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PSYCHOPHYSICAL ANALYSIS OF MICROWAVE SOUND PERCEPTION

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It has been found that humans perceive low-intensity, appropriately modulated electromagnetic energy in the microwave portion of the spectrum as a "sound" (radio frequency [rf] sound or microwave sound). This experimentation was undertaken to determine if the repetition pitch phenomenon is a characteristic of microwave sound. It was found that it is not. The data indicate, with the microwave energy parameters used, that the subjects perceive the energy as 4.8 kHz ± 0.8 kHz "sounds". This is related to the finding that clinically normal people with a marked loss in a band about 5 kHz cannot hear microwave sound, whereas clinically deaf people who are relatively normal at about 5 kHz can hear microwave sound. The data indicate that the microwave sound mechanism may involve only a portion of the cochlear apparatus. Thus, the microwave sound phenomenon may provide a unique probe for evaluating some of the concepts of auditory perception.

Through a series of experiments, it has been established that people can perceive microwave energy as a "sound" if it is appropriately modulated (1, 2, 3, 4). The characteristics of the sound vary as a function of the modulation; but in many cases, it is reported as a buzz, click, or chirp. These experiments have established that the phenomenon is not due to fillings in teeth, audible vibration of nearby materials, and other such factors.

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Microwave sound is the subject of considerable interest for two reasons. First, it is one of the reliable and easily replicable effects of low intensity microwave energy. Second, although the nature of the transduction mechanism is as yet unknown, there are data which suggest it is the sensory rather than the central processing system that is involved (5, 6). Thus, an understanding of how the energy causes the reported perception may advance our knowledge of sensory system function. In fact, the microwave sound phenomenon may provide a unique probe in the evaluation of some of the concepts of auditory perception such as those noted by Naftalin (7).

One approach to understanding the mechanism of microwave sound is through psychophysics. It has been found in acoustical studies that if two sound pulses are separated by a time period τ_s as illustrated in Figure 1, a human will perceive such a test stimulus as having tonal components. Further, he can match a train of such pulse pair test stimuli with a variety of acoustic stimuli; i.e., sinusoidal, gated sinusoidal, pulse, etc., that have a fundamental frequency equal to the inverse of τ_s (8, 9). As Bilsen and Ritsma (10) state, "In general, signals consisting of a sound, together with repetition of that sound after a delay time τ, are able to evoke well-defined strong pitch sensations corresponding to $1/\tau$. Authors refer to these pitch phenomena as sweep pitch, time-separation pitch, time difference tone, reflection tone, and repetition pitch." Actually, as Bilsen and

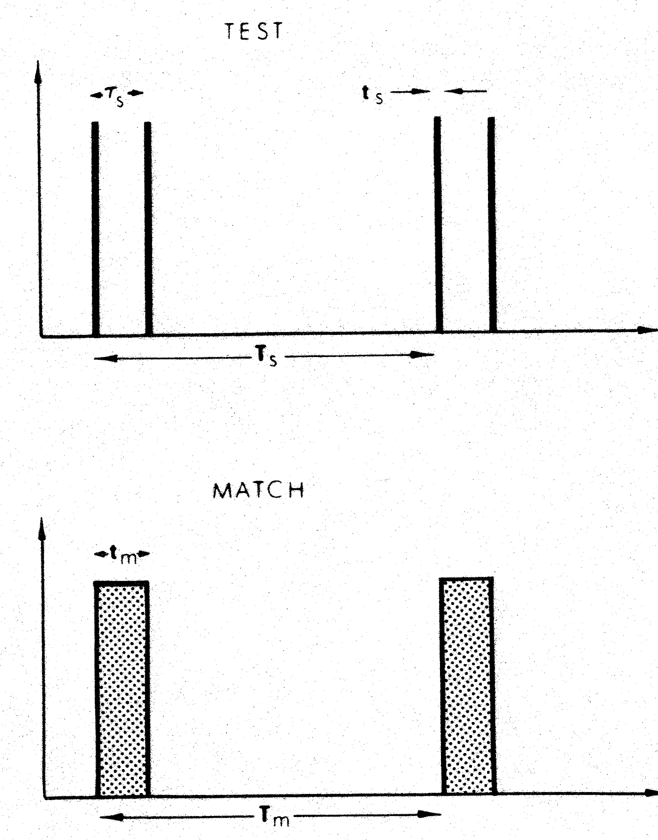

FIGURE 1

The upper portion illustrates the microwave energy signal characteristics used in this study. τ_s is the time between pulses within a pair measured from rise time to rise time. t_s is the pulse width. T_s is the time between pairs measured from rise time of the first pulse in a pair to the rise time of the first pulse in the next pair. The lower portion illustrates the acoustic signal used for matching. t_m is the pulse width. T_m is the time between pulses measured from rise time of one pulse to rise time of the next pulse.

Ritsma (10) note, "Three types of signals have been used: (a) white noise with its repetition after a time τ; (b) a random sequence of pulse pairs with pulse interval τ and average pulse pair interval $\overline{T}$; and (c) a periodic sequence of pulse pairs with pulse interval τ and pulse-pair interval T."

Although the repetition pitch phenomenon is not well understood, there are strong indications that it is the result of activity in the cochlea, and that it involves higher neural processes to only a limited extent (9, 11, 12). Thus, if the repetition pitch phenomenon appears when pulsed microwave energy is used as a stimulus, then this would be evidence that the transduction mechanism is not located at higher levels of the nervous system. If the phenomenon does not appear, this would suggest the energy is not transduced into acoustic energy before reaching the cochlea. Further, it would suggest the mechanism does not involve, in toto, the cochlear mechanisms involved in hearing. To evaluate these possibilities, a psychophysical experiment was designed and carried out to determine if the microwave sound phenomenon has repetition pitch characteristics.

METHOD

The experimentation was carried out with humans placed in a radio frequency anechoic chamber constructed to minimize microwave energy reflections. The energy source was a tunable triode cavity oscillator that emitted energy at a carrier

frequency of 1.2 GHz. This energy was conveyed by an air line (General Radio Model 874) and RG-8 coaxial cable to a coax-to-waveguide adapter (Scientific Atlanta Model 11-1.1) and a standard gain horn antenna (13). The horn antenna emitted the energy within the rf anechoic chamber. The antenna was oriented such that the energy was vertically polarized, but the results of previous rf sound experiments indicate that horizontally polarized energy would probably yield similar data.

The microwave energy was measured with a half-wave dipole antenna located where the center of the subject's head was placed during data collection. The dipole antenna was supported by a wooden pole in order to minimize field disturbance during the measurement. The dipole was connected by RG-58 coaxial cable to an attenuator (Microlab Model AF 20) located outside the chamber. The attenuator was in turn connected to a thermistor mount (Hewlett-Packard Model 477B) which was connected to a Hewlett Packard Model 430C power meter. The cable within the chamber was oriented for minimum field disturbance. This measurement equipment yields an average power measurement. The signal attenuation due to the cable and to the attenuator is accounted for in the reported measurements.

Using the reports of Ritsma (8) and Bilsen and Ritsma (10), ten values of τ_s, t_s, and T_s were selected as microwave energy modulation equivalents to acoustic white noise or tone burst signals as used in a traditional repetition pitch experiment.

Two sets of values that do not induce repetition pitch were also chosen as controls. The average incident power used was less than 500 microwatts/cm^2.

Acoustic match stimuli were provided by a Grass SD-5 signal source connected to a Model E-21 polyplanar speaker whose response is essentially flat from 50 Hz to 20 kHz. Because acoustic stimuli have timbre characteristics, a rather effective acoustic match signal is a series of rectangular electrical pulses that are applied to a speaker which has a broad frequency response such as the polyplaner speaker used in this study. When the speaker is excited with a rectangular voltage signal of duration t_m, an acoustic wave is produced with a period of approximately T_m, which is non-sinusoidal and rich in harmonics. Such a match stimulus has been shown to be effective in both repetition pitch and microwave sound matching experiments (2, 10).

The subjects were three musicians with clinically normal hearing. The subjects sat in the rf anechoic chamber on a wooden stool in the far field facing away from the horn antenna. Each subject was tested in each of two sessions to each of the ten selected combinations of τ_s, t_s, and T_s. The order of these presentations was randomized. Subjects were presented with the acoustic match stimulus after presentations of the microwave energy test stimulus. The subjects were first permitted to adjust time between acoustic pulse onsets; i.e., the length of

T_m, to try to obtain the best match in terms of T_m to the microwave sound they were hearing. For short pulse stimuli the width of the acoustic pulse, t_m, influences repetition pitch matching. Thus, the subject was allowed to adjust the width of the acoustic pulse, t_m, to optimize his match to the microwave sound. Such presentations were continued for each of the microwave test stimuli until the subject found his best acoustic match values T_m and t_m. During each subject's first session, t_m duration was initially presented as 10 msec; and during the second session t_m duration was initially presented as 0.01 msec. Alternate psychophysical techniques could have been used, but for the objectives of this investigation the one selected was most appropriate. The potentially confounding effects of timbre were controlled by the use of trained subjects; i.e., musicians, and the nature of the acoustic matching signal.

RESULTS

Repetition pitch perception is not a characteristic of the microwave sound. The T_m data expected if repetition pitch is a characteristic of microwave sound and the T_m data obtained are unrelated. Instead, the observed values of T_m are related to T_s ($\chi^2 = 3.28$, $p < .05$), as shown in Table 1. Multiple regression analysis reveals that 99 percent of the variance of the interpulse interval T_m is accounted for by specifying the microwave energy interpulse pair interval T_s. Also unrelated are

TABLE 1

UHF Microwave Parameters and Expected (If Repetition Pitch is a Characteristic of Microwave Sound) and Obtained T_m Means. Listed also are the t_m Means.

Microwave Modulation Parameters			T_m (msec)			t_m (msec)	
t_s (μsec)	T_s (msec)	τ_s (msec)	expected	obtained $\bar{X}$	SEM	$\bar{X}$	SEM
25	40	5	5	39.7	1.7	0.32	.06
25	20	3	3	25.8	1.3	0.33	.07
50	40	5	5	41.5	1.8	0.38	.06
50	40	10	*	40.0	1.4	0.27	.05
25	200	5	*	202.5	3.1	0.17	.02
12.5	40	5	5	38.7	2.6	0.27	.05
17.5	20	2	2	22.3	1.5	0.27	.05
12.5	20	1	1	22.2	1.7	0.20	.00
12.5	40	7	7	34.0	1.3	0.27	.05
37.5	40	7	7	38.7	2.9	0.33	.06

* These two conditions are outside of the existence region of the tonal residue. They test for possible experimenter bias or unexpected pitch effects of microwaves.

t_m and τ_s. Multiple regression analysis reveals that less than 1 percent of the variance of the pulse width t_m is accounted for by specifying the interpulse interval τ_s.

Having found no relationship between the above, the relationship between the acoustic pulse width t_m and the microwave pulse width t_s was tested. Regression analysis reveals that only about 3 percent of the variance of t_m is accounted for by specifying t_s.

Since it was found that the acoustic pulse width t_m is not related to τ_s or t_s, t_m was plotted as an independent variable in Figure 2. Most of the data falls in the 0.15 to 0.25 msec region, suggesting the possibility that pulse pair modulated microwave energy is perceived as equivalent to an acoustic pulse train with a pulse width of 0.2 msec ± 0.05 msec. This corresponds to an acoustic signal with a fundamental frequency approximately 4.8 kHz ± 0.8 kHz.

DISCUSSION

Foster and Finch (14) suggested that the microwave hearing mechanism involves conversion of electromagnetic energy to acoustic energy in soft tissue or in the skull. Their suggestion was based on a model study of acoustic transients in a water tank with the water as an approximation of the head and a hydrophone as an approximation of the middle ear and cochlea. When this thermoacoustic conversion hypothesis was tested physiologically

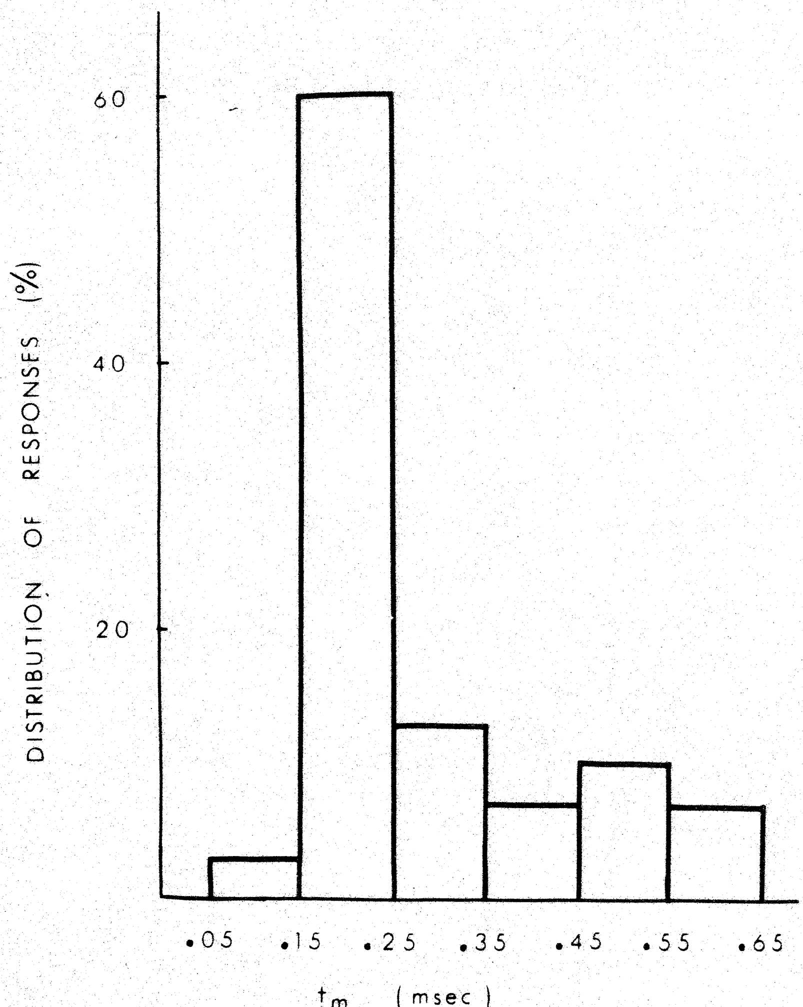

FIGURE 2

Frequency with which subjects selected various acoustic pulse widths (t_m) as matches for microwave energy pulse pair trains.

by Frey and Coren (6) and by Tyazhelov, Tigranian, Khizhnyak, and Akoev (15), neither set of investigators found that the hypothesis could account for the data obtained, though no doubt such conversion could occur under some exposure conditions. Specifically, Frey and Coren (6, 16, 17) used holographic non-destructive testing techniques and found the microwave energy pulses did not induce acoustic waves in skin, muscle, skull, or exposed brain. They also pointed out an unrecognized artifact in thermoacoustic conversion studies. Tyazhelov et al (15) studied the loudness of rf sound as pulse width and repetition rate were varied, as well as beat phenomena and other parameters. They concluded that thermoacoustic conversion in soft tissue and skull is not supported by the data at the low power levels required for microwave hearing. The test reported here for repetition pitch phenomenon also indicates that the low intensity electromagnetic energy induced hearing phenomenon can not be attributed to a transduction into acoustic energy before reaching the cochlea.

The fact that the subjects, in their attempt to match the microwave stimuli, consistently reported as a match a fundamenta frequency of 4.8 kHz ± 0.8 kHz is interesting. This finding ca be related to the findings of Frey (2) and Guy et al (4) that people who are deaf in the region of 5 kHz but who hear normally above and below that frequency do not hear the microwave sound, or do so at thresholds far above normals. The results of this experiment and the fact that stimulation deafness tends to involve the 5 kHz region of the cochlea and the outer hair cells, indicate that the microwave hearing mechanism is located in the cochlea and involves the outer hair cells. Zwislocki and Sokolich (18) and Dallos, Billone, Durrant, Wang, and Raynor (19) found that it is the outer hair cells which are primarily involved in cochlear microphonic generation. One of the investigators who has looked for microwave induced microphonics reports finding them. But the microphonic appears to be an artifact due to the set up (20, 6). Thus, a cochlear location for the mechanism of microwave sound induced by low intensity microwaves seems likely. The possible involvement of the outer hair cells is particularly interesting in view of a recent report describing the mechanical changes that they can undergo (21).

In sum, the data from this experiment, combined with the data reported by other investigators, such as Khizhnyak, Shorokhov and Tyazhelov (22) and Wilson, Joines, Casseday, and Kobler (23), indicate that there are two or more mechanisms by which microwaves can induce the perception of a sound. For low intensity microwave energy, the mechanism appears to be in a portion of the cochlea. Thus, low intensity microwave energy may be a useful tool in the analysis of the function of a portion of a sensory system that is poorly understood.

REFERENCES

1. Frey, A.H. Auditory system response to radio frequency energy. Aerospace Medicine 32, 1140-1142, 1961.

2. Frey, A.H. Human auditory system response to modulated electromagnetic energy. Journal of Applied Physiology 17, 689-692, 1962.

3. Frey, A.H. and Messenger, R. Human perception of illumination with pulsed ultrahigh-frequency electromagnetic energy. Science 181, 356-358, 1973.

4. Guy, A., Taylor, E., Ashleman, B., and Lin J. Microwave interaction with the auditory systems of humans and cats. Paper presented at the IEEE G-MTT Microwave Symposium, Boulder, CO, 1973.

5. Frey, A.H. Biological function as influenced by low-power modulated rf energy. IEEE Transactions on Microwave Theory and Techniques MTT-19, 153-164, 1971.

6. Frey, A.H. and Coren, E. Holographic assessment of a hypothesized microwave hearing mechanism. Science 206, 232-234, 1979.

7. Naftalin, I. The peripheral hearing mechanism: New biophysical concepts for transduction of the acoustic signal to an electrochemical event. Physiological Chemistry and Physics 9 337-382, 1977.

8. Ritsma, R.J. Existence region of the tonal residue I. Journal of the Acoustical Society of America 34, 1223-1229, 1962

9. Schouten, J.F., Ritsma, R.J., and Cardozo, B.L. Pitch of the residue. Journal of the Acoustical Society of America 34, 1418-1424, 1962.

10. Bilsen, F.A. and Ritsma, R.J. Some parameters influencing the perceptibility of pitch. Journal of the Acoustical Society of America 47, 469-475, 1970.

11. Butler, R.A. The auditory evoked response to stimuli producing periodicity pitch. Psychophysiology 9, 233-237, 1972.

12. Bilsen, F. and Goldstein, J. Pitch of dichotically delayed noise and its possible spectral basis. Journal of the Acoustical Society of America 55, 292-296, 1974.

13. Slayton, W.T. Design of microwave gain standard horns. Electronics, July, 150-154, 1955.

14. Foster, K.R. and Finch, E.D. Microwave hearing: Evidence for thermoacoustic auditory stimulation by pulsed microwaves. Science 185, 256-258, 1974.

15. Tyazhelov, V.V., Tigranian, R.E., Khizhnyak, E.P., and Akoev, I.G. Some peculiarities of the auditory sensation evoked by pulsed electomagnetic radiation. Paper presented at the 1977 International Symposium on the Biological Effects of Electromagnetic Waves, Airlie, VA, 1977.

16. Chou, C-K, Guy, A.W., Foster, K.R., Galambos, R., and Justesen, D.R. Holographic Assessment of Microwave Hearing. Science 209, 1143-1144, 1980.

17. Frey, A.H., and Coren, E. Holographic Assessment of Microwave Hearing. Science 209, 1144-1145, 1980.

18. Zwislocki, J.J. and Sokolich, W.G. Velocity and displacement responses in auditory nerve fibers. Science 182, 64-66, 1973.

19. Dallos, R., Billone, M.C., Durrant, J.D., Wang, C-Y, and Raynor, S. Cochlear inner and outer hair cells: Functional differences. Science 177, 356-358, 1972.

20. Frey, A.H. Behavioral biophysics. Psychological Bulletin 63, 322-337, 1965.

21. Brownell, W.E., Bader, C.R., Bertrand, D., and DeRibaupierre, Y. Evoked mechanical responses of isolated cochlear outer hair cells. Science 227, 194-196, 1985.

22. Khizhnyak, E.P., Shorokhov, V.V., and Tyazhelov, V.V. Two types of microwave auditory sensation and their possible mechanisms. International Symposium on Electromagnetic Waves and Biology, Paris, July 1980, 101-103.

23. Wilson, B.S., Joines, W.T., Casseday, J.H., and Kobler, J.B. Responses in the auditory nerve to pulsed, CW, and sinusoidally-modulated microwave radiation. Bioelectromagnetics 1, 237, 1980.