of each subject's responses were measured separately, their mean was -8.04 dB as reported. The 3-dB discrepancy is attributable to accumulated small FFR phase differences between subjects.
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Symbolic Communication Between Two Chimpanzees (*Pan troglodytes*)

Abstract. *Through use of learned symbols, two chimpanzees accurately specified 11 foods by name to one another when the food item's identity was known by only one. They could not do this when denied use of the symbols. The chimpanzees then spontaneously requested specific foods of one another by name. Requests resulted in cooperative and reciprocal symbolically mediated food exchange.*

Following the Gardners' (*1*) report of the chimpanzee Washoe's use of signs (Ameslan) with human beings, the question of whether or not chimpanzees might be able to use learned symbols to enhance their communication with one another has often been raised (*2*). Fouts (*3*) reported that Ameslan-tutored chimpanzees occasionally sign "tickle" and "gimme fruit" in the presence of one another; however, wild chimpanzees also request tickling and food through nonverbal vocalizations and gestures (*4*). Additionally, Menzel (*5*) has demonstrated that untutored chimpanzees can, by means of vocalizations, gestures, and purposive locomotion, communicate whether they are traveling toward a food or nonfood substance. Clearly then, because of the chimpanzee's extant nonverbal communicative ability, any report of interanimal communication that purports to depend on symbolic or language-like skills must show that the communications did not and could not occur through nonverbal modes already available to the animal.

This report presents what is, to our knowledge, the first instance of such symbolic communication between nonhuman primates. The communication system is described in detail elsewhere (*6*). In brief, the chimpanzees use a graphic system of geometric symbols, or lexigrams, in which each symbol is intended to represent an English word (*7*). Words are expressed by depressing keys embossed with their respective lexigrams. Each key depression results in the reproduction of a facsimile of that lexigram on projectors above a keyboard. The experimenter can also communicate with the animal through these projectors on a separate keyboard outside the animal's room to eliminate cueing. All output is monitored and recorded by a computer (PDP8E) (Fig. 1).

The two chimpanzees of the present study were Sherman ($4\frac{1}{2}$ years old) and Austin ($3\frac{1}{2}$), both born in the laboratory. Both had received previous language training with the computer-based system; details of their original learning of the food names used during the communication task will be described (*8*). Following acquisition of food names, two additional stages of training provided them with the skills prerequisite to the specific type of communication reported here.

First the animals were asked to name, on their keyboards, various foods in response to the projector-posed question, "What this?" They could not request or eat the foods during the task—only name them. If they were correct, they received social praise or the opportunity to request a different food from the machine (*9*). The animals accurately named all the foods once they learned, through