AUDITORY REACTION TIME AND THE DERIVATION OF EQUAL LOUDNESS CONTOURS FOR THE MONKEY[1]

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Monkeys were trained to release a telegraph key at the onset of a pure tone. Latency of the response was measured over a 70-db range of sound pressure (re 0.0002 dyn/cm²) at six frequencies (250 to 15,000 cps). Latency was found to be an inverse exponential function of intensity at all frequencies. Equal loudness was inferred from the equal latency contours which were constructed from the latency-intensity functions at each frequency. These data indicate peak auditory sensitivity for the monkey near 1000 cps. At the frequencies above and below 1000 cps consistently more sound energy was required for equal latency.

In conventional usage the simple reaction time experiment implies a set of contingencies designed to ensure a "minimal" interval between presentation of a stimulus and emission of an operant response. A sequence of two responses is established, and each is under the control of a different stimulus. The response to the first stimulus is "preparatory" and places the subject in a favorable position to make the second response "quickly" after the onset of the second stimulus. The latency of this second response is taken as the primary dependent variable in simple reaction time experiments. With human subjects the contingencies are put into effect through verbal instructions. Frequently included is the request to "respond as rapidly as possible" to the onset of the second stimulus.

The same contingencies can be applied as effectively to lower organisms when selective reinforcement with food or water is used to obtain the necessary stimulus control (Stebbins and Lanson, 1961; Stebbins and Reynolds, 1964). Under the conditions of the simple re-

action time experiment, response latency varies inversely with both frequency and amount of reinforcement for rats (Stebbins and Lanson, 1962; Stebbins, 1962) with the intensity of a peripheral auditory or visual stimulus for monkeys (Stebbins and Miller, 1964) and with the intensity of an electrical stimulus to the visual cortex of monkeys (Miller and Glickstein, 1965). In addition, by differentially reinforcing short latencies the stimulus-response interval can be further decreased (Stebbins and Miller, 1964; Miller, Glickstein, and Stebbins in preparation).

The present series of experiments seeks to apply the simple reaction time design to psychophysical problems with animals. In the study reported here, monkeys were trained to depress a telegraph key after onset of a light and to release the key in response to a pure tone presented from 1-4 sec later. The latency of the key release response was measured over a wide range of intensities at several frequencies. From the latency-intensity functions at each frequency, a family of frequency-intensity curves was plotted with latency as the parameter. These equal latency curves may be regarded as equal perceptibility contours and may, in fact, be the equivalent of equal loudness contours for the monkey.

METHOD

Two naive young (2-3 yr) male monkeys (*Macaca irus*) were restrained in primate chairs and placed in a double-walled sound-treated room (Industrial Acoustics). They had

free access to water but were deprived of food for 22 hr before each daily session. During each session they received about 200 pellets (190 mg banana flavored, whole diet, Ciba) as reinforcement. No water was given during this time. They also received a Purina Chow supplement (about 40 g daily).

For each daily session each subject was further restrained to prevent all but minimal head movement, so that head phones (PDR-600) could be fitted precisely over the opening to the external auditory canal and kept there throughout the session (about 1 hr). The animal's muzzle was held in position between two vertical rods by a Plexiglas support on top of and behind its head. The weight of the phones was reduced by suspending them on a spring attached above the chair. Since restraint of the animal's head prohibited self-feeding, the food had to be delivered directly to its mouth. A slightly modified version of the feeder described by Thompson, Schuster, Dockens, and Lee (1964), connected directly to a Foringer pellet dispenser, was used for this purpose. A small pilot light was attached to the feeder at the subject's eye level. Finally, a telegraph key was affixed to the animal's chair at waist level. The experimental arrangement is shown in Fig. 1.

The PDR phones were calibrated at each frequency to be used with a 2½-in. probe tube, 1 mm in diameter, connected to a Bruel and Kjaer condenser microphone and a Bruel and Kjaer wave analyzer. The reference level for sound pressure level was 0.0002 dyn/cm². The probe was inserted between each phone and the monkey's ear to measure sound pressure accurately at the entrance to the external canal. The phones did not differ by more than 4 db at any frequency. The sound system included an audio oscillator, variable attenuator, and an electronic switch which gated the tones with a rise time of 15 msec and decay time of 30 msec. Tones were presented binaurally.

Experimental events were programmed automatically with silent transistorized digital logic (40 kcps) located outside the sound chamber. Responses were recorded on counters, and latencies (in msec) on a four-stage BCD counter and digital printer. The time base for the counter was a 1000-cps (±0.1%) clock. Both tone intensity and frequency were continuously monitored.

In the first training stage, subjects were reinforced with food for pressing a telegraph key in the presence of the light on the feeder. After conditioning, the light was presented only when no response had occurred on the key for 10 sec. In addition, subjects were required to hold the key down while the light was on until a tone (1000 cps at 95 db) was presented. Release of the key when both light and tone were on was reinforced. The light and tone were terminated with reinforcement, and subsequent stimuli were presented at 10-sec intervals. However, a response during the interval between presentations (inter-trial interval) postponed the next stimulus for 10 sec. The time between key press and tone onset (foreperiod) was varied between 1 and 4 sec. If a release response occurred during the light but before the tone, reinforcement was withheld and the light turned out until the next trial. Finally, only those responses which occurred within 1 sec after tone onset were reinforced and tone duration was shortened to 100 msec. Data for longer tone durations show no significant effect on response latency.

When behavior had stabilized, tone intensity was varied between 95 and 25 db. For two sessions the intensity was changed on every trial and 60 trials were given at each of six intensities (95, 65, 55, 45, 35, and 25 db). On subsequent sessions the tone frequency was changed, and for each frequency the intensity was varied over at least a 40-db range. An attempt was made to keep most intensities clearly above threshold. In this sequence data were obtained from two consecutive sessions at each frequency. Frequencies used, in addition to 1000 cps, were 250, 500, 5000, 10,000, and 15,000 cps. They were presented in a mixed order, and, at the end, the 1000-cps value was reinstated for two sessions. Identical frequency and intensity values were used for each animal.

RESULTS

Figure 2 shows a typical latency-intensity function for subject M-1 at 1000 cps. The upper solid curve is drawn through the median latency at each of the six intensities presented. The vertical slashes through the upper curve indicate the extent of the interquartile range for each point (median). The lower broken curve is a corresponding plot of the quartile
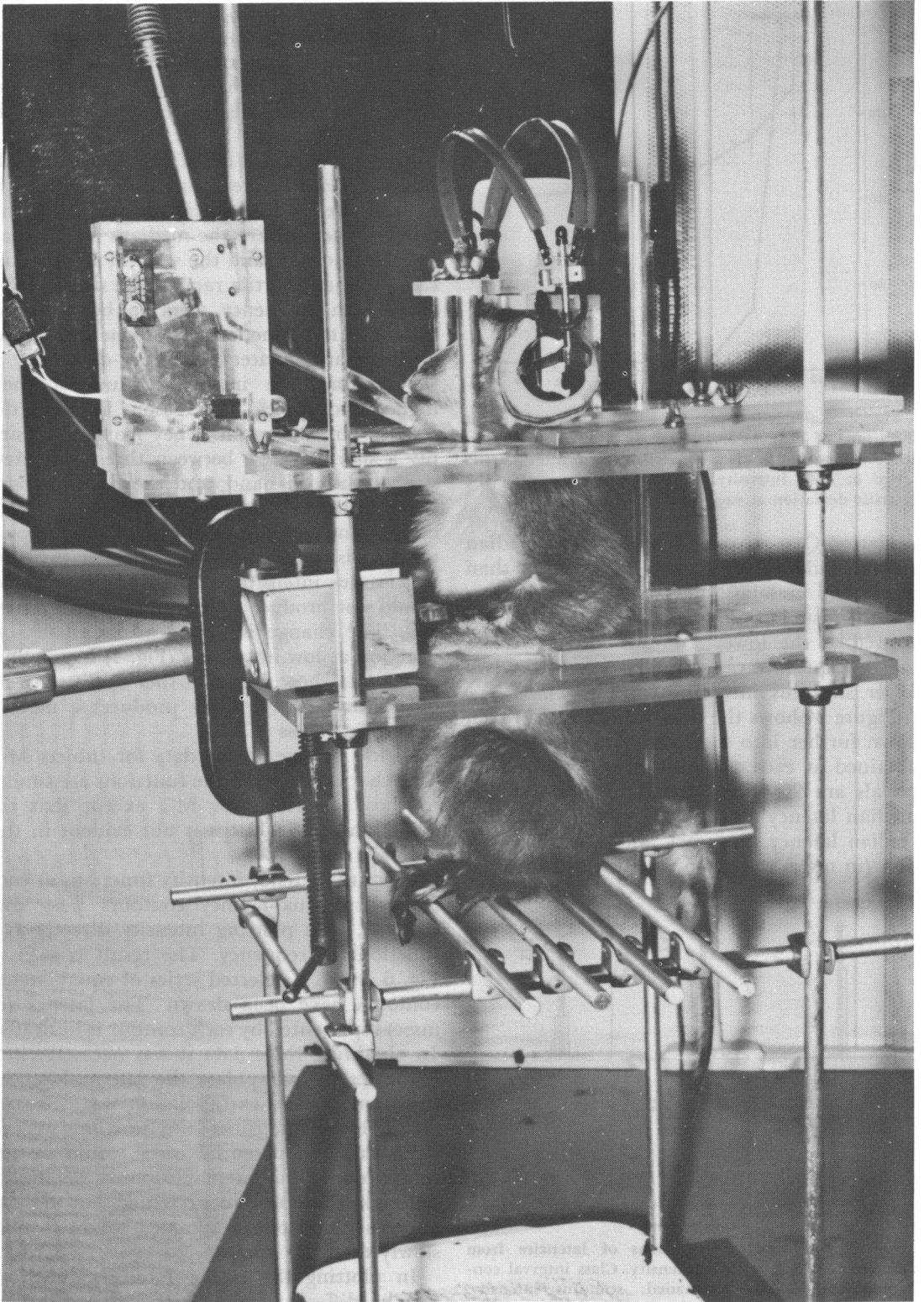
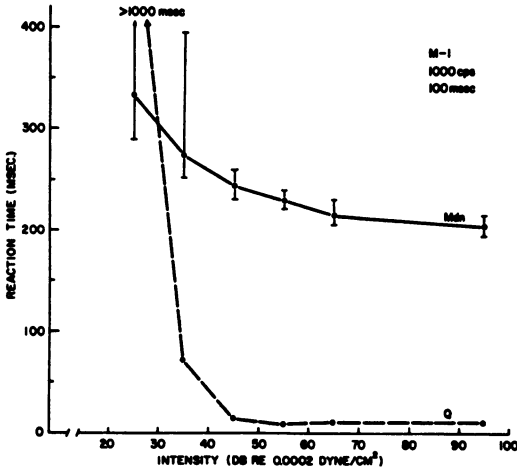Fig. 1. Photograph of arrangement for subject restraint.

Fig. 2. Latency-intensity function for one subject for a tone of 1000 cps and 100 msec in duration. Upper curve indicates the median latencies and interquartile range at each intensity. Lower curve represents the quartile deviation at each intensity.

deviation Q as a function of intensity. Median and quartile deviation were used rather than mean and standard deviation since the frequency distribution for latency becomes very skewed at the lower stimulus intensities (see the interquartile range for latency at the two lower stimulus intensities in Fig. 2).

Figure 3 shows the data from Fig. 2 broken down further into the frequency distributions obtained at each stimulus intensity. Class intervals are 20 msec, intervals containing the median latency are shaded, and the intensity, median latency (in msec), and quartile deviation (in msec) are given for each distribution.
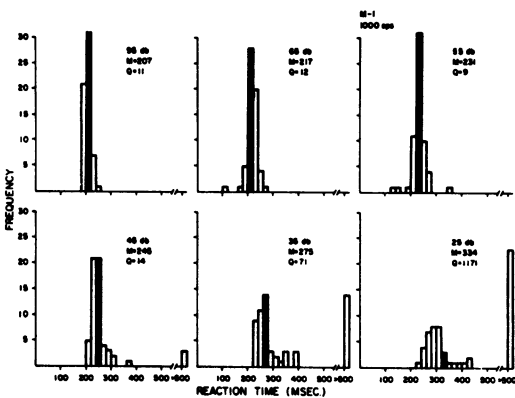

Fig. 3. Frequency distributions of latencies from the data of Fig. 2 at each intensity. Class interval containing the median is shaded; stimulus intensity, median latency, and quartile deviation are indicated on each distribution.

In both Fig. 2 and 3 the increases in median latency and variability of latency as the intensity is decreased are clearly evident. These figures are fairly representative examples of changes in these measures with variation in stimulus intensity.

Figure 4 contains all of the data from subject M-1, *i.e.*, the latency-intensity functions at each of the six frequencies. Again the points on the functions are the medians for 60 trials at each intensity, and the vertical slashes indicate the interquartile range. The major differences with frequency seem to be a steeper slope for the functions at frequencies above 1000 cps and greater variability of latency at the intermediate intensity values at these higher frequencies. The reasons for these differences are uncertain. They may reflect simply a shorter range between threshold intensity on the one hand, and the high intensity value which produces minimal latency on the other. Under the conditions of this experiment, it is quite certain that further increases in stimulus intensity at any of the frequencies would not produce significantly shorter latencies. The change in shape of the 15,000-cps function at low intensities (Fig. 4) is puzzling; other data show that a further decrease in intensity at this frequency produces a median latency in excess of 1 sec.

Figure 5 presents the data for subject M-2. The characteristics of the functions are similar to those described for M-1 except that the deviation at 15,000 cps is not evident in this animal's data.

From the latency-intensity functions at each frequency equal-latency contours were constructed, thus plotting intensity directly as a function of frequency. The result is seen in Fig. 6 and 7. A selected series of equal-latency contours have been drawn. The latency (in msec) represented by each contour is indicated. In obtaining these data it was necessary in a few cases to extrapolate the latency-intensity functions. Where extrapolation was necessary (at the lower intensities) the functions were so steep that the potential error would be less than 5 db on the latency contours. Somewhat different contours are presented for the two animals since one responded slightly more slowly than the other.

In plotting the latency-intensity functions for the different frequencies and in deriving the equal latency contours, the simplest possi-
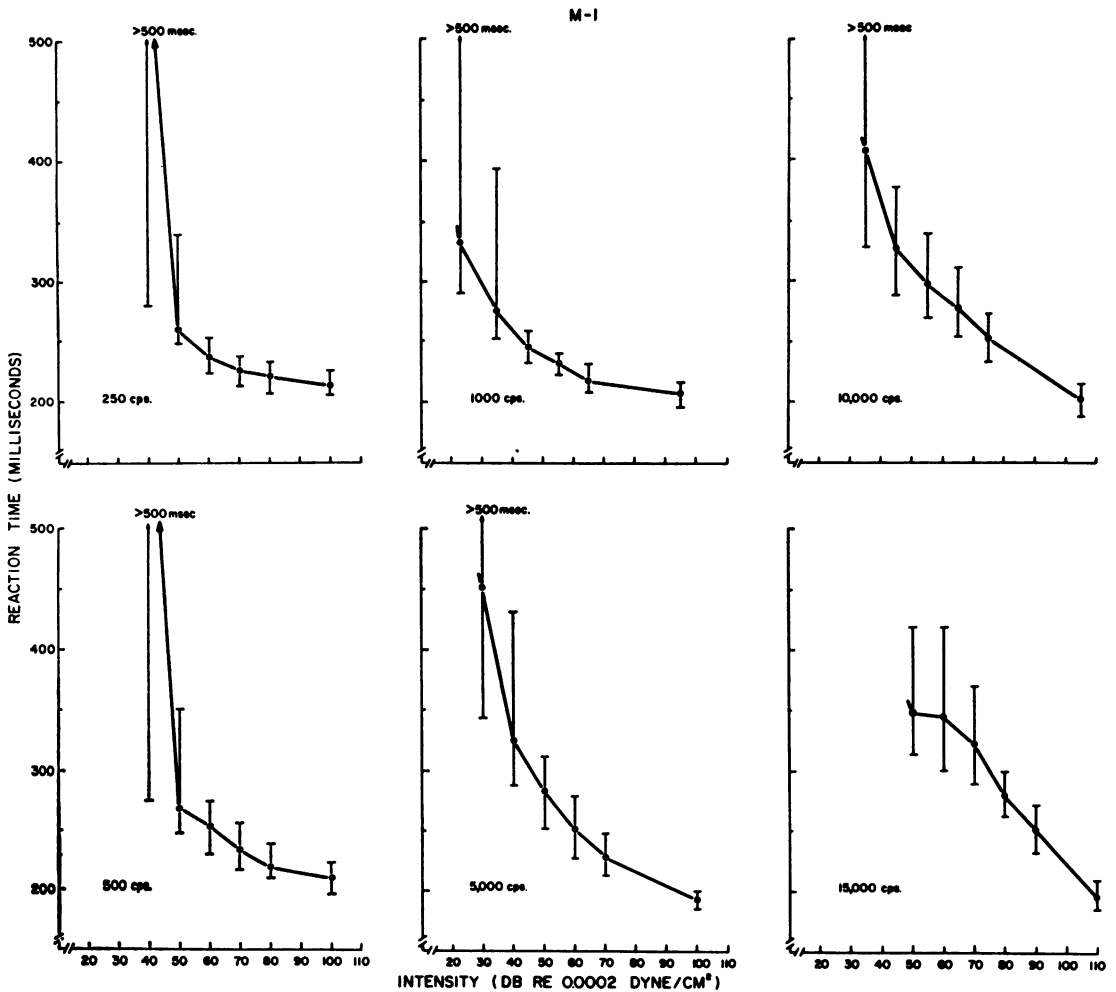
Fig. 4. Latency-intensity functions for subject M-1 at six frequencies. Medians and interquartile ranges are shown.

ble assumptions were made about the data. For the latency-intensity functions the medians were connected point-to-point with a straight line. The points on the latency contours were derived directly from these functions and, again, these points were connected with straight lines. No curve fitting procedures have been employed.

Although the exact shape of the family of latency contours differs to some extent for the two subjects, there are two important similarities. First, to produce a given response latency less sound intensity is required at 1000 cps than at any other frequency. Second, the intensity (sound pressure) required for equal response latency increases with an increase or decrease in frequency on either side of 1000 cps.

DISCUSSION

There is some precedent for calling the equal-latency contours equal-loudness contours. Chocholle (1940) obtained latency-auditory intensity functions at several frequencies with human subjects and found a good fit between his equal latency contours and the Fletcher-Munson curves for verbally instructed "loudness" matching. The general characteristics of the present equal-latency contours are not inconsistent with the Fletcher-Munson curves (Fletcher and Munson, 1933) although for one subject they are less flat at the higher intensities. For the frequencies presented to the monkey, present data indicate maximal auditory sensitivity in the range between 500 cps and 5000 cps. For a pure tone of a given
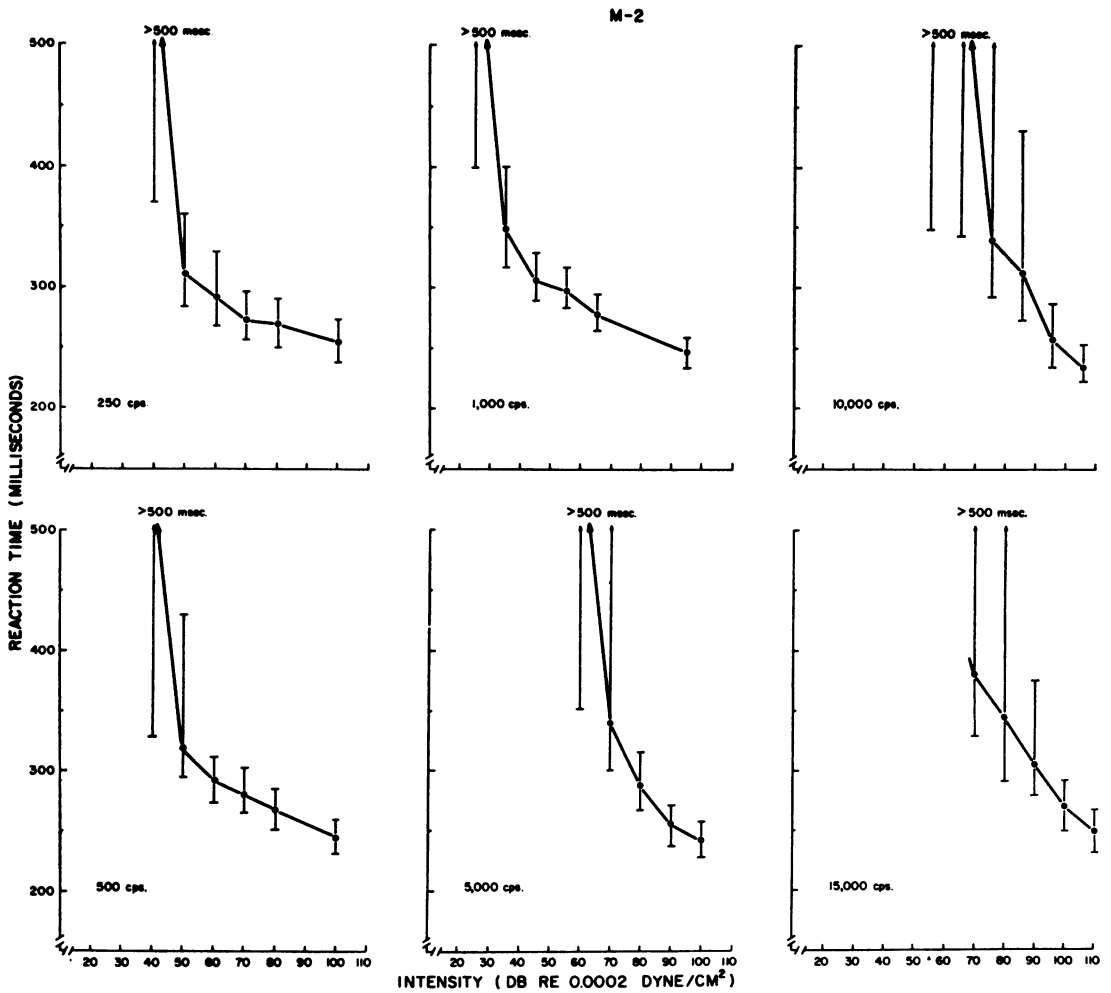
Fig. 5. Latency-intensity functions for subject M-2 at six frequencies. Medians and interquartile ranges are shown.
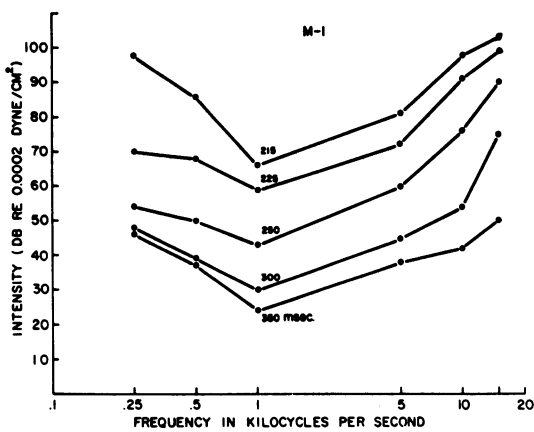

Fig. 6. Equal latency contours for subject M-1. Latency value for each contour is indicated.
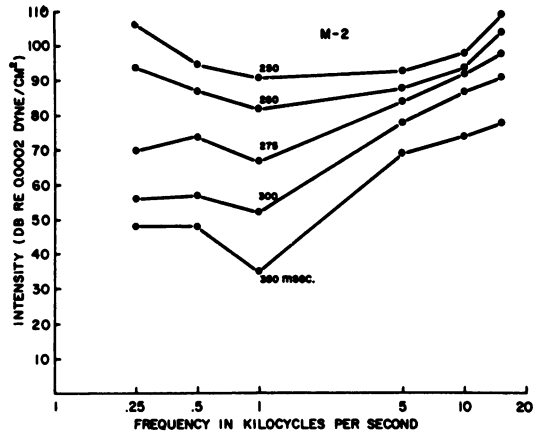
Fig. 7. Equal latency contours for subject M-2. Latency value for each contour is indicated.

frequency to sound equally as loud as a tone of 1000 cps, more sound energy is required in proportion to the distance òf that tone from 1000 cps. In addition, if the characteristics of the loudness curves reflect the properties of the absolute threshold function, as they do for human subjects, then the present results agree closely with recent data for absolute thresholds for *Macaca nemestrina* obtained by Semenoff and Young (1964), who also used earphones. These authors report maximal auditory sensitivity for the monkey at 1000 cps, with a sharp decrease in sensitivity on either side of that frequency. The present results, at least at the higher frequencies, are less compatible with other data for auditory thresholds obtained for a variety of primates under free field conditions (Fujita and Elliott, 1965; Behar, Cronholm, and Loeb, 1965) and indicate a relatively flat threshold function between 500 and 20,000 cps. Whether the differences in these two sets of threshold data for the monkey can be explained in terms of the mode of stimulus presentation and/or method of sound calibration is uncertain. Certainly there were also considerable differences in the behavioral testing procedures employed.

If the traditional definition of loudness is not independent of verbal instructions then it becomes impossible to extend the concept of loudness to non-verbal organisms. However, if loudness is to have any behavioral or even neurophysiological generality it must be separated from its thus far purely human implications. The present experiment represents one attempt to extend the concept of loudness to lower animals.

To produce a psychophysical scale for loudness from the present data, one might simply plot the reciprocal of latency as a function of intensity. A new unit emerges, which is a contraction of the terms loudness and latency. Figure 8 illustrates the function, loudness level in louts versus intensity in db, at 1000 cps for each subject from this experiment. The ordinal scale is arithmetic, but it is clear that the data would not subscribe to the power function so familiar from human data. Latency reaches a minimum at moderately high stimulus intensities (100 db); the function becomes flat, and no mathematical transformation will change that portion of the function. The fact that latencies are not free to decrease beyond a certain value indicates that latency could

not be used as a measure of loudness at stimulus intensities in excess of 100 db.

In summary, data are presented on simple reaction time for the monkey as a function of the intensity and frequency of a pure tone. Reinforcement procedures were used to obtain stimulus control. Short latencies were ensured by withholding reinforcement for reaction times in excess of 1 sec. The characteristics of the latency-intensity functions closely resemble those obtained for man by Chocholle (1940) and more recently McGill (1963) and Greenbaum (1963), and for monkeys by Romba, Gates, and Martin (1963) and Stebbins and Miller (1964). In addition, the shape of the functions and the changes in variability with stimulus intensity are very similar to those obtained by neurophysiological recording of the latency of discharge of the first spike from single units in the auditory system of cats (Hind, Goldberg, Greenwood, and Rose, 1963), and the latency of intracellularly recorded excitatory post-synaptic potentials from the somatosensory system of cats by Towe and Morse (1962). In any attempt to correlate conditioned behavior in the intact organism with electrical activity from the nervous system obtained in an electrophysiological preparation, there is always the risk of oversimplification. Nevertheless careful examination of all these data indicate preservation of the functional relation between intensity of a stimulus and latency of a response from the level of the single cell to the entire organism (peripheral stimulus to motor response).
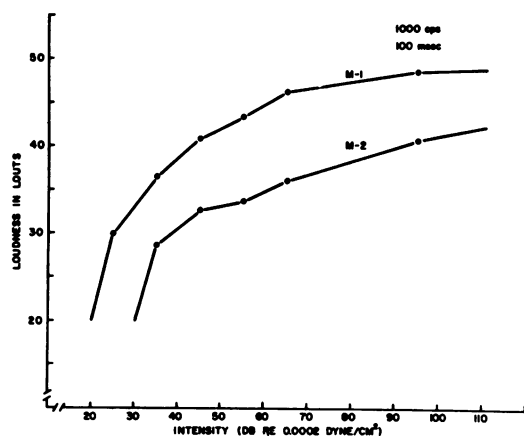

Fig. 8. Loudness in louts as a function of sound intensity for both subjects for a tone of 1000 cps and 100 msec in duration. One lout = $1/L \times 10,000$ where L is the latency of response in msec.

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