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Auditory reaction time as a function of stimulus intensity, frequency, and rise time

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The effects of signal intensity, frequency, and rise time on auditory reaction time (RT) were investigated in this study. Equal-loudness data were first obtained for 100-, 1,000-, and 10,000-Hz tones at intensity levels of 20, 40, 60, and 80 phons. These tones were presented subsequently as RT signals with variable rise times. The main effects indicated that (1) RT increased systematically with signal rise time, (2) RT was inversely related to signal intensity, and (3) equally loud stimuli did not produce equivalent RTs at different signal frequencies. In view of our failure to obtain equal-RT functions across signal frequencies, it was proposed that the detection of a stimulus and the judgment of its loudness require different perceptual processes.

Reports of the effect of stimulus intensity on auditory reaction time (RT) appear within the early literature (e.g., Chocholle, 1940; Woodworth & Schlosberg, 1954) and have been verified subsequently by many investigators in a variety of experimental conditions. It is a well-known fact that RT is an inverse function of stimulus intensity; the more intense the stimulus, the faster the response. Stimulus intensity, however, is only one of several important variables that can influence the time required for an observer to detect the onset of a sinusoidal stimulus. For example, stimulus frequency, as well as signal rise time (the rate at which a tone reaches its maximum amplitude), are also variables worthy of investigation. Yet, very few studies have been designed to determine the effects of either rise time or stimulus frequency on auditory RT.

It appears that Chocholle's (1940) classic research has remained as the definitive study on the relation between auditory RT and stimulus intensity and frequency. In his study, three trained subjects made equal-loudness matches between pure tones over a wide range of intensity levels for frequencies ranging from 20 to 10,000 Hz. Upon presentation of the tones which were matched for equal loudness, Chocholle found that (1) RT varied systematically with signal intensity and (2) equally loud tones produced equal RTs regardless of stimulus frequency. Although the effect of signal intensity has been replicated in numerous subsequent investigations, there remains a dearth of literature concerning the relation between RT and signal frequencies of equal loudness.

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The effect of rise time on auditory RT has also been studied by relatively few investigators. In this vein, Grier (1966) combined factorially six levels of signal intensity (20, 30, 40, 50, 60, and 70 dB, SPL) with six levels of signal rise time (.5, 10, 25, 50, 100, and 250 msec) in order to determine their effects on auditory RT to a 1,000-Hz tone. Both signal intensity and rise time as well as their interaction were found to be significant factors in determining the latencies to auditory signals. Grier concluded that as rise time increased, RT increased more than could be accounted for by a simple delay in the time required for the signals to reach their peak amplitude. He also suggested that the auditory system may be less efficient when required to integrate slowly rising signal energy. Moreover, Grier reported an intensity/rise time interaction in which a large intensity effect occurred when the rise times were very long, while RT was much quicker and the stimulus-intensity effects smaller when short rise times were employed. In contrast to Grier's findings, Warm and Foulke (1970) reported fewer fluctuations in RT to a 1,000-Hz tone as a function of its rise time.

Based upon the results of the previous studies, the effects of signal rise time on auditory RT remain open to investigation. Furthermore, a study of the interactions among signal intensity, frequency, and rise time seems warranted in view of the paucity of available evidence. Accordingly, in our present study we examined the effects on RT of sinusoidal stimuli which varied in intensity, frequency, and rise time. Specifically, tones which differed in frequency were first judged to be equally loud and then were presented as RT signals, having different intensities at varying rise times.

METHOD

Subjects

The subjects were two male graduate students, 25 and 26 years of age. Both possessed normal hearing thresholds

(20 microN/m² at 1,000 Hz) and were familiarized with the equal-loudness matching procedures prior to data collection. The subjects were also thoroughly practiced in the RT procedures, such that asymptotic levels of performance were maintained throughout experimentation.

Apparatus

During the loudness-matching sessions, the subjects sat in a sound-attenuating chamber. Separate audio oscillators generated alternating bursts of the standard and comparison tones. An electronic switch gated each tone for 2.5 sec with a rise and decay time of 10 msec. Two adjustable attenuators under the experimenter's control were located outside the chamber. All communications between the subject and experimenter were conducted easily by means of an intercom system. The tones were presented monaurally through a pair of headphones calibrated in a NBS-9A coupler. The voltage across each earphone was calibrated and monitored carefully throughout each session. Specifically, the subject's task was to match subjectively alternating bursts of a 1,000-Hz tone (left ear) at a standard intensity with a comparison tone (right ear) at a variable intensity. The experimenter adjusted the attenuation of the comparison tone based upon the subject's verbal instructions (i.e., "up" or "down").

All RT sessions were also conducted in the sound-attenuating chamber. The response signals, generated by an audio oscillator, were gated through a Grason-Stadler Model 1287B electronic switch, and then adjusted for intensity by means of a decade attenuator. A weak-intensity white light with a duration of 1 sec served as the ready signal, followed by a 1-sec foreperiod interval. The response signals were presented binaurally through the same set of calibrated headphones as used in the equal-loudness matching. Termination of the response signal was contingent upon the subject's pressing a response button and was followed by a 1-sec intertrial interval. Response signal intensities, frequencies, and rise times were adjusted manually prior to each RT session. The timing of events was conducted by means of a programmed sequence on plastic tapes read through a system of solid state logic. RT was measured in milliseconds by a digital counter.

Procedure

Following the determination of each subject's absolute threshold for a 1,000-Hz tone, equal-loudness matches were conducted over four daily experimental sessions, one for each of the 80-, 60-, 40-, and 20-phon intensity levels. During each session, matches for the stimulus frequency of 100 Hz were followed by matches for the 10,000-Hz tone. The subjects matched the alternating standard (1,000 Hz) and comparison tones by instructing the experimenter to increase or decrease the intensity of the latter in steps of 1 dB. Each subject made 20 matches at each combination of intensity and frequency, 10 increasing adjustments (comparison to standard intensity) and 10 decreasing adjustments. The intensity difference between the standard and comparison tones was set arbitrarily by the experimenter prior to each loudness match.

Subsequently, RTs were obtained in each of the intensity-frequency combinations measured during the equal-loudness matching. In addition, the rise times of the response signals were varied in order to generate a 48-cell factorial design: 4 (20, 40, 60, and 80 phons) by 4 (1-, 10-, 100-, and 250-msec rise times) by 3 (100, 1,000, and 10,000 Hz). Although the intensities (phons) of the response signals varied according to each subject's equal-loudness matches, the frequencies and rise times remained as specified above.

A Donders Type C method of stimulus presentation was employed such that the subject responded as quickly as possible upon detection of the RT signal (a "go" trial) and withheld a response when no signal appeared (a "catch" trial). The RT sessions were divided into blocks of trials (32 RT trials/block), and each block could be initiated by the subject. In the 32 trials/block, the presentation order of the 24 "go" trials and 8 "catch" trials was randomized to prevent the subject from initiating a response before the RT signal was presented. Two blocks, or a total of 48 RT measures, were obtained from each subject in each of the phon frequency/rise time stimulus conditions. Order of the frequencies and rise times was randomized within each of the four phon conditions. A short practice period of approximately 10 trials was provided prior to data collection whenever a change was made in any one of the stimulus parameters. As noted previously, the two subjects employed for this research had at least a year of experience serving in comparable, Donders Type C RT paradigms.

Table 1
Mean Equal-Loudness Judgments in Decibels, SPL

Stimulus Frequency (Hz)	Stimulus Intensity (Phons)			
	20	40	60	80
100	80	88	94	100
1,000	20	40	60	80
10,000	56	71	81	92

RESULTS

The results of the equal-loudness matches are shown in Table 1. Each entry represents the mean value (in decibels, SPL) of 20 measures/subject. It is evident that considerably greater levels of signal energy were required for the low- and high-frequency tones in each of the equal-loudness matches. Furthermore, the data are very similar to those reported by Molino (1973) and by Schneider, Wright, Edelheit, Hock, and Humphrey (1972), who employed equal-loudness procedures like those in the present study (2,500 Hz was the upper frequency limit of Schneider et al.). The present data also correspond to the equal-loudness contours reported by Fletcher and Munson (1933) and Kingsbury (1927).

Figure 1 depicts mean RT as a function of signal

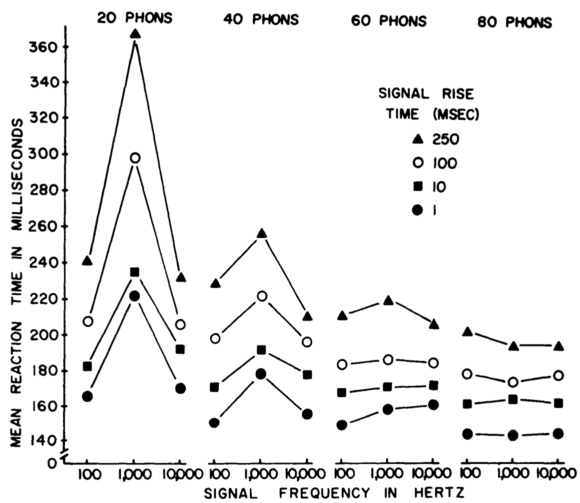

Figure 1. Mean reaction time as a function of stimulus frequency and rise time at four levels of loudness.

intensity (phons), frequency (hertz), and rise time (milliseconds). It can be seen that RT was inversely related to signal intensity, as found in numerous other investigations. Furthermore, RT maintained a systematic relation to the rise time of the auditory signals; the longer the rise time, the slower the response. It is also apparent, although contrary to previous literature, that equally loud tones did not produce equivalent RTs across the signal frequencies employed in our study. This is particularly evident at the 20- and 40-phon intensity levels, as shown by the consistently longer RTs to the 1,000-Hz tones. However, the effects of signal frequency appear to become less pronounced at the 60- and 80-phon intensity levels, as compared to lower levels of intensity, which implies an interaction between stimulus intensity and frequency.

Supporting these conclusions were the results of a 4 (phons) by 4 (rise times) by 3 (hertz) repeated-measures analysis of variance which indicated the following significant effects: stimulus intensity [$F(3,3) = 31.41$, $p < .01$], rise time [$F(3,3) = 75.11$, $p < .001$], frequency [$F(2,2) = 25.52$, $p < .01$], and Intensity by Frequency [$F(6,6) = 43.76$, $p < .01$]. The stimulus factors of intensity, rise time, frequency, and the interaction of Intensity by Frequency accounted for 27%, 39%, 10%, and 14%, respectively, of the total variance in the RT measures. The remaining 10% of the variance was distributed among higher order interactions which were statistically small and not readily interpretable.

DISCUSSION

An important result of our study which deserves elaboration was the uniform effect of rise time across the stimulus intensities and frequencies. While it is obvious that RT became progressively longer as signal rise time was increased (see also Grier, 1966; Warm & Foulke, 1970), the RT/rise time functions, as shown in Figure 1, cannot be interpreted solely in terms of the actual delay required for signals to reach peak-amplitude levels. In this vein, we think that it is essential to differentiate physical rise time (i.e., the setting on an electronic switch) from "neural" rise time (the point in time when neural processing of a signal is initiated). For example, in several conditions our RT data indicate that both signal detection and response initiation (the necessary components in the simple RT response) were completed before a signal reached its maximum amplitude. In other words, RT was sometimes quicker than the rise time setting on a "modern" electronic switch. This finding is contrary to Grier (1966), who reported that RT always occurred after the signal rise time had peaked. Apparently our two subjects were so highly experienced that the onset of a RT signal initiated a slight change in the neural impulse flow (see subsequent discussion) that was sampled immediately and detected prior to the time when the signal reached its peak amplitude. This implies that the rise time of a signal determines the rate of change of neural activity in the auditory sensory system which is necessary to trigger the detection process and, consequently, the RT response.

An unexpected finding in our results was the substantial Frequency by Intensity interaction in the RT measures. Specifically, consistently longer RTs were obtained in response to the 1,000-Hz tone at low levels of intensity, while the effect of signal frequency was much less pronounced at the higher intensity levels. This differs from Chocholle's (1940) conclusions, and demonstrates clearly that equal loudness did not produce equal RT in our research. It is interesting to note that Chocholle reported that he was unable to gate adequately the auditory signals presented to his subjects by means of a relay system, thus resulting in high-amplitude click transients associated with the onset of the RT signals (p. 73). However, in the present study click transients were not present because all of the RT signals were gated through an electronic switch. In view of this difference in instrumentation, it is feasible that the problematic relay clicks in Chocholle's study might have equated the intensity and frequency properties of the signals, resulting in spuriously equivalent RT measures. Our click-free data, on the other hand, indicate that response latencies differed to equally loud tones varying in frequency, particularly at the lower levels of intensity.

If we assume, based on our data, that equal loudness does not yield equivalent RT, one can speculate that the detection of a signal and a judgment of its loudness may require different perceptual processes. Several investigators have provided evidence to indicate that the sensation of loudness develops as stimulus duration increases. For example, von Békésy (1967) discovered that the loudness of a tone develops throughout a period of 180 msec. Others have determined that the gradual growth of loudness may take as long as 600 msec (Ekman, Berglund, & Berglund, 1966), or even 1 sec (Littler, 1965); these differences are probably based upon differences in methodology, however slight. We propose that the gradual development of loudness in a signal results from the temporal summation of acoustic energy, as reflected by the total number of neural impulses that are recruited, a view which receives support from the work reported by Troland (1929), Wever (1949), and Zwislocki (1960, 1969). In other words, two sinusoidal stimuli are judged to be equally loud when the total number of neural impulses is the same for both auditory sensations over a sufficient period of time (see also Ross, 1968). However, most of the RT responses generated by our two subjects were completed before signal energy reached its peak amplitude; therefore, loudness could not have developed completely before the signals were detected. In simple RT tasks a highly practiced participant responds to the onset of a signal immediately upon detecting a change (e.g., an increase) in the level of spontaneous neural activity in the auditory system. In relation to our experiment, this means that the faster the rate of change in the neural impulse flow, the sooner the "detector" is satisfied that a change (stimulus) has occurred. Any further recognition or discrimination (i.e., a judgment of loudness) of the signal requires an analysis of the neural impulse flow at a point later in time.

In summary, our data indicate that the physical rise time of a RT signal is different from its "neural" rise time. Furthermore, the finding that equally loud stimuli did not yield equivalent RTs at different signal frequencies deserves future investigation.

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