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THE PERCEPTIBILITY OF THE FREQUENCY DROP CAUSED BY THE DOPPLER EFFECT FOR SIMULATED SOUND SOURCE MOTION IN THE MEDIAN PLANE

U. JORASZ* and G.J. DOOLEY**

* Institute of Acoustics
Adam Mickiewicz University
(60-769 Poznań, Matejki 48/49)

** Dept. of Otolaryngology
University of Melbourne
(Parkville, Victoria 3052, Australia)

Simulations of constant velocity (10 m/s and 20 m/s), pure-tone (1 kHz and 2 kHz) sound source moving in the median plane relative to a stationary observer were set up. The simulations were either simulations of approaching sources which stopped at the point of closest passing or of retreating source which began at the point of closest passing. The durations required for the detection of the Doppler-induced frequency drop were determined in a two-alternative, forced-choice task. One interval contained the Doppler-induced frequency drop and in the other the frequency was kept constant. Two types of signals were used: One simulated frequency and level changes which would occur for a moving source. The other simulated only the frequency changes, with the level steady at 65 dB SPL. Threshold durations were determined for simulations of both approaching and retreating source. The pattern of results was similar for all three subjects. In general, the faster the source the smaller the duration needed to detect the frequency drop. Source frequency had little effect on the duration thresholds indicating that a constant percentage frequency change may be required.

1. Introduction

A sound source moving with constant velocity in the median plane relative to a stationary observer results in a change in intensity and frequency of the sound wave that reaches that observer. The extent of these changes is determined by the emission characteristics of the sound source, its velocity and the distance of closest passing with respect to the observer. The frequency drop induced by the Doppler effect is most marked in the region where the source passes closest to the observer irrespective of its velocity or emmission characteristics. This region was called the "passage zone" by Ryffert *et al.* [7]. It is possible to derive equations for the level and frequency of the sound field at the observer at any time t. The most convenient mathematical representation is obtained by letting the time $t=0$ represent the time at the point of closest passing of the source relative to the observer; this means that negative time represents an approaching object and positive time a retreating object. For example $t=-5$ s is the time 5 seconds before the object reaches its point of closest passing and $t=5$ s is the time 5 seconds after the object has passed through its point of closest passing. The sound level generated at the observer by such a source is given by the relationship:

$$L(t)=I+10\log\left\{\frac{d^2}{d^2+v^2t^2}\left(1-\frac{4v^2t}{c\cdot(d^2+v^2t^2)^{1/2}}\right)\right\}, \tag{1.1}$$

where $L(t)$ is the level in dB at the observer at time t; I is the level at the moment when the source passes closest to the observer, v is velocity of the source; d is the distance from the observer at the point of closest passing; and c is the propagation velocity of the tonal signal in the medium [4]. This relationship is valid under the assumption that $v \ll c$.

A simulation of sound source movement based on this equation assumes a point observer who remains stationary with respect to the plane of movement of the source; consequently, alterations of the sound field produced by the head and by the pinnae are not taken into account. Thus, sound fields of this type are spatially ambiguous; when presented diotically they could represent approach followed by retreat of the sound source either from in front of, or from behind and either over the head of, or underneath the observer. In this experiment symmetry of the head is also assumed so that any sound in the median plane is assumed to result in identical signals reaching both ears.

Because the source velocity component in the direction of the observer changes during the sound motion there is a corresponding frequency change at the observation point due to the Doppler effect. This change in frequency can be represented by the function:

$$f(t)=f_0\left[1-\frac{v^2t}{c\cdot(d^2+v^2t^2)^{1/2}}\right], \tag{1.2}$$

where $f(t)$ is the frequency at the observer at any time t and f_0 is the frequency of the tone emitted by the moving source. The parameters c, d and v are as described above.

The first purpose of this experiment was to determine the duration necessary for detection of the frequency drop induced by constant-velocity sound source motion in the median plane. Sound sources of different velocities passing through different points with respect to a stationary observer were used. Another aim was to determine whether the presence of the intensity change induced by these motions in any way 'masked' the detection of the frequency drop in the manner described by Ryffert *et al.* [7] and called 'automasking'. In order to test this some of the simulations that we used were accurate simulations of both frequency and level changes and others simulated the frequency change alone with the level kept constant.

The results obtained correspond only approximately to the real conditions of a specific physical effect: the Doppler effect. They rather correspond to an explanation of some general phenomena in a simultaneous perception of frequency and intensity changes in simple sounds.

2. Stimuli

All stimuli were sinusoids derived from a Farnell DSG 1 signal generator controlled by a Texas Instruments 990/4 computer. The frequency was digitally controlled and was changed every 10 ms.

The desired amplitude envelope was achieved by multiplying the output from the signal generator by a voltage produced by a digital-to-analogue converter (DAC). The level was changed every 10 ms, the changes occurring midway between frequency changes. The DAC output was low-pass filtered through both halves of a Kemo VBF 8/03 filter (96 dB per octave slope, cut-off frequency 400 Hz); this resulted in a smooth sounding overall change.

Each signal had an envelope with 10-ms linear rise-fall times generated by updating the DAC output 10 times per ms. The signals were band-pass filtered through a Kemo VBF 8/03 filter (48 dB per octave slope, bandpass with cut-off frequencies 0.5 f and 1.5 f) to smooth frequency and level changes and to attenuate unwanted distortion products. The signal was then fed through a Hatfield 2125 manual attenuator.

3. Procedure

Thresholds were determined using an adaptive two-alternative forced-choice (2AFC) procedure that estimates the 70.7% correct point on the psychometric function [3]. In this experiment the values of the distance of closest approach (*d*) and the velocity (*v*) were chosen so that, for long duration signals, the frequency drop was clearly audible and the steepest part of the frequency drop covered a time period of between one and two seconds. To this end, velocities of 10 m/s and 20 m/s were chosen along with a distance of closest passing of 10 m. The experiment was run with two different emission frequencies (1 kHz and 2 kHz). Figures 1 and 2 show the level and frequency profiles, respectively.

Two conditions were run:

1) *Changing Level Condition* — in this condition one interval always contained a simulation of the frequency and intensity change and the other interval had the same intensity change but with the frequency fixed at the median frequency of the first interval.

2) *Fixed Level Condition* — in this condition the level was always set at 65 dB SPL in both intervals. In one interval the frequency drop associated with the simulation was present and in the other interval the frequency was fixed at the median frequency of the first interval.

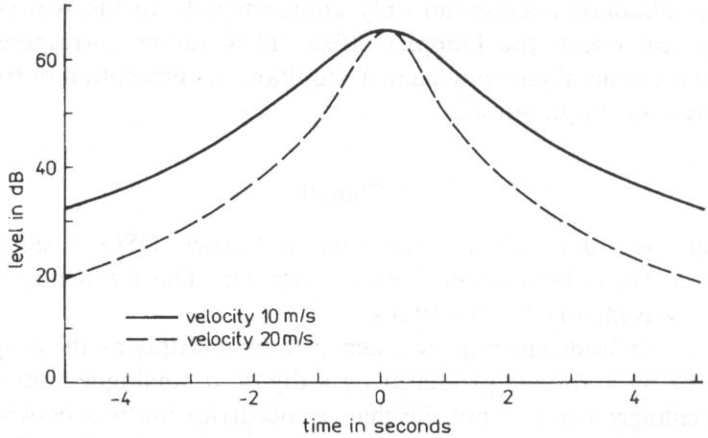

Fig. 1. The level change profiles for two different values of source velocity. The duration of source motion is 10 s.

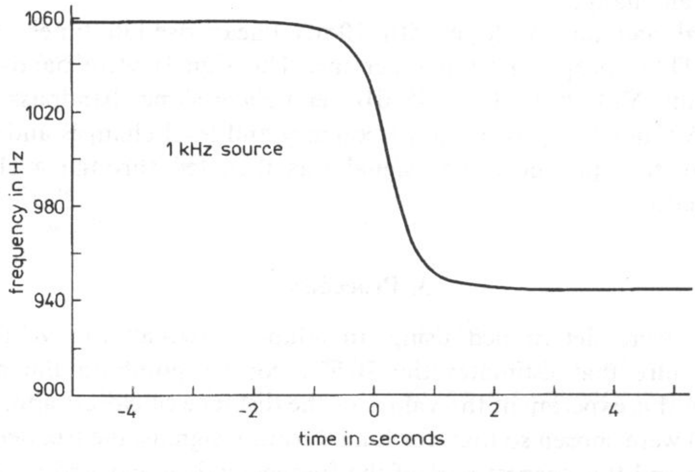

Fig. 2. The frequency change profile for source frequency 1 kHz.

Subjects were instructed to indicate which of the two signals contained the frequency drop by pressing the appropriate button on a response box in front of them. The stimuli were presented to the subject diotically over a Sennheiser HD414 headset and feedback was provided by means of lights. A run always started with a duration fixed such that the frequency drop was clearly audible (This was usually about 1 second). The duration was decreased after two consecutive correct responses and increased after one incorrect response. For both approaching and retreating stimuli the point of closest passing was the fixed point for all intervals. This means that for approaching stimuli the signals were made shorter by subtracting from the beginning of the signal and for retreating stimuli they were made shorter by subtracting from the end of the stimuli. All duration changes were accurate to the nearest millisecond.

The transition from increasing to decreasing duraton or vice-versa defines a turnaround. For each threshold determination testing continued until 12 turnarounds had been obtained, and threshold was taken as the geometric mean of the last 8 turnarounds. The step size was 50 ms for the first four turnarounds and was reduced to 10 ms thereafter. Each threshold reported is the geometric mean of five runs. The order of presentation of runs was randomised across all sessions.

4. Subjects

Three subjects were used: all received at least four hours of practice on frequency discrimination tasks before data collection began. Two subjects were the authors; the other was a male (aged 27 years) and was paid for his participation. None of the subjects had any known hearing defects. All had absolute thresholds within 10 dB of the 1969 ISO standard at all audiometric frequencies.

5. Results and discussion

Mean threshold values and standard deviations for individual subjects in all conditions are shown in Table 1. We conducted an ANOVA, which showed the following:

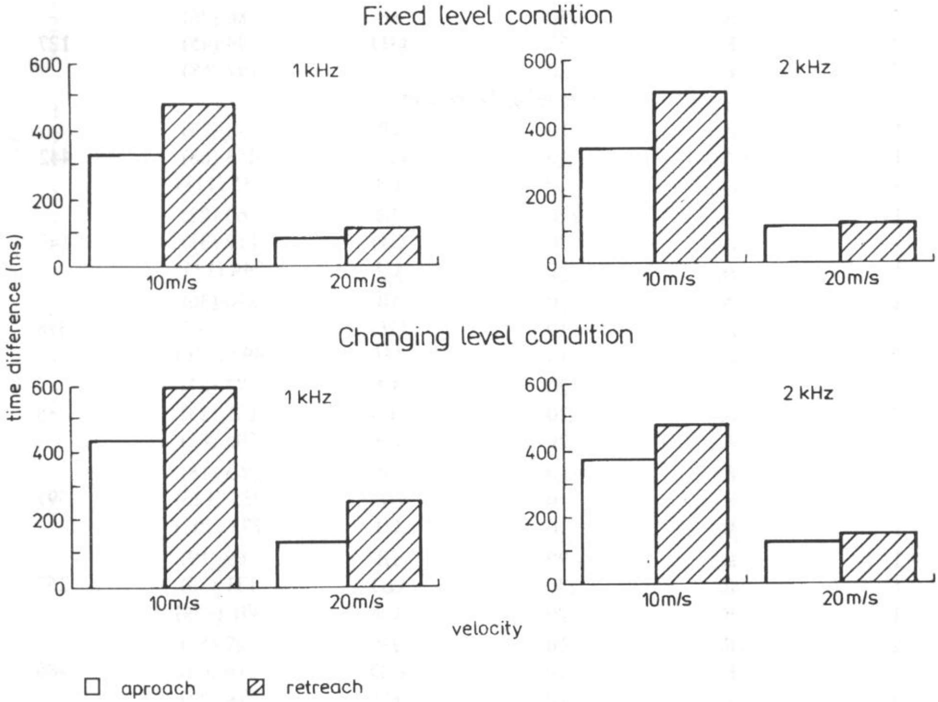

Fig. 3. The time thresholds collapsed across subjects in all experimental conditions

Table 1. Individual mean duration thresholds and standard deviations for detection of the frequency drop in moving source simulations.

FREQUENCY (1/2 kHz)	APPROACH RETREAT	VELOCITY (10/20 m/s)	SUBJECT	THRESHOLD & S.D. (ms)	MEAN (ms)
		Fixed Level Condition			
1	A	10	JB	258 (51)	
1	A	10	GD	387 (42)	342
1	A	10	UJ	381 (87)	
1	A	20	JB	58 (17)	
1	A	20	GD	106 (15)	93
1	A	20	UJ	115 (35)	
2	A	10	JB	331 (59)	
2	A	10	GD	315 (91)	350
2	A	10	UJ	405 (114)	
2	A	20	JB	94 (33)	
2	A	20	GD	95 (25)	118
2	A	20	UJ	164 (50)	
1	R	10	JB	287 (58)	
1	R	10	GD	606 (88)	486
1	R	10	UJ	564 (134)	
1	R	20	JB	88 (45)	
1	R	20	GD	120 (35)	118
1	R	20	UJ	147 (62)	
2	R	10	JB	314 (90)	
2	R	10	GD	378 (83)	510
2	R	10	UJ	838 (123)	
2	R	20	JB	86 (26)	
2	R	20	GD	99 (45)	127
2	R	20	UJ	197 (68)	
		Changing Level Condition			
1	A	10	JB	288 (73)	
1	A	10	GD	453 (68)	442
1	A	10	UJ	585 (111)	
1	A	20	JB	60 (22)	
1	A	20	GD	119 (31)	141
1	A	20	UJ	244 (124)	
2	A	10	JB	290 (36)	
2	A	10	GD	353 (31)	378
2	A	10	UJ	492 (136)	
2	A	20	JB	77 (27)	
2	A	20	GD	131 (23)	138
2	A	20	UJ	205 (82)	
1	R	10	JB	263 (18)	
1	R	10	GD	755 (125)	597
1	R	10	UJ	773 (201)	
1	R	20	JB	69 (19)	
1	R	20	GD	131 (33)	267
1	R	20	UJ	601 (254)	
2	R	10	JB	229 (53)	
2	R	10	GD	316 (66)	486
2	R	10	UJ	914 (55)	
2	R	20	JB	78 (23)	
2	R	20	GD	111 (27)	162
2	R	20	UJ	298 (198)	

Table 2. Individual mean thresholds expressed as percentage frequency drop in Hz for detection of the frequency changes in moving source simulations.

FREQUENCY (1/2 kHz)	APPROACH RETREAT	VELOCITY (10/20 m/s)	SUBJECT	%FREQ. DROP	MEAN (Hz)
		Fixed Level Condition			
1	A	10	JB	0.73	
1	A	10	GD	1.05	0.94
1	A	10	UJ	1.04	
1	A	20	JB	0.67	
1	A	20	GD	1.21	1.06
1	A	20	UJ	1.31	
2	A	10	JB	0.92	
2	A	10	GD	0.89	0.97
2	A	10	UJ	1.09	
2	A	20	JB	1.08	
2	A	20	GD	1.09	1.33
2	A	20	UJ	1.82	
1	R	10	JB	0.80	
1	R	10	GD	1.51	1.25
1	R	10	UJ	1.43	
1	R	20	JB	1.01	
1	R	20	GD	1.36	1.34
1	R	20	UJ	1.64	
2	R	10	JB	0.88	
2	R	10	GD	1.03	1.26
2	R	10	UJ	1.88	
2	R	20	JB	0.99	
2	R	20	GD	1.14	1.43
2	R	20	UJ	2.14	
		Changing Level Condition			
1	A	10	JB	0.81	
1	A	10	GD	1.20	1.16
1	A	10	UJ	1.47	
1	A	20	JB	0.69	
1	A	20	GD	1.35	1.53
1	A	20	UJ	2.56	
2	A	10	JB	0.81	
2	A	10	GD	0.97	1.02
2	A	10	UJ	1.29	
2	A	20	JB	0.89	
2	A	20	GD	1.48	1.53
2	A	20	UJ	2.21	
1	R	10	JB	0.74	
1	R	10	GD	1.76	1.43
1	R	10	UJ	1.78	
1	R	20	JB	0.80	
1	R	20	GD	1.48	2.25
1	R	20	UJ	4.48	
2	R	10	JB	0.65	
2	R	10	GD	0.88	1.16
2	R	10	UJ	1.96	
2	R	20	JB	0.90	
2	R	20	GD	1.27	1.72
2	R	20	UJ	2.99	

1) Source frequency has no significant effect on the thresholds. This indicates that subjects require a fixed amount of frequency change as a proportion of center frequency for correct detection. We can test this by looking at the thresholds for the different velocities and seeing whether they are consistent with a fixed change being required. Table 2 shows the mean thresholds expressed as percentage frequency drop for detection of the frequency changes.

2) The duration data collapsed across subjects are shown in Fig. 3. From this we see that thresholds for approach are lower than those for retreat. This is consistent with Dooley [1] who found that for simulations of median plane motion outside of the passage zone (where intensity change provides the cue for detection) subjects required a longer presentation to discriminate a retreating source from a stationary source than they did for discriminating an approaching source from a stationary source.

3) The thresholds for the fixed level condition — which are comparable with the absolute frequency difference limen [5] — are generally lower than those for the changing level condition. This implies that the presence of the additional intensity change makes the detection of the frequency drop more difficult. It is unclear whether this is due merely to increasing the difficulty of the task by having the extra change present, in other words a sort of confusion effect, or whether it is actually due to some real acoustic masking effect as reported by Ryffer *et al.* [7] and Jorasz [2].

4) Zwicker [8, 6] attempted to account for the size of the frequency and intensity discrimination limens in terms of changes in the excitation pattern evoked by the stimulus. According to Zwicker's model, a change in frequency or intensity will be detected whenever the excitation on the steeply sloping, low frequency side of the excitation pattern changes by 1 dB or more. This model would predict that increasing the level of the tone would facilitate the detection of frequency drops compared with decreasing the level of a tone during a presentation. Our data are consistent with this model as approaching objects required a shorter duration for detection than retreating objects and approaching sources are associated with rising level and falling frequency and retreating sources are associated with falling level and falling frequency.

5) We should remember that — as it follows from the nature of this particular signal — the duration thresholds are strictly connected with the frequency discrimination thresholds [2] and intensity discrimination thresholds.

6. Conclusions

1. A fixed amount of frequency change as a proportion of center frequency is required for correct detection of the frequency changes in moving source. This is comparable with the absolute frequency difference limen if there is no level change (fixed level condition).

2. The presence of the intensity change elevates the thresholds. It may be like the masking effect inside the same sound sensation ('automasking').

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