Canadian Acoustics / Acoustique canadienne, 1989, 17 (4): 3-11

QUANTIFYING THE PERCEIVED URGENCY OF AUDITORY WARNINGS

Elizabeth Hellier & Judy Edworthy

Department of Psychology
Polytechnic South West
Plymouth, England

ABSTRACT

Advanced auditory warning design based on Patterson's guidelines (1982) allows a degree of matching between a warning sound itself and the subjective response it elicits. One important parameter along which a warning and the subjective response can be matched is that of perceived urgency. In order to do this matching successfully, it is important to know the nature and the power of the effects of many spectral and temporal parameters. Three experiments are reported in which the effects of number of repetitions, warning speed and length upon perceived urgency were investigated. Results show that increases in all three parameters individually increased the perceived urgency of the stimulus. A fourth experiment tested a set of stimuli which varied in both number of repetitions and speed, whilst the length was held constant. This showed that large differences in the perceived urgency of a warning can be achieved over a fixed period of time. Steven's Power Law (1957) was applied to the data, enabling the power of the relationship between the objective value of the stimuli (number of repetitions, speed or length) and the subjective values of the warnings (the perceived urgency) to be quantified.

SOMMAIRE

La conception d'avertisseurs sonores fondée sur les propositions de Patterson, permet d'établir une certaine relation entre le son avertisseur lui-même et la réponse subjective qu'il engendre. Une relation entre le son avertisseur et la réponse subjective qu'il provoque peut être établie à partir d'un paramètre important à savoir la perception de l'urgence. Afin d'établir cette relation, il est important de connaître la nature et la force des effets de plusieurs paramètres spectraux et temporels. Trois expériences portant sur l'effet du nombre de répétitions, de la vitesse et de la longueur du signal sur la perception de l'urgence sont rapportées. Les résultats démontrent qu'un accoissement sur l'un ou l'autre des paramètres étudiés se traduit par un accroissement de l'urgence véhiculée par le signal. Une quatrième expérience avait pour but de tester un ensemble de stimuli qui variaient à la fois en fonction du nombre de répétitions et de la vitesse, alors que la durée du signal était maintenue constante. Les résultats démontrent que des différences majeures dans la perception de l'urgence d'un avertisseur sonore peuvent être mesurées même si la durée de l'avertisseur est maintenue constante. La loi de puissance suggérée par Stevens a été appliquée aux données dans le but de quantifier la relation de puissance entre les paramètres physiques des stimuli (nombre de répétitions, vitesse et durée) et les valeurs subjectives (perception de l'urgence).

Auditory warnings have found their way into many working environments and have obvious advantages over visual warnings. However, there are many problems associated with the use of auditory warnings; many are too loud, aversive and insistent and often too many warnings are found in one working environment. It is possible, however, to predict the appropriate level for many warnings to ensure that they are neither too loud nor too quiet. It is also possible to design warnings that do not startle and which are non-aversive (Patterson, 1982). Warnings of this sort inform, rather than alarm. Sets of warnings based on Patterson's guidelines for ergonomic auditory warning construction have now been made for helicopters (Lower, Wheeler, Patterson, Edworthy, Shailer, Milroy, Rood & Chillery, 1986), fixed-wing aircraft and hospitals (Patterson, Edworthy, Shailer, Lower, & Wheeler, 1986).

The method of construction of these advanced warnings is as follows: first, the appropriate level for the components of the warnings is predicted using theoretical notions based on the auditory filter (e.g. Patterson, 1976). When this is done, individual pulses of sound lasting from 100-300 ms in length are designed, one of which will form the basis of each warning required. These pulses then form the building-block of an auditory warning burst, in which the pulse is played several times, at different pitches, amplitudes and with different time intervals between the pulses. The burst typically lasts from one to two seconds, and is like an atonal melody with a rhythm. Several bursts are then assembled, together with silent intervals, to form a complete warning. The resulting warnings are non-aversive and allow people to communicate at the very time that communication is vital.

Another advantage of warnings created in this way is that a degree of matching can take place between the warning sound itself and the situation which it is signalling. This matching could take place along many subjective parameters, one of which is urgency. Auditory warnings are intended to alert the hearer; if it is possible to convey the degree of urgency with which the hearer should respond, or to convey the different priorities of urgency when many warnings go off together (which sometimes happens), then a large step forward in auditory warning design will have been made. The level of urgency can only be conveyed through the warning sound itself, so it is essential to establish these design principles at an early stage in work of this sort. At Polytechnic South West we are beginning to formulate these principles by carrying out a range of experiments on perceived urgency and other subjective parameters important in auditory warning design.

One of the cues contained in many of the complex sounds in our environment is an indication of urgency. We can even tell when a situation is increasing in its urgency by several cues such as increasing loudness, pitch, speed and so on. It is possible to make changes of this sort in warnings designed in the way described by Patterson (1982), as the type of warnings produced lend themselves to change in loudness, speed, pitch and other temporal and musical parameters which lead to changes in subjects' assessment of their urgency. This should enable some matching to take place between auditory warning and the situation for which it is designed.

The first part of our research program was to take many of the most important sound parameters used in auditory warning design (e.g. pitch, speed, pitch range, rhythm, number of repetitions, harmonic content and so on) and to establish the nature of the relationship between objective and subjective variables. We confirmed many intuitive opinions about the relationship between the sound parameters and perceived urgency. For example, we found that an increase in pitch increased the urgency of a stimulus. Such findings are demonstrated elsewhere (Edworthy, 1988; Edworthy, Loxley, Geelhoed & Dennis 1989; Edworthy, Loxley, Geelhoed & Dennis 1988). Many of our findings confirm received opinion, but some of our findings were counterintuitive as has been shown by earlier work (Halpern, Blake & Hillenbrand 1986).

We are now charting the relationship between objective change in the most important sound parameters and subjective change in urgency in more detail. The work reported here summarises four experiments relating three temporal variables to perceived urgency. These are three variables which are often naturally confounded; number of repetitions, speed and overall warning length. Our hypotheses, based on our earlier findings and our own intuitions, was that often-repeating, fast warnings (with a necessarily long length) will be perceived as more being urgent than slow, non-repeating warnings. We expected a gradation of urgency between these two extremes. Our experiments show this to be the case. In each experiment, a number of levels of the parameters under investigation were played to subjects, who were asked both to rank and to rate the urgency of the stimuli. This allowed us not only to confirm the predicted order of urgency, but to describe the power of the relationship between objective change and subjective change within the framework of Steven's Power Law (1957). Steven's Power Law takes the form

$$S = kO^{m}. \qquad (1)$$

S is the subjective value, O is the objective value, and k and m are the intercept and the slope of the line of best fit drawn when the logarithmic values of objective and subjective values are plotted as xy coordinates. It is the usual method of describing the objective/subjective relationship. In the case of perceived urgency, the slope of the line (m) indicates the ability of the parameter under investigation to produce changes in perceived urgency - the steeper the slope, the more effective the parameter should be. Deriving the power function will indicate more formally the degree of change in each of the parameters that is required to produce a predetermined change in perceived urgency. In addition, the power functions derived should enable us to make comparisons between parameters in order to establish which changes would be most effective in increasing the urgency of a warning. For example, merely lengthening a warning may make it more urgent, but it might be more effective to hold the length constant and communicate urgency through another parameter. For this reason, we imposed a 2.5 second limit on the stimuli.

In each experiment, a multiple comparisons procedure (Gulliksen & Tucker, 1959) was carried out whereby each stimulus was effectively compared with every other, producing paired-comparisons data without the usual fatigue problems. The consistency of subjects' responses is measured by a corrected form of Kendall's W (W') which is calculated by examination of the number of inconsistent responses given by each subject. An inconsistency occurs when a subject ranks Stimulus C as more urgent than Stimulus A, when they have previously ranked Stimulus A as being more urgent than B, and B as more urgent than C. W' has a maximum value of 1, which indicates completely consistent performance. Subjects were also asked to carry out a magnitude estimation task on the urgency of the stimuli previously ranked, from which the power functions (the relationship between objective and subjective change) were derived.

METHOD

Subjects.

Twelve subjects, two males and ten females, participated in this study. All of the subjects were undergraduate psychology students whose ages ranged from 18 to 27 years, none reported having a history of hearing problems. The study was a within-subject design run in two half-hourly sessions which were held two weeks apart. In the first session subjects completed Experiments One and Two, in the second session, Experiments Three and Four. The order in which the two experiments were presented in each session alternated between subjects.

Apparatus.

The experiment was conducted in a two-roomed sound-attenuated laboratory. In Laboratory One a Tandon microcomputer linked to a Cambridge Electronic Design 1401 interface and 1701 low-pass filters set at a cut off of 4 kHz was used to produce the experimental pulses and bursts. Laboratory Two housed a BBC B microcomputer which controlled the experimental design. The two computers were connected via a serial line.

Stimuli.

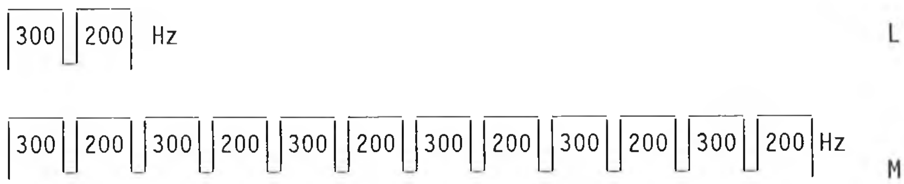
A single experimental pulse lasting 200 ms with a 20 ms onset and offset envelope was used in all four experiments as the basis of the experimental bursts. This pulse possessed a fundamental frequency of 300 Hz with 15 regular harmonics. Bursts lasted approximately 2 seconds in length and were played at the same loudness level. Seven bursts were generated for each experiment (Figure 1). They were constructed in the following way:

EXPERIMENT ONE (Number of repetitions): Two pulses, the first played at 300 Hz, the second at 200 Hz, represented one unit of repetition. The seven bursts contained 1, 2, 3, 3.5, 4, 5 and 6 such units. The stimuli were thus different total lengths.

EXPERIMENT TWO (Speed): The inter-pulse intervals of the seven stimuli were as follows: 950, 475, 237, 118, 59, 29 and 9 ms. All stimuli were approximately the same total length, with each pulse played at a fixed fundamental of 300 Hz.

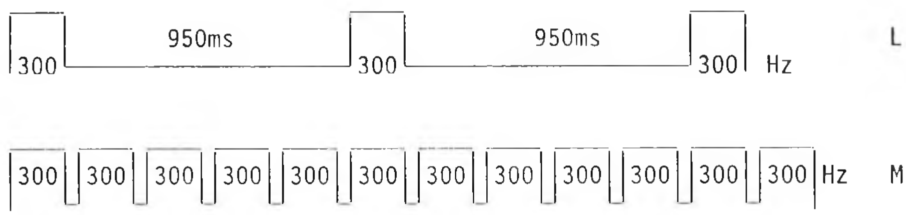
Figure 1: Least and most urgent experimental stimuli

Experiment 1



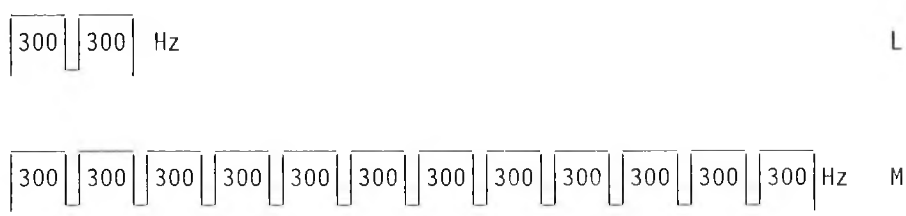
5ms gap between pulses for both L and M

Experiment 2



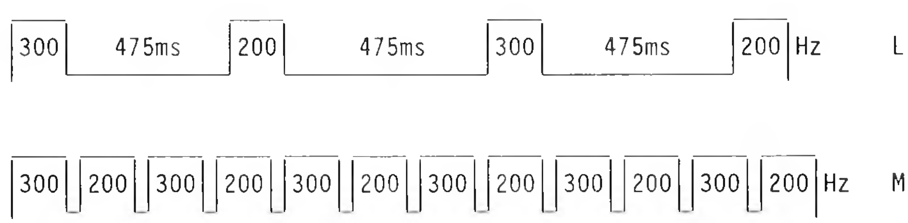
9ms gap between pulses for M

Experiment 3



5ms gap between pulses for both L & M

Experiment 4



9ms gap between pulses for M

L = Least urgent

M = Most urgent

EXPERIMENT THREE (Length): The number of pulses in the seven bursts was 2, 4, 6, 7, 8, 10 and 12, resulting in stimuli that became increasingly longer. All pulses were played at a fixed frequency of 300 Hz, and at a fixed speed.

EXPERIMENT FOUR (Number of repetitions and speed): The seven bursts varied along two parameters, speed and number of repetitions. The number of repetitions/speed combinations were as follows: 2/475 ms, 2.5/300, 3/237, 4/118, 4.5/59, 5/50 and 6/9. All stimuli were approximately the same length, and the basic unit of construction was the two-pulse 300 Hz/200 Hz unit described in Experiment One. The values of the repetitions and interpulse intervals used were not identical to those in Experiments One and Two in order to minimise the use of incomplete units of repetition.

Procedure.
Subjects were required both to rank and rate the bursts according to their urgency. The procedure was identical for all four experiments. In each trial they heard three bursts separated by a gap of approximately 1 second, presented at a comfortable, fixed level. They were required to select the most, and then the next most urgent of the three bursts. Seven trials were presented to each subject, during which each burst was compared with every other. The rankings stage of the experiment was over when subjects had completed all seven trials. In the ratings stage of the experiment, a magnitude estimation task was employed. Subjects were given the following instructions: "Imagine the most urgent sound possible. Let this represent 100 on an urgency rating scale. Let 0 represent the other end of the continuum (the most non-urgent sound that you can imagine). You are required to assign a number between 0 and 100 to each of the following sounds". They were asked to preserve ratios between urgencies in the numbers that they assigned to the stimuli.

RESULTS

Mean rankings (from 1, the most urgent to 7, the least urgent) of the stimuli for all twelve subjects are shown in Table 1. These were ranked in the predicted order - stimuli which contained more units of repetition, and/or were faster or were longer, were assigned higher rank orders, that is, two of the stimuli were not ranked exactly as predicted.

TABLE 1: Mean rankings of stimuli, Experiments One to Four.

EXPT. 1	REPETITION RATE (IN UNITS)							W'
6	5	4	3.5	3	2	1		
RANKING.	1	2	3	4	5	6	7	0.849
EXPT. 2	SPEED (INTER-PULSE INTERVAL)							
9	29	59	118	237	475	950		
RANKING.	1	2	3	4	5	6	7	0.843
EXPT. 3	LENGTH (M. SECS)							
2455	2045	1635	1430	1225	815	405		
RANKING.	1	2	3	4	5	6	7	0.890
EXPT. 4	REPETITION RATE (IN UNITS)							
6	5	4.5	4	3	2	1		
	SPEED (INTER-PULSE INTERVAL)							
9	50	59	118	237	300	475		
RANKING.	1	2	3	4	5	6	7	0.939

In all four Experiments Kendall's coefficient of concordance, W', was high and very significant. For Experiment One, F = 61.744, (df = 5,64, p <.001); for Experiment Two, F = 59.212, (df = 5,64, p <.001); for Experiment Three, F = 88.941, (df = 5,64, p <.001); and for Experiment Four, F = 167.927, (df = 5,64, p <.001). There was thus a high level of agreement between subjects as to the rank orderings of the stimuli. Each subject's ranking of each stimulus was correlated with their magnitude estimation (rating). The means of these correlations are shown in Table 2.

TABLE 2: Mean Spearman correlations between rankings and ratings.

EXPT. 1 Ranking v Rating	EXPT. 2 Ranking v Rating	EXPT. 3 Ranking v Rating	EXPT. 4 Ranking v Rating
0.841	0.855	0.790	0.940

The high correlations between subjects rankings and ratings of the stimuli indicated that the magnitude estimation task had produced a reliable measure of perceived urgency. As in the rankings task, stimuli that contained more units of repetition, and/or were faster or were longer, were perceived as being more urgent.

In the final stage of analysis the ratings data from Experiments 1-3 was fitted to Steven's Power Law (Figure 2). This requires a logarithmic transformation of the data. For Experiment 1 the objective values of the stimuli were calculated by taking the logarithm of the number of repetitions. In Experiment 2 the logarithm of 2500 (maximum stimulus length in milliseconds) divided by the inter-pulse intervals provided an objective measure of stimulus speed, giving the number of pulses possible in a unit of time. Here, smaller figures indicate a slower speed. In Experiment 3 the logarithm of stimulus length was calculated to represent the objective value. In all three experiments the mean subjective value plotted for each stimulus was the logarithm of its magnitude estimation. The data from Experiment 4 was omitted from this analysis because the stimuli varied along two objective parameters, repetition rate and speed.

Application of the Power Law quantified the relationship between the objective values of the stimuli (number of repetitions, speed, or length) and the subjective values (perceived urgency). Thus for Experiments One, Two and Three:

$$\text{Perceived urgency} = 22.13 \ \text{Number of repetitions}^{0.69} \quad (2)$$

$$\text{Perceived urgency} = 18.32 \ (2500/\text{pulse-to-pulse time})^{0.61} \quad (3)$$

$$\text{Perceived urgency} = 1.65 \ \text{length}^{0.49} \quad (4)$$

Repetition rate and speed are therefore the stimulus parameters that are most powerfully related to perceived urgency. A linear regression showed that the data from all three Experiments was well fitted by a straight line when plotted in log-log co-ordinates, as predicted by Steven's Power Law. The percentages of variance accounted for by the straight line were 99.8% (Expt. 1); 99.7% (Expt. 2) and 99.0% (Expt. 3).

DISCUSSION

Our experiments show that, individually, the number of repetitions, the speed and the length of an auditory warning each have individual effects on perceived urgency. Increasing the number of repetitions without increasing the speed (although necessarily increasing the length) of a warning increases its urgency; increasing the speed of a warning without increasing either the number of repetitions nor the length of a warning also increases its urgency; and simply increasing the length of a stimulus appears to increase its urgency. In practice, these three variables would tend to be confounded - indeed there is no way to separate number of repetitions from overall stimulus length if speed is held constant - but our experiments separate the parameters as far as possible. Moreover, the high values of W' for the ranking tasks suggests that subjects are very sure about the direction of

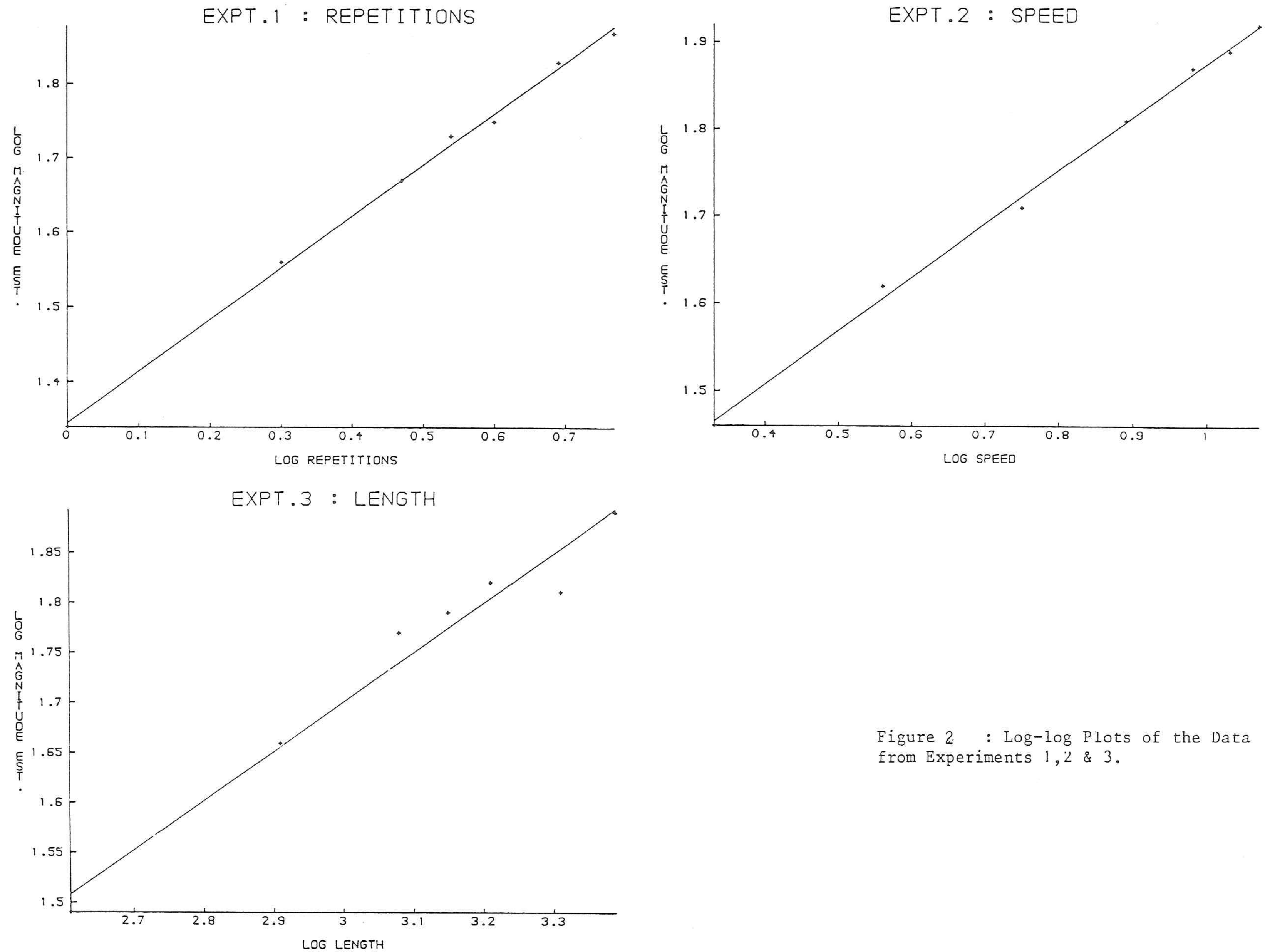


Figure 2 : Log-log Plots of the Data from Experiments 1,2 & 3.

change in perceived urgency for all three parameters. The power functions derived for the three parameters suggest that the number of repetitions and the speed of the warning are more powerful in producing changes in perceived urgency than is a simple length change. When all three parameters are combined (Experiment Four), subjects are even more sure about the direction of the change in perceived urgency as evidenced by the value of W' of .939, the highest for the experimental series.

The high correlations obtained between the rankings and the ratings suggests to us that magnitude estimation is an effective way of measuring perceived urgency. Other experimenters have supported the use of magnitude estimation techniques (for example, Haverland, 1979; Kowal, 1987).

These results suggest that the perceived urgency of an auditory warning is readily manipulated when the warnings are of the pulse-burst variety proposed by Patterson (1982), and the power functions begin to suggest the contributions of individual sound parameters to the overall urgency of a warning, which may be of use to the manufacturer with only one or two parameters at his or her disposal. Our results will eventually lead to a set of design principles for use in advanced auditory warnings work.

We are continuing our work on auditory warning design by looking in more detail at the measurement of the objective/subjective relationship and at auditory signals other than warnings such as auditory icons (e.g. Gaver 1989) where urgency is no longer the most important dimension, but where the signal is an analogue of a mechanical or other function.

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