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Effects of Time-Varying Noise on Annoyance: A Review

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
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ABSTRACT

This report summarizes the literature dealing with the adverse response of people to time-varying noise, and identifies both the acoustial and non-acoustical factors that influence the relationship between time-varying noise and annoyance. An examination of the laboratory research concerned with the functional relationship between annoyance and the temporal and acoustic parameters of noise shows the tenuousness of such relationships. The adequacy of currently used and/or proposed rating procedures for predicting subjective response to time-varying noise is examined. Critical gaps in current knowledge are identified.

Key words: duration; general adverse effects of noise; intermittency; loudness; noise criteria; time

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1. INTRODUCTION

This report is a survey of the literature concerning the adverse response of people to time-varying noise. This survey was undertaken at the request of the Federal Highway Administration (FHWA) as part of a larger research program having the following main objectives:

- to identify and quantify important physical parameters which affect human response to time-varying traffic noise associated with varying densities of both free-flowing highway traffic and stop-and-go traffic;
- to investigate and compare various measures and computational procedures for rating time-varying traffic noise and to investigate which method (or methods) best predicts the adverse response of people to the noise from various types of traffic situations;
- to develop, if necessary, improved procedures for rating time-varying traffic noise in terms of measurable parameters of the noise; and
- to formulate procedures by which the most useful of the above rating procedures may be related to other commonly used environmental noise descriptors.

The FHWA is interested in the effects of time-varying noise because social surveys have consistently shown that "of all the impacts of highways, [time-varying] noise from highways and urban traffic disturbs the public most" [1]*. Indeed, recognition of the annoyance to the public caused by traffic noise has led Congress to direct the Secretary of Transportation, through an amendment to Title 23 of the United States Code, Section 109(i), to promulgate highway noise standards compatible with different land uses. Based on this directive the Federal Highway Administration promulgated highway design noise levels in 1973, initially as Policy and Procedure Memorandum 90-2, and revised in 1976 as Federal Highway Manual, Volume 7, Chapter 7, Section 3.

During development of its highway noise standards, the FHWA considered the environmental, social and economic impacts of various design noise levels. Hearing impairment and general adverse response were considered to be the most relevant human responses to noise. Based upon the then available data, the FHWA judged that in most instances community exposures to traffic noise were not severe enough to induce hearing impairment. Adverse response was considered to result from a combination of several factors such as speech interference, sleep interference, the desire for a quiet environment, and the inability to satisfactorily use the telephone, TV, and radio. Insufficient information existed at that time concerning the effect of time-varying noise on adverse response. Therefore, for design purposes, speech interference from steady-state noise became the basis for selecting noise criteria.

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* Figures in brackets indicate the literature references in section 5 of this report.

When these highway noise design criteria were promulgated, the FHWA recognized that speech interference caused by steady-state noise was not a sufficient basis for standards applying to predominantly time-varying noise. Therefore, the FHWA committed itself to reevaluating its noise standards as research data on the effects of time-varying noise became available. The work reported here is designed to provide the FHWA with a data base upon which to reevaluate its noise criteria.

The first part of the present report (sec. 2) is an examination of the findings of social surveys on the adverse response of people to time-varying environmental noises. The scope and nature of the problems with time-varying noise are defined and some of the factors involved in producing the adverse response are identified in this part of the report. One factor not examined in the present report is the effect of different frequencies of the time-varying noise. There appears to be a consensus among researchers that use of A-weighted sound levels for measuring time-varying noises is adequate. Therefore, all levels discussed in the present report are A-weighted unless otherwise specified. In the next section (sec. 3) the findings of laboratory studies on the effects of temporal factors on the adverse response to time-varying noise are presented. The temporal factors investigated in laboratory experiments, typically, are those that were identified as contributing to the adverse response in the social surveys. The final section (sec. 4) is an examination of the various noise indices devised to predict human response to time-varying noise from measurements of the physical parameters of such noise. It also contains a survey of several laboratory studies that attempted to assess the ability of different noise indices to predict adverse response.

2. EFFECTS OF TEMPORAL FACTORS ON ADVERSE RESPONSE: SOCIAL SURVEY FINDINGS

Over the past 30 years, noise levels in residential communities have increased in most industrialized nations. This increased environmental noise has given rise to increased public concern, and an awareness by public officials of a need to curb community noise. However, the success of any noise abatement and control program requires understanding the community response to environmental noises. Since the early 1950's, a number of investigations combining social surveys and physical noise measurements have been conducted in several countries, in an effort to assess the effects of environmental noise in residential areas.

Basically, there are two approaches to assessing community response to environmental noise. The first is to examine the actions, such as complaints to officials or law suits, taken by individuals or groups of individuals against identifiable noise sources. The second approach is to obtain the individual responses of impacted residents by interviews in social surveys. Once such data have been acquired, relationships between the physical parameters of the noise and people's response may be sought.

Although all such field investigations have had a similar goal -- to arrive at a methodology for relating human response to the physical attributes of the noise -- diverse methods have evolved to express such a relationship. These include, for example, Community Noise Exposure Level, Noise Exposure Forecast, Community Noise Rating, Noise Pollution Level, Noise and Number Index, and Traffic Noise Index, to name just a few.* In this section an attempt is made to summarize the major findings of community noise surveys conducted in this country and abroad, to identify the relationships between noise ratings and human response, and to examine why so many ratings have been developed.

2.1 Procedures Used to Derive Dose-Response Relationships from Field Studies

Most social surveys have resulted from public expressions of dissatisfaction with either the introduction of a new noise source or system in the environment or an increase in the noise produced by an existing system. Accordingly, most social surveys were designed to assess the annoyance and community response produced by a specific noise system, such as an airport or an urban freeway.

One of the most conspicuous aspects of environmental noise is that it varies greatly in magnitude and character, both among various locations within a community and, at any given location, with the time of day. Essentially, the approach has been to sample the noise levels, throughout the day or on a continuous basis, at several locations throughout the community. In addition, other characteristics that describe the noise system are usually recorded. In the case of traffic noise, for example, traffic volume, traffic mix, speed, and other variables are typically recorded.

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* Descriptions and references for all noise-rating schemes discussed in this report can be found in the appendix of the present report.

In order to assess the response of individuals to noise, social surveys are used. Residents are selected and interviewed at locations having exposure to different noise levels. Two general approaches have been used in social surveys. The first consists of asking people direct questions about noise: how often they experience it, how it affects them, and how they feel about it. The second is an indirect approach in which questions about noise are hidden among questions relating to other aspects of the neighborhood such as safety, crime, schools, access, air pollution. Although the first approach is straightforward and easy to implement, it has the disadvantage that people may attempt to reply as they think the interviewer expects them to answer. An indirect approach partially alleviates this problem. It has the added advantage of allowing the investigators not only to assess the noise impact, but also to assess the importance of the noise problem relative to other community concerns.

Different methods of scaling annoyance also have been used. For example, with the method of category scaling, people may be asked which of several descriptors (e.g., "not annoyed, a little annoyed, annoyed, very annoyed") best describes their feelings about noise in general or about a particular noise source. Alternatively, people may be asked to give a numerical rating to the annoyance caused by the general noise environment in which they live, or to rate the noise from a given source on a thermometer type scale. This approach is called numerical scaling. This type of scaling typically anchors the two end points with a pair of verbal descriptors, such as "not annoying" and "extremely annoying."

Regardless of which method of scaling is used, the number of categories or the range of numbers available to the respondents may vary greatly depending upon the particular preferences of specific investigators. For example, some investigators [2,3] prefer to use a five-point scale, while others argue [4-11] that a seven-point scale is best, and still others prefer either a nine-point scale [12] or an eleven-point scale [13-16]. Thus, the type of information gathered through social surveys varies from study to study, and the annoyance scales derived from such studies are not readily comparable.

In a specific social survey, once the physical and subjective data are gathered, the physical data base may be transformed to yield a noise descriptor that correlates well with the subjective data. Since many investigations were designed to assess the noise from a specific noise source or system, and since little uniformity exists as to how data are obtained and interpreted, it is not surprising that a plethora of indices currently exists to characterize environmental noise.

2.2 Social Survey Data: Overall Findings

A common result of social surveys is that people exposed to noise in their homes show a generalized adverse response which increases with increasing noise level. This general adverse response is complex and involves a combination of factors, including speech interference, sleep interference, a frustrated desire for quiet, and the inability to use telephone, radio, and TV satisfactorily

[17-22]. Thus, it appears that the major factor contributing to the adverse response to environmental noise is frequently the activity interference produced by the noise [2,5,17,23,24].

The investigations reviewed in the course of the present study indicate that, in the aggregate, the average response of groups of individuals can be predicted and is correlated well with a number of different measures of cumulative noise exposures [23,25,26]. In fact, the various cumulative noise indices that have evolved from social surveys are highly correlated among themselves, with correlation coefficients often greater than 0.9 [23,25]. These high correlations occur, in large part, because all of the ratings rise with increase in sound pressure level.

While the average response of groups of people is predictable, individual responses vary greatly. Correlation coefficients between noise exposure and individual annoyance scores are typically lower than 0.4 [6-8,27,28], although Bradley [21,22] has reported correlation coefficients of 0.5. Similar results have been observed in laboratory studies, as will be seen in the next section. For example, Borsky [29], in a laboratory study of aircraft noise, noted a correlation coefficient of 0.5 between noise exposure and individual annoyance scores, while a measure of group annoyance yielded a correlation coefficient of 0.9 or better. Griffiths and Delauzun [11] reported correlation coefficients of 0.6 for retests of dissatisfaction with traffic noise, which seem to be the upper limit for what can be expected for correlations of individual annoyance to noise exposures.

Two very different types of dose-response relationships can be derived from social surveys. These can differ significantly in terms of their usefulness. In one type of dose-response relationship, the percent of people experiencing a particular degree of annoyance is related to a measure of the noise exposure. In the second type, the median (or mean) annoyance score is expressed in terms of a measure of the noise exposure. To assess the impact of a proposed action, it is often desirable to know the extensity, or number of people affected, as well as the intensity, or severity of the reaction. The first type of dose-response relationship allows for predictions of both extensity and intensity [25]. The second type yields data only for predicting the intensity or the "average" annoyance of the population for a given level of exposure. Noise abatement and control programs are often based upon a philosophy of satisfying most people most of the time. For this purpose a dose-response relationship which specifies the extensity of annoyance for a specific level of exposure is necessary. For research purposes, it is also necessary to have information about the intensity of the annoyance response. Accordingly, it is desirable that both types of dose-response relations be included in reports of social surveys.

Table 1 summarizes the dose-response relationships derived in some of the major social surveys in which the responses obtained in the survey were expressed in terms of the percent of people annoyed. Also contained in table 1 is a statement about the noise system studied, the descriptor used to characterize the noise, and the type of responses required from those interviewed.

Table 1. Dose-Response Relationships Obtained in Various Social Surveys.

Survey	Primary Noise Source or System	Type of Response	Noise Measure*	Noise Level* (dB)	Percent Respondents
Hall and Taylor [12]	Road Traffic	Disturbed	L_{eq} (0700-2200)	50	2
				60	25
				70	50
				80	85
		Volunteered dislike for noise	L_{dn}	50	0
				60	25
				70	60
				80	90
Wanner, et al. [13]	Traffic	Annoyed and very annoyed	L_{50} (0600-2200)	50	20
				55	25
				60	45
				65	65
				70	80
Rylander, et al. [30]	Traffic	Very Annoyed	L_{eq} (24 hours)	55	1
				60	3
				65	6
				70	12
				75	20
Rylander, et al. [3]	Aircraft	Highly Annoyed	L_{dn}	50	3
				55	8
				60	12
				65	17
				70	22
				75	26

* All descriptors refer to A-weighted levels.

Table 1 (continued)

Survey	Primary Noise Source or System	Type of Response	Noise Measure*	Noise Level* (dB)	Percent Respondents
Alexandre [25] (synthesis of 5 surveys)	Aircraft	Annoyed	NNI	20	<10
				30	15
				40	30
				50	55
				60	80
				70	>90
			CNR	80	<10
				90	15
				100	30
				110	55
				120	80
				130	>90
Patterson and Connor [31]	Airports (in large cities)	Highly Annoyed	CNR	90	15
				100	20
				110	45
				120	55
				125	70
	Airports (in small cities)	Highly Annoyed	CNR	90	5
				100	5
				110	20
				120	30
				125	70
Kajland [16]	Traffic	Much Annoyed	L_{eq} (24-hours)	52	15
				60	30
				68	45
				76	60

* All descriptors refer to A-weighted levels.

Table 1 (continued)

Survey	Primary Noise Source or System	Type of Response	Noise Measure*	Noise Level* (dB)	Percent Respondents
Fields [32]	Railway	Annoyed a little	L_{eq} (24 hours)	30	9
				40	20
				50	30
				60	43
				70	60
Vallet, et al. [18]	Traffic	Very Annoyed	L_{eq} (0800-2000)	59	10
				62	17
				65	20
				68	27
				71	41
				74	50
Schultz [23] (Synthesis of 11 Clustering Surveys)	Aircraft, Traffic and Railways	Highly Annoyed	L_{dn}	55	3-4
				60	8
				65	15
				70	25
				75	36
				80	52
				85	70

* All descriptors refer to A-weighted levels.

There appears to be a fair amount of agreement across studies in spite of the fact that little uniformity exists among studies regarding the methods used to measure either the physical attributes of the noise or the subjective response.

The data of table 1 agree in general with a recent finding of Schultz [23], reproduced here in figure 1. In the Schultz study, data were examined from 18 social surveys, conducted in 9 countries, and dealing with several types of noise sources. The physical data from each study were converted by Schultz into a common metric, the day-night average sound level (L_{dn}). Annoyance scores were converted into categories of "percent highly annoyed." These were plotted as a function of day-night average sound level. Eleven of the eighteen surveys were similar enough to allow Schultz to derive a single dose-response relationship (fig. 1). However, among the surveys examined by Schultz, seven could not be fitted to the curve shown in figure 1 for reasons that remain somewhat obscure. A partial reason that the seven studies do not agree with the other survey data may be that the subjective data in these seven surveys were reported in a manner that made estimates of the "percent highly annoyed" difficult, if not meaningless.

2.3 Reliability of Noise Exposure Indices in Predicting Community Annoyance

The accuracy with which a particular noise exposure index predicts community annoyance typically has been inferred from the correlation coefficients relating measured annoyance scores and predicted scores. A number of studies have attempted to assess how well some of the commonly-used noise descriptors predict community annoyance. The results of such studies are summarized in table 2. As expected, for any given noise exposure index the range of correlation coefficients is smaller within a given study than across studies. This finding is not surprising since these indices are computed from the measured physical attributes of the noise. Thus, in any given study those attributes vary less than across studies.

In order to compare the predictions of different noise descriptors, it is necessary to establish the relationships among noise decriptors within a survey, and then to determine if these relationships are the same across surveys. Referring to table 2, it can be seen that some generalizations about the predictions of certain descriptors can be made. For example, the statistical descriptors (L_{10} and L_{50}) and those based on mean energy values (e.g., average sound level, L_{eq}) predict human response at least as precisely as some of the more complex sound descriptors such as the Traffic Noise Index (TNI), the Community Noise Rating (CNR), the Noise Exposure Forecast (NEF), and the Noise Pollution Level (NPL).

However, in one instance, Griffiths and Langdon [8] found that the Traffic Noise Index predicts annoyance better than the simple statistical descriptors. Later survey data [4-6,20,21,35,36] have failed to confirm the superiority of the Traffic Noise Index (TNI) and indicated that in fact TNI yielded predictions that were observably worse than those obtained using other, and in general simpler, descriptors [6,20,36].

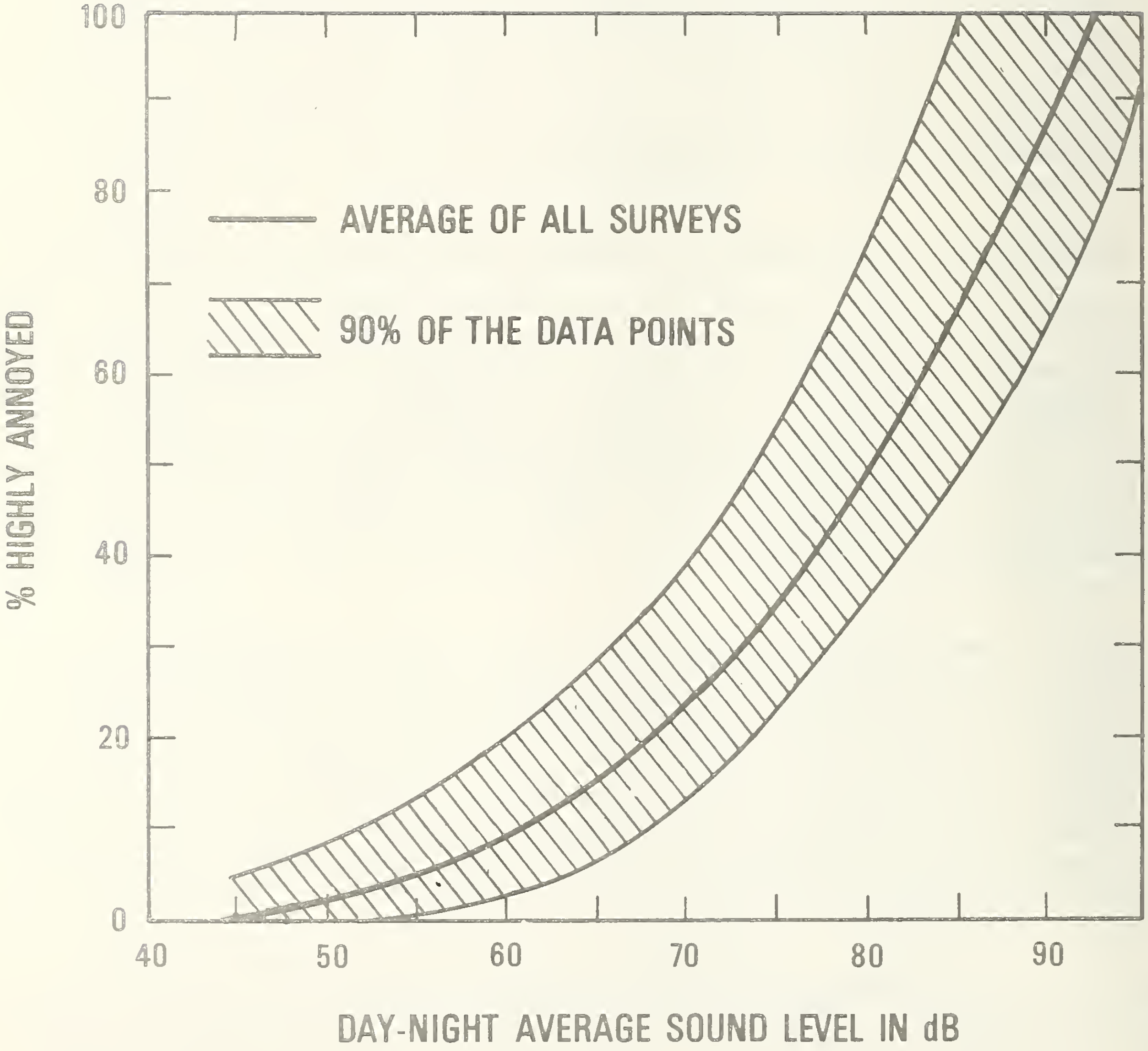

Figure 1. Mean percent of highly annoyed respondents as a function of L_{dn} for eleven "clustering" social surveys [23].

Table 2. Examples of Correlation Coefficients Observed Between Noise Measures and Average Adverse Response

Survey	Primary Noise Source or System	Type of Response	NOISE MEASURES									
			L_{eq}	L_{dn}	NPL	TNI	NNI	L_{10}	L_{50}	L_{90}	CFR	NEF
Fidell [2]	General Neighborhood	% Highly Annoyed		.7								
Bottom [33]	Aircraft	Median Dissatisfaction			.96							
Hall and Taylor [12]	Traffic	% Disturbed	.88	.88				.88	.90			
		Volunteered Noise Disliked	.90	.90				.91	.92			
Gambart, et al.[4]	Traffic	Mean Disturbance	.85D		.75D	.49D*		.85D	.82D	.68D		
		Diurnal Activity			.94N	.90N						
Galloway and Jones [5]	Traffic	Mean Noisiness			.48D .59N	.55DN		.66DN	.60DN			
Langdon [6]	Mixed Traffic	Median Dissatisfaction	.51	.55				.52	.45	.37		
	Free Flow	Median Dissatisfaction	.84	.75		.4		.85	.82	.77		
Langdon [7]	Stop-and-Go Traffic	Median Dissatisfaction	.32*		.43			.34*	.22*	.14*		
Griffiths and Langdon [8]	Traffic	Median Dissatisfaction				.88 .42D* .68N		.60	.45*	.26*		
Rylander, et al. [3]	Aircraft	% Annoyed					.68				.70	.67
		% Very Annoyed					.60				.64	.58
		% Annoyed					.72				.81	.82
		% Very Annoyed					.75				.87	.88

Table 2 (continued)

Survey	Primary Noise Source or System	Type of Response	NOISE MEASURES									
			L_{eq}	L_{dn}	NPL	TNI	NNI	L_{10}	L_{50}	L_{90}	CNR	NEF
Edmiston [28]	Aircraft	Median Annoyance			.97						.99	
Patterson and Connor [31]	Aircraft (Large City)	Annoyance									.43	
	Aircraft (Small City)	Annoyance									.27	
Grandjean, et al. [15]	Aircraft	Mean Annoyance					.91					
	Traffic	Mean Annoyance							.94			
Ollerhead [10]	Aircraft	Mean Annoyance					.94					
Kajland [16]	Traffic	Mean Annoyance	.91					.88	.82			
Yeowart, et al. [20]	Traffic	Median Dissatisfaction	.74	.74	.55	.33		.73	.77	.75		
Fields and Walker [34]	Railway	Annoyance	.44	.44			.42					
Large and Ludlow [35]	Construction Traffic	Annoyance		.51	.51			.52	.51	.51		
		Annoyance		.38	.34	.28		.38	.51	.37		
Cops, et al. [36]	Traffic	Mean Disturbance		.86	.70	.47		.85	.86	.78		
		Diurnal Activity		.86	.76	.51		.86	.83	.78		

Note: D refers to measurements taken in daytime (0700-2200), N refers to measurements taken at night (2200 - 0700),
DN refers to measurements made over 24-hour period; these distinctions are given only if they point out a difference within a given survey.

* Correlation stated by authors not to be statistically significant at the .05 significance level.

One can observe in the data reviewed in the present study a trend among the statistical descriptors (e.g., L_{10}, L_{50}, L_{90}). In several studies [4-6,8, 16,21,26] correlation coefficients between predicted annoyance and measured annoyance decrease as the statistical descriptor proceeds from a "peak" value (L_{10}) to a "background" value (L_{90}). This finding suggests that, everything else being equal, the annoyance produced by noise increases as either the number of distinguishable discrete events, and/or their levels, increase.

Langdon [7] examined the responses of people to noise produced by "nonfree-flowing traffic," i.e., traffic impeded by traffic lights, intersection signals, crosswalks, and congestion. He found that in congested urban traffic situations, conventional noise descriptors such as the average sound level (L_{eq}), the Noise Pollution Level (NPL), and the statistical descriptors (L_{10}, L_{50}, L_{90}) do not provide precise indications of the annoyance produced by the noise. Low correlation coefficients -- typically below 0.43 -- were obtained between predicted and measured annoyance. Moreover, Langdon's data indicated that in such situations the percent of heavy vehicles present in the traffic correlates better with measured annoyance than any of the noise indices, as shown by correlation coefficients between percentage of heavy vehicles and annoyance scores on the order of 0.7.

Bradley and Jonah [22] report that vehicle flow measures can be equal or better predictors of human response to traffic noise than the 24-hour L_{eq}. Further, they note that predictors that include vehicle flow measures as well as both day and night L_{eq} values improve the prediction of annoyance and activity interference relative to predictions by the 24-hour L_{eq}. These findings are in agreement with data reported by Yeowart, et al. [20], but slightly diverge from data obtained by Vallet, et al. [18], who report that vehicle flow measures do improve predictions of annoyance only as experienced in the evening (10:00 p.m. - midnight) and at night (midnight - 5:00 a.m.).

If noise descriptors that account for either the number of discrete events or the variability of noise levels over time are better predictors of community annoyance, they should predict community response more precisely than those that are based either on energy averages (e.g., L_{eq}, L_{dn}, $\bar{Q}$) or statistical descriptors (e.g., L_{10}, L_{50}). Yet, the overall evidence from social survey data indicates that, in most instances, the more complex descriptors (e.g., NPL, TNI) do not predict annoyance better than the simpler descriptors.

The apparent contradiction discussed above remains unexplained at the present time. A possible reason for the failure of TNI and NPL to improve the predictions of human response to noise, relative to simpler descriptors, is that both of these indices predict that the adverse response increases as the variability in noise levels increases. However, some social survey data indicate that the adverse response decreases as the variability in noise levels increases [20, 21]. Moreover, both NPL and TNI only account for the range of variations in noise levels with time, but omit other temporal parameters such as the repetition rate of discrete noise events or the rate of change of levels with time -factors that may be important. While no direct evidence from social survey data has shown that these factors have major effects on human response to noise, laboratory studies of the adverse response to multiple events indicate that these factors can affect the adverse human response to noise [27,37,44]. Details of these laboratory studies are given in section 3 of the present report.

2.4 Effect of Time of Day on Adverse Response

Several studies have shown that noise events occurring at night are more annoying than those that occur during the day [2,9,10,13,14,18,20,21]. People's awareness of discrete noise events at night is increased as a result of the general decrease in background noise level that accompanies the typical decrease in both neighborhood and indoor activities at night.

Wanner, et al. [13] reported that the proportion of people "strongly annoyed" by a given noise exposure doubles at night. Similarly, Buchta and Kastka [14] found that to produce an equal-annoyance score, the night-time average sound level (L_{eq}) due to traffic noise must be reduced by roughly 10 dB below the daytime value while Bradley [21] found a 9 dB difference. These findings are in close agreement with data reported by Fidell [2] indicating that social survey respondents found noise occurring at night the most annoying; the average sound level differential reported by Fidell for a matching annoyance score was about 8 dB. Further evidence for this effect is provided in the Wilson Report [9], where it is stated that although aircraft traffic is reduced at night (producing a drop of 15 to 20 in the Noise and Number Index relative to the daytime value), people still were most annoyed in the evening and early part of the night, and were most desirous of quiet at those times of day.

Although most of the data available suggest that noise events are more annoying at night than during the day, there are some exceptions. The number of aircraft noises reported as disturbing was examined as a function of time of day by Ollerhead [10], who reported that disturbances from day, evening and night events fell into the ratio 3:10:1, respectively. This finding suggests that people are more disturbed by aircraft noise events occurring in the evening and during the day than by those at night. In a study of railway noise conducted in Britain, Fields [32] found no evidence for a nighttime penalty. The reason for this is unclear.

Both the Vallet, et al. [18] and the Ollerhead [10] studies suggest that noise events occurring in the evening hours may have a greater impact than those occurring during the night. However, to date the impact of noise occurring during the evening, as opposed to during the night, has received only limited attention. Whether or not a penalty for events occurring during the evening would be appropriate is unclear. Evidence, does exist, however, indicating that noise events that occur at night should receive increased weight when computing cumulative noise exposure measures. However, the magnitude of this penalty is not well defined. At present, different penalties are used in different indices. It does appear that the 10-dB penalty used in computing the day-night average sound level (L_{dn}) is a useful approximation. The need for an evening penalty and its magnitude has not been demonstrated yet, but, as mentioned previously, there may be a need for such an adjustment.

2.5 Role of Specific Noise Sources in the Generation of Community Annoyance

Two social surveys [2,5] conducted in the United States indicate that people usually can identify the specific noise sources that annoy them. These data reveal that traffic noise is by far the most annoying noise source in most urban areas [2]. Studies of "non-free-flowing traffic" by Langdon [7] and of traffic and tramway noise by Rylander, et al. [30] also suggest that when a specific noise source is identifiable it becomes the major contributor to annoyance. In the Langdon and Rylander studies, measures based on the relative mix of traffic (i.e., percent of heavy vehicles and number of trains, respectively) yielded better predictions of annoyance than the usual statistical descriptors such as L_1 and L_{10}. Bradley [21] reports that the logarithm of the flow rate, of either trucks alone or of all vehicles, predicted annoyance nearly as well as, if not better than, L_{eq}. These studies imply that identifiable, discrete noise events play a significant role in the annoyance reaction.

Since specific noise sources usually are identified by survey respondents, Fidell [2] and Galloway and Jones [5] have assumed that a modest lowering in the noise level of specific noise sources might produce a significant reduction in the annoyance produced by the overall noise environment. The suggestion has been made that it may not be necessary to lower the noise levels of all sources by a comparable amount to produce significant improvements [5]. It also has been suggested that annoyance can be reduced by decreasing the noise of a specific source without significantly lowering the overall noise level [2]. Vallet, et al. [18] found that respondents reported that vehicles were of increasing noisiness in the following order: private cars, mopeds, motor cycles, and trucks. Vallet, et al. also argued that lowering the noise emissions from these specific sources would reduce annoyance.

Although people can identify which noise source annoys them most, two separate studies by Bottom [33] and Grandjean, et al. [15] have shown that annoyance with a specific noise system can be influenced by other noise systems. For example, the annoyance produced by aircraft noise of a given level was found to decrease as background traffic noise increased. Moreover, in a neighborhood in which traffic rather than aircraft noise is the major contributor to the overall noise level, the "general noise dissatisfaction" with the overall noise environment is a direct function of the amount of traffic [33]. However, as the number of aircraft and thus the aircraft noise, increases, the effect of traffic noise on the "general noise dissatisfaction" reverses; i.e., for high aircraft noise levels dissatisfaction decreases as traffic noise level increases. This suggests strongly that the ratio between peak levels due to specific events and the overall background noise level is a major contributor to human response to noise, an idea which is compatible with the suggestions of Fidell [2] and of Galloway and Jones [5]. The practical implication of these findings is that the contrast between single events and steady background noise is an important factor in itself. Accordingly, the success of any noise abatement and control program may require an understanding of the interactions between specific, identifiable events and background levels.

2.6 Relationship Between Annoyance and Complaints

Citizens' action against noise has taken many forms, ranging from the registration of a complaint to court action. Although the rate of complaint has been found to reflect only partially the number of people annoyed in a community, relationships exist among rate of reported annoyance, rate of complaints, and environmental noise levels [15,25,27].

Fidell [2] has noted that the proportion of people annoyed is typically much larger than that which would be predicted on the basis of complaint rate alone. He attributes this finding to the fact that, for most of the ordinary neighborhood noises found annoying, there are no obvious persons or organizations with which to register a complaint. When this hypothesis is combined with the finding that socio-economic factors and political cohesiveness affect the rate of complaints much more than the rate of annoyance, it is not surprising that the rate of complaints yields unreliable predictions of the degree of annoyance present in a community.

Finally, complaint rates are typically influenced by publicity. For example, McKennell [45] found that the number of registered complaints about sonic booms during a six-month period had no relationship with the actual number of sonic booms that occurred. Rather, peaks in the rate of complaints correlated highly with newspaper articles about aircraft noise.

2.7 Noise-annoyance Relationship: Intervening Variables

In the previous discussion, the major emphasis was on the relationship between noise exposure and annoyance. However, another important aspect of research in this area has to do with the development of models that attempt to explain how noise causes annoyance. For this reason the present section examines the relationship among noise, the individual sensitivity of people to noise, and other possible causal factors.

Leonard and Borsky [47] have argued that the relationship between certain noises and human response is modified by intervening variables such as fear and misfeasance. These investigators developed their conceptual model from the results of multiple regression and correlation analyses of questionnaire data obtained from populations living around John F. Kennedy International Airport -- an area heavily impacted by aircraft noise. These early analyses suggested that exposure to aircraft noise causes a fear reaction which in turn causes annoyance. However, similar analyses of data gathered from the same population at a later date show a direct link between noise exposure and annoyance.

Analyses performed by Alexandre [48] on the Leonard and Borsky data and on earlier British survey data show that, in the case of aircraft noise, there is a relationship between fear of crashes and annoyance; however, the nature of this relationship could not be ascertained with any certainty. Therefore, Alexandre concluded that the Leonard and Borsky [48] model may not be correct, and that additional information, such as personality characteristics, would be required to determine accurately the relationships among noise exposure, fear, and annoyance.

Both Langdon [6,7,26] and Fidell [2] asked respondents to self-rate their sensitivity to noise. Fidell [2] found that about 25 percent of those interviewed rated themselves as being more sensitive to noise than most, and Langdon [6,7] found that a third of his subjects placed themselves in the most sensitive group. Langdon also found that as the reported sensitivity to noise increases the reported annoyance due to noise also increases. These studies would support the hypothesis that a noise measure incorporating a sensitivity adjustment might improve predicted annoyance scores.

To test the role of individual sensitivity to noise, Langdon [6,7] used multiple correlation analyses to investigate the effect of including a sensitivity factor in a noise index derived from the physical rating of noise. The data show that while the inclusion of a sensitivity factor does improve the correlations between actual and predicted dissatisfaction scores for individuals, it does not improve the correlation between observed and predicted median group scores.

Griffiths and Delauzun [11] investigated individual differences in sensitivity to traffic noise and their relationship to dissatisfaction with noise. They found that the reliability of respondents' self-ratings of their noise sensitivity was quite low, although statistically significant, and did account for some of the variability in dissatisfaction for respondents exposed to the same noise level. Two personality scales (Eysenck Personality Inventory and Cattell 16 PF) were also administered and failed to demonstrate any consistent correlations with the reported dissatisfaction; nor did they relate to the self-ratings of noise sensitivity. Consequently, they concluded that individual differences in general do not account for variations in noise dissatisfaction, although sensitivity to noise accounts for a small fraction of the variation.

The overall evidence from social surveys tends to indicate that people are most bothered by noise when it interferes with their daily activities. Fidell [2] reports that noise-sensitive individuals, as a group, are more susceptible to the activity interference produced by the noise, thus suggesting that the intervening variable may be activity interference. Indeed, in many of the social surveys examined in this report, respondents reported that noise interfered with specific activities such as face-to-face conversation; listening to television, telephone and radio; sleep; rest; or work [2-4,6,8,9,13,23-25,45,49,50]. These activity disturbances may, in fact, be the strongest variables influencing the annoyance response to environmental noise.

3. EFFECTS OF TEMPORAL FACTORS ON ADVERSE RESPONSE: LABORATORY FINDINGS

The social survey data discussed in the previous section demonstrate the complexity involved in describing the relationship between time-varying noise and human response. A large volume of data also has been collected in laboratory studies where specific temporal factors can be investigated under controlled conditions. Basically, two types of laboratory studies have been done. The first type involves studies of human response to noise as that noise would be encountered in real-life situations (e.g., near airports or highways). The second type of study has concentrated on the effects of specific temporal parameters of discrete noise events, such as single aircraft or vehicular passbys. In the present section the major findings of both types of studies are examined.

3.1 Adverse Response to Multiple Noise Events

In the 1960's laboratory studies of the adverse response of people to noise focused on parameters of single events (e.g., airplane flyovers, vehicle passbys). In the next decade the focus shifted to studies of the adverse response caused by typical time-varying noises such as produced by streams of vehicles. These laboratory investigations have been used to study the effects on human response of such parameters as the number of events discernable in a background noise, the variability in the noise levels over time, the rate of interruption, or the interaction of various noise sources (e.g., aircraft noise superimposed on traffic noise). The primary purpose of many studies performed in the 1970's was to develop indices for predicting human response to noise from measured physical parameters of the noise -- the success of such developments is discussed in section 4 of this report. Accordingly, the validity and accuracy of such indices will be touched upon only tangentially in the present section.

3.1.1 Relationship Between Interruption Rate and Adverse Response

Anderson and Robinson [38] examined the effect of the rate of interruption on the annoyance produced by the noise from a road drill. Twenty-four subjects performed paper and pencil tasks during four 30-minute test sessions. During each session subjects were exposed to 15 minutes of road drill noise presented at an A-weighted level of 87 dB and at four different rates of interruption corresponding to one burst of 15 minutes, 3 bursts of 5 minutes, 60 bursts of 15 seconds, and 180 bursts of 5 seconds duration. The durations of the bursts were such that the average sound level in each 30-minute test session remained constant for each condition. Following each session, subjects were asked to complete a noise questionnaire as well as a semantic differential scale of paired adjectives, from which an annoyance scale was derived. As the rate of interruption increased from 1 burst of 15 minutes to 3 bursts of 5 minutes the annoyance produced by the noise increased. However, no significant change in annoyance response was observed between interruption rates of 3 bursts of 5 minutes and 60 bursts of 15 seconds. At the highest interruption rates (i.e., 180 bursts of 5 seconds each), the annoyance decreased somewhat.

Thus, Anderson and Robinson demonstrated that at low interruption rates annoyance increases as the rate of interruption increases, but at high interruption rates annoyance decreases with further increases in the interruption rate. What happens in between these two conditions is unclear, since Anderson and Robinson did not explore this region.

3.1.2 Relationship Between the Number of Events and Adverse Response

Several laboratory investigations have been performed to assess how the number of noise events present during a given interval of time affects the adverse response to noise. A hypothesis frequently examined in such studies is that the equal energy rule holds, i.e., equal amounts of sound energy will produce the same subjective response. However, as will be seen below, the relationship between adverse response and the number of events is not clearly defined at the present time.

In a study exploring the effects of level, duration, and number of events, Langdon, Gabriel, and Creamer [37] exposed subjects to simulated aircraft flyovers while the subjects watched television. After each half-hour session the subjects rated the acceptability of the flyovers. These stimuli were presented at maximum A-weighted levels of 75 and 85 dB, had durations of 2, 4, 8, and 16 seconds, and were presented at rates of 7.5, 15, 30, and 120 flyovers per hour.

Eighty subjects participated in this experiment. These subjects were split into two groups of 40 each. Each group was then exposed to a different experimental condition. Subjects in Group 1 were exposed to each of the four flyover rates; in this case all flyovers were kept at the same duration for a given subject. Subjects in Group 2, on the other hand, were exposed to all four durations, but only one of the four flyover rates was presented to any given subject. Equal numbers of subjects in Group 1 heard each of the four durations, while equal numbers of subjects in Group 2 heard each of the four flyover rates.

The results of this study indicate that the relationship between acceptability of aircraft flyovers and the number of flyovers varies with the experimental conditions. For subjects in Group 1, the acceptability ratings approximated predictions based upon the equal-energy rule; that is, as the number of events doubled, the unacceptability increased by the same amount as if the noise levels had increased by 3 dB. For subjects in Group 2, however, acceptability ratings were independent of the number of events. Accordingly, it would appear that caution must be exercised in accepting the 3 dB per doubling-of-events rule.

In two recent articles [27,39], Rice reports data from experiments on the influence of the number of aircraft takeoffs and landings on the adverse reaction of subjects engaged in either "quiet activities" [39] or playing bridge [27]. The number of aircraft flyovers ranged from 4 to 64 per hour in one experiment [39] and from 4 to 15 per 25-minute session in the other experiment [27]. Stimuli used in these studies were presented at five average A-weighted peak levels ranging from 45 to 85 dB. At the end of a session the subjects filled out a questionnaire about the noise. From the response to these questionnaires subjective scale values were calculated. Both of Rice's studies indicate that the number of aircraft had little effect on the subjective reaction to the noise until the number reached about 16 per hour. The data indicated that further increases in the number of aircraft flyovers increased the adverse response to the noise.

The data obtained by Langdon, et al. [37] for the subjects in Group 1 in the study reported previously and the data of Rice [27,39] at first may appear to be discordant. However, in the Langdon, et al. study, in only one instance was the aircraft traffic volume below 15 flyovers per hour. For this case Langdon's findings indicate a rate of annoyance above that predicted by the equal-energy hypothesis. As the air-traffic volume is increased above 15 flyovers per hour, the ratings of the noises in Langdon's study closely fit the 3 dB per doubling-of-events trade-off, as do Rice's data.

The practical implication of Rice's finding is that when the number of events is low enough, they do not appear to generate any adverse response. This value represents therefore a threshold above which further increases in the number of events leads to increased annoyance.

Rylander, Sjöstedt, and Björkman [40] provide evidence that there may be an upper boundary above which annoyance no longer increases as the number of events increases. In the Rylander, et al. study [40] subjects were exposed to noise from auto traffic for 45 minutes while reading textbooks. In each of eight sessions different numbers of truck passbys were included, varying from 1 to 70 trucks per session. The A-weighted average sound level in each 45-minute session was held constant at 60 dB. At the end of each session the subjects were asked to complete a noise questionnaire. The results showed that the percentage of subjects annoyed increased as the number of trucks increased from one to four, stayed constant up to 20 trucks, and then decreased as the number of trucks increased to 70.

The data presented by Rylander, et al. [40] do not agree with those of Rice [27,39], who did not find an upper boundary. A possible reason for the differences between the two sets of data may be that Rice's data were obtained in studies involving aircraft noise, while Rylander's data were obtained with traffic noise. Indeed, Rice [39] presents evidence that for the same A-weighted average level, traffic noise is more annoying than aircraft noise, suggesting that human response to these two types of noises differs.

In real-life situations, as the number of events occurring in a fixed period of time increases, the average sound level also increases. Consequently, the increased annoyance associated with this increased noise exposure level may offset the decreased annoyance reported by Rylander for noise exposures held constant in average sound level as the number of discrete events varied between exposures.

Rylander, et al. [40] also report results from an experiment in which the noise exposures lasted two hours. In this study, subjects were exposed to three different volumes of truck traffic (i.e., 6, 50, and 186 trucks/two hours), presented at a constant L_{eq} of 60 dB. Results of this phase of the study indicate that as the number of trucks increased, the percentage of subjects annoyed decreased (53, 37, and 20 percent annoyed). Given the non-monotonic relationship between the number of trucks present in traffic and annoyance found in the first part of this study, and the few and widely spaced values for the number of trucks used in the second part of the Rylander, et al. [40] study, the relationship between the number of trucks and annoyance for this relatively long noise exposure cannot be adequately assessed.

In summary, there is evidence that annoyance is influenced by the number of discernable discrete events occurring in the noise. However, the nature of the relationship between the number of events and annoyance varies among studies, and possibly, among types of noise sources.

3.1.3 Contribution of Noise Variability to the Adverse Response to Time-Varying Noise

The effect of fluctuations in noise level on adverse response is not clear. Although specific formulations have been proposed to account for the effects of fluctuations [51-53], the experimental evidence discussed below makes it evident that the relationship between fluctuation and annoyance is still ill-defined.

The studies discussed in the present section share several common features. In all studies reviewed here subjects were exposed to either time-varying traffic [27,43,54-56] or aircraft [27,39,44] noise. All studies were performed in a laboratory setting, in either a semi-realistic living room setting [27,39, 44,54] or an anechoic chamber [45,55,56]. Typically subjects were asked to rate their annoyance to the noise they were exposed to at the end of each exposure. Exposures typically lasted from two to thirty minutes depending on the particular study. One exception is worth mentioning. In a series of studies conducted by Cermak [44,56,57], pairs of stimuli were presented for about one minute. Subjects were asked to judge, for each pair of stimuli, which member of the pair "they would rather be exposed to"; and, independently to judge also the relative similarity among pairs of sounds.

In most of these studies the relationship between adverse response and average sound level, L_{eq}, was determined. Then the average sound level was adjusted to account for the variability in sound level over time so as to determine whether indices that take into account variability were better predictors of human response than just the average sound level. The variability in sound level over time has been expressed in several ways. These are listed in table 3 together with correlation coefficients between adverse response and L_{eq} (when reported).

As can be seen in table 3, the noise level, as expressed by L_{eq}, is a primary determinant of the adverse response to noise. This is seen in high correlation coefficients between L_{eq} and adverse response. The effect of the variability in noise levels is not as clear. Shepherd [44] performed a multiple regression analysis combining L_{eq} and σ. However, his analyses show that the addition of σ to the regression equations does not improve the prediction of annoyance at the 95 percent confidence level. Andrew and May [54] did a stepwise regression

Table 3. Comparison of Laboratory Studies Designed to Assess the Role of Noise Variability on General Adverse Response.

Study	Type of Noise Source or System	Type of Human Response Measure	Background Activity	Number of Subjects	Number of Stimuli	Duration of Stimuli (s)	Range of L_{eq} (σ) (dB)	Correlation Coefficients Between L_{eq} and Human Response Scores
Rice [39]	Aircraft	Questionnaire	Reading Conversation	191	25	3600	30 - 70	.953
Rice [27]	Aircraft Traffic	Questionnaire Questionnaire	Playing cards Playing cards	16 16	9 9	1500 1500	40 - 60 40 - 60 (2.0-7.1)	.968 .943
Andrew and May [54]	Traffic	Annoyance Scale 0 to 10	Listening to recorded speech	32	30	120	58 - 83 (2.3-7.2)	.695
Shepherd [44]	Aircraft	Annoyance Scale 0 to 10	Reading or Needlework	160	10	1800	43 - 65 (8.5-13.9)	.940
Pearsons [55]	Traffic	Annoyance Scale 1 to 5	Listening to recorded speech or none	20	23	30	44 - 83	

Table 3 (continued)

Study	Type of Noise Source or System	Type of Human Response Measure	Background Activity	Number of Subjects	Number of Stimuli	Duration of Stimuli (σ)	Range of L_{eq} (*s*) (dB)	Correlation Coefficients Between L_{eq} and Human Response Scores
Cermak and Cornillon [56]	Traffic	Choose which member of pair of stimuli preferred; identity similarity among pairs of stimuli	none	20	13	60	6 - 83 (2.5-6.9)	.93
Cermak [43]	Traffic	Choose which member of pair of stimuli preferred; identity similarity among pairs of stimuli	none	12	13	45	65 - 77 (1.3-4.7)	

analysis including such factors as L_{eq}, σ, sex, number of truck gear changes, and different statistical descriptors (e.g. L_{10}, L_{50}, L_{90}). The data thus obtained showed that 33 percent of the variation in subject responses could be explained by L_{eq} alone and that only 5 percent more variation could be accounted for by the other variables included in the equation. Thus, Andrew and May concluded that, since 62 percent of the variance was still unaccounted for when all the factors listed above are taken into account and since any determination of such variables increases the complexity of the measurement of noise, "no appreciable improvement stems from considering terms besides L_{eq}."

Based on a series of preference studies for pairs of traffic sounds, Cermak [43,56,57] also questioned the importance of noise variability in assessing aversion to noise. Based on his data he concluded that there are physical parameters, other than noise level, that could account for aversion to traffic noise, but that those "variables are of limited effectiveness and generality." In experiments where all the stimuli were presented at a constant L_{eq} level, but where the variability, as represented by σ, was systematically changed, use of σ did not improve the prediction of the subjects' preference choices. In one experiment, predicted preference (when σ was taken into account) was significant for only 4 out of 14 subjects. In a second experiment, σ failed to improve predictions for any of the subjects. The failure of σ to improve predictions in human response led Cermak to question the necessity of incorporating noise level variability in noise indices, particularly when variability is expressed in terms of σ.

From the above-mentioned studies there is some question about the importance of variability, as expressed by the standard deviation in noise levels, in predicting annoyance due to noise. In experiments reported by Rice [27,39], correlation coefficients were calculated between subjective response and physical noise measures of the form $L_{eq} + k\sigma$, where $k = 0, 0.5, 1, 2, 2.56$. In all three experiments a consistent trend was found. As k increased from 0 to 2.56, the correlation between the physical and subjective measures gradually decreased.

Further evidence is produced by Pearsons [55] who used L_{10} minus L_{50} rather than σ, as a measure of variability. For traffic sounds having an average sound level of 70 dB or higher, Pearsons reported that variability did not affect the reported annoyance. However, for average sound levels of 55 dB or lower, the highly variable noises were less annoying than the steady sounds. Pearsons also reported that for traffic noises of moderate levels (L_{eq} = 60 dB) an increase in variability tended to decrease the annoyance due to the noise, especially in conditions where subjects were trying to understand speech. Pearsons' findings are supported by the social survey work of Bradley [21] and Yeowart, et al. [20].

From the above experiments it appears that the variability, per se, in noise levels is not a major factor contributing to annoyance. However, there is some evidence that under some conditions increased variability may decrease annoyance due to noise. Some caution must be exercised in interpreting this finding, however, since the role of the variability in the noise levels could depend upon which activity coincides with the noise exposure. For example, while a highly variable noise exposure may decrease speech interference, it may increase sleep disruption.

3.1.4 Adverse Response to Combined Aircraft and Traffic Noise Sources

In the earlier parts of this section only the adverse response to a single noise source, either traffic or aircraft, was considered. However, in the real world noise often results from the superposition of several noise sources. Recently several studies [42,58-60] examined the annoyance caused by noise exposure to combined aircraft and traffic noises.

Typically, in such studies, subjects were exposed to background traffic noises in which aircraft flyover noises were embedded. Subjects were instructed to rate the annoyance or noisiness of the individual aircraft flyovers. Powell and Rice [58] found that increasing the level of a continuous background traffic noise decreased the annoyance produced by individual aircraft flyovers. This annoyance drop was significant and roughly equivalent to decreasing the level of the aircraft flyovers by 5 dB, when background traffic noise levels were increased from an A-weighted level of 45 dB to 65 dB. Powell [59] obtained similar results in a pair of experiments in which aircraft type and noise levels were varied, as were the level and variability of the background traffic noise. Again a reduction in annoyance, equivalent to a 5 dB decrease in the level of the individual aircraft, was obtained by increasing the background noise level from an average sound level, L_{eq}, of 30 to 40 dB. The effect of the variability in traffic noise was unclear, although an interaction between the levels of the aircraft and traffic noises was observed. The maximum reduction in annoyance occurred when the aircraft noise level was 10 dB above the traffic noise level; however, when background traffic noise was high, annoyance increased with any further increases in noise level.

Johnston and Haasz [60] examined the interaction between traffic and aircraft noise and included the effect of duration of the aircraft signal as a parameter. They examined the effects of aircraft flybys protruding above background traffic noise, 20, 40 or 80 percent of the time during an 11-minute session. Six flybys were presented in each session. For the conditions when the flyovers were protruding above the background noise levels (which increased from a mean value of 44 to 68 dB 20 and 40 percent of the time), the decreased annoyance was as if a 5 to 6 dB reduction in the peak level of the aircraft flybys had occurred. No decrease in annoyance was observed for increases in the background noise when the aircraft noises were discernable 80 percent of the time. This latter condition approached the situation where the aircraft signals were steady-state and the background noise was effectively masked by the aircraft signal. Consequently, the traffic background had no effect on the observed annoyance produced by the aircraft signals when the rate of flyovers was very high.

In another study by Powell [42], subjects rated the annoyance produced by noise exposures lasting 15 minutes. A total of 17 noise conditions was presented. These included exposures to aircraft and road traffic presented separately at four average sound levels, ranging from 30 to 60 dB in 10 dB steps, as well as exposure to nine combinations of mixed aircraft and road traffic in which each source was presented at average sound levels of 40, 50, or 60 dB.

The data thus obtained showed that when aircraft and road-traffic noises were presented separately, the aircraft noises were found to be more annoying than road-traffic noise presented at the same average sound level. For the combinations of the two sources, a significant interaction was found between aircraft and road-traffic noise levels. At the lowest traffic noise level (L_{eq} = 40 dB), as the aircraft noise level increased there was a slight decrease in annoyance followed by a substantial increase as the aircraft noise level was further increased. For the middle traffic noise level (L_{eq} = 50 dB), as the aircraft average noise level increased from 40 to 60 dB, there was a substantial increase in annoyance followed by a very slight decrease. For the high traffic noise level (L_{eq} = 60 dB), there was a decrease in annoyance followed by a substantial increase as the airplane noise level was increased. Accordingly, there were several conditions for which the combined noises were judged less annoying than the aircraft noise alone. Thus, for the combined exposures, an interaction was found between aircraft and traffic noise levels which appears complex and is not adequately assessed by the total energy concept embodied in L_{eq}.

The data discussed above [42,58-60] suggest that the level of a background traffic noise influences the annoyance produced by aircraft flyovers. Moreover, when the traffic noise level is moderate to high, the maximum reduction in the annoyance caused by aircraft noise appears to correspond to that which would be expected if the maximum level of the aircraft noise were reduced by 5-6 dB. Complex interactions can be observed in the adverse response of people to combinations of noise sources. When such combinations exist, some of the noise sources play the role of signal while others act as background noise. The difference between the "signal" and the "background" levels is an important element of the human response since annoyance is reduced as this difference is decreased by either lowering the signal level or raising the background level. However, when the source which plays the role of the signal increases to the point where events occur very frequently, those discernable events become the predominant factor in the adverse response and the effect of the difference between, say, traffic noise levels and aircraft noise levels, is greatly diminished. It should be noted that similar results have been found in social surveys [15,33]. In these surveys the data reported showed that annoyance due to aircraft flyovers decreased as the level of the background traffic noise increased, until the frequency of aircraft flyovers became very high.

3.1.5 Speech Interference as an Intervening Variable

It has been generally argued that the adverse response to noise exposure is actually a secondary effect brought about by the activity interference produced by noise (i.e., speech interference, sleep interference) [2,5,17-24].

Pearsons [55] has explored the relationships among annoyance, speech intelligibility, and comprehension as a function of noise exposure and variability. In these series of experiments, conducted under laboratory conditions, subjects were exposed to various levels of traffic noise while listening to either phonetically balanced lists of words (speech intelligibility) or connected discourse (speech comprehension). In addition, each subject was asked to rate the annoyance produced by the noise when presented alone and in the presence of the speech on a five-point category scale.

The data obtained by Pearsons demonstrated that annoyance caused by traffic noise in the presence of speech decreased as the level of the speech increased. Further, these data demonstrated that the degree to which words could be identified in the presence of traffic noise influenced the annoyance caused by the noise. Speech-to-noise ratios were determined by adjusting the speech levels for three different levels of speech comprehension, defined as the percent of words correctly identified. The three groups were: low (less than 10 percent correctly identified), moderate (50 percent identification) and high (greater than 95 percent correct) comprehension. The subjects then rated the noise samples in the three different speech comprehension conditions without speech being present. The L_{eq} levels of the traffic samples varied from about 45 to 85 dB. For L_{eq}'s below 70 dB, the traffic samples presented with speech for the low and moderate comprehension groups were rated more annoying than the same samples without speech present. However, the annoyance ratings for the same traffic samples in the high comprehension condition were lower than the ratings in the no-speech condition.

In section 3.1.3, it was stated that Pearsons found that annoyance decreased as the variability in the noise levels increased, especially when subjects were trying to understand speech. However, the study noted above indicates that the effect of noise is dependent upon the level of the speech. At high noise levels (above an L_{eq} of 70 dB), variability had no effect, whereas at lower noise levels, annoyance decreased as the variability in the noise increased. Pearsons also presented evidence indicating that speech comprehension is an intervening variable between noise level variability and annoyance. For speech-to-noise ratios corresponding to moderate speech comprehension, the effect of variability in the noise levels was clear. However, when the variability in the noise level was low, subjects on the average answered correctly less than one question out of three about the material presented in the noise. When the degree of variability in the noise levels was moderate or high, subjects answered two out of the three questions correctly, on the average. Pearsons showed further that as the number of questions correctly answered increased, the annoyance caused by traffic noises decreased. Consequently, it appears that the improvement in speech comprehension associated with the increased variability in the traffic noise levels is an intervening variable which reduces the annoyance produced by noise.

In conclusion, Pearsons' [55] results indicate that when background noises degrade speech comprehension, the adverse response to the noise is increased. It also appears that the characteristics of the background noise (e.g., level and/or variability) affect speech comprehension, which itself affects the adverse response to the noise.

Similar data obtained by Pearsons and Bennett [61] showed that in an aircraft noise environment, subjects found the aircraft noise more annoying when instructed to rate the environment "assuming that people would want to be able to converse in it" than when they were instructed just to rate the annoyance. The work of Pearsons and that of Pearsons and Bennett both support the concept that the degree to which verbal communication is successful influences the adverse response to environmental noise. This finding is consistent with the results from social surveys discussed in section 2 of the present report.

3.1.6 Time-of-Day Effects on Annoyance and Comparisons to Social Surveys

Powell [42] and Shepherd [44], in two recent studies, attempted to compare laboratory-based predictions of community annoyance, as a function of time of day, with similar predictions from social surveys as synthesized by Schultz [23]. Subjects were asked to rate the annoyance produced by noise, presented under laboratory conditions, as if that noise were heard in their homes during the day, evening, or night. Both Powell [42] and Shepherd [44] found differences in the mean annoyance ratings for day, evening, and night conditions.

Powell [42] obtained equivalent annoyance ratings when the L_{eq} levels for the night condition were 5 to 10 dB less than the levels for the day condition. The differences were influenced by the type of noise the subjects heard, with the day-night difference being greatest for aircraft alone, then for mixed aircraft and traffic, and lowest for traffic alone. He also found equivalent annoyance ratings for the evening hours at levels 2 to 6 dB less than the daytime levels, with aircraft again causing greater annoyance.

Shepherd [44] conducted laboratory studies in which subjects were asked to assess how annoying aircraft noises would be if heard in their homes during the day, evening, and night hours. In addition, these same aircraft noises were rated in terms of annoyance using a 10-point numerical scaling procedure. From the data thus obtained Shepherd concluded that projected home annoyance judgements agreed well with community annoyance as expected from Shultz' [23] synthesis of social survey data. That is, the relationship between noise levels and percentage of people highly annoyed reported by Shultz and that observed by Shepherd were in good agreement. Further, the Shepherd data suggest that a 7-12 dB nighttime penalty and a 5-7 dB evening penalty, relative to daytime values, may be required in the derivation of cumulative noise exposure indices. However, for combined aircraft and traffic noise conditions, increases in the percent highly annoyed of 20 to 30 percentage points were found, relative to the social survey data, for nearly half of the stimuli. This suggests that communities impacted by multiple noise sources at equivalent noise levels may experience more annoyance than communities impacted by a single noise system.

3.1.7 Summary of Multi-Event Laboratory Findings

From the above discussion it is clear that the adverse response to time-varying noise is not only dependent on the level of the noise but on other parameters as well, particularly intermittency and number of discrete noise events. Moreover, the adverse response typically increases as the rate of intermittency and/or number of events increases. However, variability per se does not appear to increase annoyance significantly. Actually, there are suggestions that in some situations the more variable noises are less annoying than steady-state noises.

When the offending noises originate from two different and distinct noise systems there are level-dependent interactions between the resulting noises that influence annoyance. In particular, the lower level noise seems to act as background noise that "masks" the more intense noise.

The activity of the exposed people influences annoyance. Someone trying to understand speech may be more annoyed by low-level sounds than someone just relaxing, and annoyance increases as speech comprehension decreases. Laboratory results also indicate that time of day is an important factor and that, if asked how they would rate the annoyance caused by a given noise exposure level as a function of time of day, subjects rate evening and night exposures as more annoying than similar exposures occurring during the day.

3.2 Adverse Response to Discrete Noise Events

The experiments discussed in the present section [63-75,77] indicate that as the duration of a single noise event increases, the adverse response to that event also increases and that the trade-off between the noise level and duration varies from study to study (see table 4). Some researchers [67-70,76] have attempted to account for the differences observed among various studies on the effects of duration of single noise events. These attempts are also reported below.

Kryter and Pearsons [63] investigated the effects of temporal factors on the noisiness of sound and reported that these effects were different from those observed on loudness. Their conclusions were derived from psychoacoustic data obtained on 14 subjects; these data consisted of noisiness judgments obtained by the method of constant stimuli in which subjects compared each experimental sound to a standard sound presented at 100 dB SPL having a duration of 4 seconds and rise and fall times of 1 second each. The experimental stimuli were presented at four levels, and had different durations (1.5 to 12 seconds) as well as different rise and decay times (0.5 to 4 seconds). (In most of the experiments described herein, noise duration is taken to be the time interval over which the instantaneous weighted noise level is within a predetermined level (usually 10 dB) of its peak value.)

For the spectra, intensities, and durations used in the Kryter and Pearsons study, changes in the rise and decay times did not significantly influence the noisiness judgments. However, duration was found to be a significant factor. The level of the comparison sounds judged to be as noisy as the standard sound decreased by 4.5 dB for each doubling of the duration of the comparison sound. That is, as the duration of test signal was doubled, that signal had to be reduced by 4.5 dB in order to be perceived as having the same noisiness as the reference signal. The change in intensity necessary to maintain equal judgments of a perception (e.g., noisiness, annoyance) as the duration changes is referred to as the "time-intensity trade-off."

Table 4. Summary of Studies on the Time-Intensity Trade-off for Discrete Noise Events.

Study	Type of Noise	Number of Subjects	Levels	Range of Durations (s)	Average Trade-off Value (dB/dd*)
Kryter and Pearsons [63]	Aircraft	14	91-112 dB, SPL	1.5 - 12	-4.5
Pearsons [64]	Aircraft, Tones, and Noise	18	77-104 dB, PN	4 - 64	-2.7
Hiramatsu, et al. [71]	White Noise	20	60-90 dB,SPL	0.03 - 90	-3.4
Little and Mabry [67]	Random Noises Jet Noise	94	76-100 dB, SPL	1 - 34	-2.6
Pearsons and Bennett [65,66]	Shaped Random	20	80-90 dB, SPL	1 - 100	-2.6
McCurdy and Powell [72,73]	Synthesized Aircraft Noise	48	70-88 dB, A-weighted	10 - 20	-3
McCurdy [74]	Synthesized Aircraft Noise	32	70-85 dB, A-weighted	10 - 40	-3
Fuller and Robinson [77]	Traffic Noise	20	85 dB, A-weighted	30 - 3600	-3.3

* dd = doubling of duration

In a later study, Pearsons [64] reported data obtained on 18 subjects for durations ranging from 4 to 64 seconds. Over this range of durations the level of the comparison sound decreased by an average of 2.5 dB per doubling of duration for equal judgments of noisiness as compared to the 4.5 dB decrease per doubling reported by Kryter and Pearsons [63] for durations between 1.5 and 12 seconds. Thus it appears that noisiness is a function of duration, but that the trade-off between level and duration for judgments of equal noisiness may decrease as duration increases.

By piecing together the results of the above studies [63,64], Pearsons [64] approximated the time-intensity trade-off function for annoyance by a three-line-segment function, with each segment corresponding to a specific duration range. For durations between 1.5 and 4 seconds, the time-intensity trade-off function is -6 dB per doubling of duration, dropping to -3.5 dB in the range from 4 to 16 seconds, and to -2 dB for durations between 16 and 64 seconds. If a regression line is fitted to the data between 4 and 64 seconds the slope of the line is -2.7 dB per doubling of duration. This value has been used often in support of the equal energy concept; however, this interpretation may be questioned since the slope of the time-intensity function changes depending upon the particular durations of experimental stimuli included in the calculations.

An alternative approach for combining the above data [63,64] is to perform a linear regression analysis on all the data points reported in those studies, that is for stimuli durations from 1.5 s to 64 s. This approach yields a time-intensity trade-off of -3.4 dB per doubling of duration. The goodness-of-fit of the data points to the regression line is strong, with the coefficient of determination being 0.84.

Later reports by Pearsons and Bennett [65,66] present a time-intensity trade-off value of -2.6 dB per doubling of duration for aircraft spectra lasting from 1 to 100 seconds. This value agrees well with the value of -2.7 dB reported previously by Pearsons [64] for stimuli ranging in duration from 4 to 64 seconds. However, neither value agrees with the time-intensity trade-off value of -3.4 dB computed on the same combined data [63,64] for durations ranging from 1.5 s to 64 s.

In a study by Hiramatsu, Takagi, Yamamoto, and Ikeno [71], the effects of duration and level of white noise on annoyance were examined. The twenty subjects who participated in this experiment were asked to "judge the whole perceived magnitude of the sound, for example, annoyance and unpleasantness, etc. ..." by the method of magnitude estimation. The signals varied over a range of duration from 30 milliseconds to 90 seconds and over a range of levels between 60 and 90 dB. Over the range of intensity and duration examined, the results indicated that duration effects were dependent upon level. On the average, however, the trade-off value for equal annoyance was -3.4 dB per doubling of duration; a value that agrees well with that computed above for the combined data of Kryter and Pearsons [63] and Pearsons [64].

Little and Mabry [67] confirmed that duration has an effect on the annoyance produced by noise. Using random noise and jet noise, durations of 1 to 34 seconds, and noise levels ranging from 76 dB to 100 dB SPL, their data indicated that the time-intensity trade-off value is greatly variable and ranges from -0.6 to -3.1 dB per doubling of duration. Judgments obtained without instructing subjects to attend to duration yielded time-intensity trade-off values in the range of -0.6 to -1.9 dB per doubling of duration. However, if the instructions to subjects included cues for duration, the values were typically between -2.1 and -3.1 dB per doubling of duration. The median trade-off value reported by Little and Mabry was -2.0 dB per doubling of duration.

The effect of duration cues in the instructions given to subjects on the perceived noisiness of single events was examined also by Parry [68]. In a study of the perceived noisiness of aircraft flyovers, two groups of subjects were required to adjust a pair of two signals until they appeared equally noisy. One group of subjects received instructions that included duration as a judgment parameter while the other group did not. The results of this study showed that duration cuing had a slight effect on the noisiness judgments obtained but this effect was not statistically significant.

In 1972, Parry and Parry [76] reviewed the status of the research on the effects of duration on the annoyance of noise [63,64,67-69]. They concluded that duration was not a primary factor in noisiness judgments, and that the effects of signal duration are only observed when subjects are specifically cued to attend to differences in signal duration. However, the experiments of Pearsons and Bennett [65,66] showed duration effects without duration cues being given in the instructions, as did two recent experiments by McCurdy and Powell [72,73] and McCurdy [74] on the annoyance of aircraft flyovers. In the first experiment a factorial design was used to explore the effects of duration, level, aircraft velocity, and the presence of tones as factors in simulated flyovers [72]. In the second experiment a factorial design was used also, with the parameters studied including duration, level, and fluctuation. In both experiments the instructions did not cue the subjects to any of the parameters under study, yet a clear effect of duration was observed. For the durations used -- 10, 20 and 40 s -- the effect of duration on annoyance was effectively the -3 dB per doubling of duration predicted by the equal-energy hypothesis.

In a study of actual aircraft flyovers heard on location near an airport, Bishop [69] reported data on the effects of duration on noisiness that diverge from those of other investigators. In the Bishop study, a series of psychoacoustic tests was conducted in dwellings located under the approach and takeoff paths of Los Angeles International Airport. In these tests, 55 residents were asked to judge (by the method of magnitude estimation) the noisiness of actual aircraft flyovers. Median judgments for the noisiness of approach and takeoff noises of essentially the same perceived noise levels were the same despite the fact that on the average the duration of an approach (10 s) is about 6 seconds shorter than that of a takeoff (16 s).

Bishop's data differ from the results found by other investigators. Although on approach the acoustical signals are briefer than on takeoff, they contain more tonal components. One could argue that the increased noisiness associated with the pure tones present in approaching flyover signals may offset their shorter durations. Hence, differences in spectral content might offset effects due to differences in duration.

Another clue as to why Bishop's data may differ from other data comes from a study by Rosinger, Nixon, and von Gierke [70] in which subjects were asked to judge the annoyance of artificial sounds constructed to represent approaching and receding aircraft flyovers. The data obtained in this study indicated that stimuli representing approaching aircraft were generally more annoying than those representing receding aircraft, even though the two sets of stimuli had the same energy content, frequency distribution, and duration. This finding was attributed to the fear which may be associated with approaching aircraft. A similar finding was reported by Hiramatsu, Wakasa, Takagi, and Yamamoto [75], where artificial noises that increased in level with time were found to be more annoying than otherwise identical signals that decreased in level with time. Thus, there appears to be a difference in the degree of annoyance produced by noise stimuli, depending on whether they increase or decrease in level over time. Whether this difference is due to, or augmented by, fear of an approaching object has not been tested, but it could be a further explanation for the effects observed earlier by Bishop.

Fuller and Robinson [77] have studied the effects of long durations on annoyance. During one hour sessions, while performing a pencil and paper task, subjects were exposed to steady-state traffic noise at a mean A-weighted level of 85 dB for either the last 5, 15, or 30 minutes of the session, or for the entire hour. The noises were due to a steady stream of traffic in which individual car passbys were not discernable. At the end of the session, subjects answered direct questions about the noise and completed semantic differential scales of adjective pairs.

The authors found that as the duration of exposure increased from 5 to 15 minutes, the adverse response decreased slightly. As the duration of exposure increased from 15 to 30 minutes, the adverse response increased sharply. As the duration of exposure increased further from 30 to 60 minutes, a slight decrease in the adverse response was observed. Fuller and Robinson reported that a non-monotonic function fits their data best and that statistically significant results were obtained only with the data derived through the use of the direct questionnaire. For this subset of data a time-intensity trade-off value of -3.3 dB per doubling of duration was estimated.

The time-intensity trade-off ratio reported by Fuller and Robinson [77] is certainly within the range of values obtained for single event exposures. However, due to the high intersubject variability and the non-monotonic nature of the function, the precision of the time-intensity trade-off estimate must be viewed with caution. The data obtained in the Fuller and Robinson study do indicate that the adverse response to noise is affected by the duration of long exposures, but that the exact nature of this relationship is complex and ill-defined.

To summarize, although there exists a substantial literature concerning the effects of discrete events of various duration on adverse response, the data do not provide definitive answers regarding the time-intensity trade-off, as seen in table 4. The slope of the time-intensity trade-off appears to be influenced by the spectra of the signal used, the level of the stimuli, the range of duration under consideration, instructions to subjects, and emotional reactions (e.g., fear) to the signal. Accordingly, all that can be said with confidence is that the duration of a noise influences the annoyance response in such a manner that as the duration of a discrete noise event increases, from around 1 s up to at least 100 s, its aversive quality increases.

4. UNIFICATION OF NOISE INDICES: VARIOUS EFFORTS

As mentioned previously, a large number of environmental noise indices has been put forward to account for human response to time-varying noise. The reason for this plethora of indices is that most indices currently used were derived on the basis of studies dealing with the effects on people from specific noise sources or systems. For example, the Noise and Number Index (NNI) and the Noise Exposure Forecast (NEF) deal specifically with the problem associated with aircraft flyovers, while statistical descriptors such as L_{10} and the Traffic Noise Index (TNI) have been derived from social survey data on traffic noise.

The proliferation of noise indices has led to situations where, even within a single country, several indices are used. For example, in the United Kingdom three different noise ratings are currently in use to characterize the environmental noise produced by transportation systems. To characterize traffic noise, the level exceeded 10 percent of the time (L_{10}) is used. Railway noise is characterized by the maximum A-weighted level. Aircraft noise is described in terms of the Noise and Number Index (NNI). At the international level the situation is further complicated since each country actively involved in environmental noise research has developed its own system(s). Table 5 shows some of these systems together with an indication of what noise sources they are intended to characterize. In developing table 5, the intention was not to produce an inventory of the various noise descriptors, but, rather, to provide an indication of the complexity that currently exists.

This proliferation of environmental noise indices has complicated the development of meaningful noise abatement and control programs, both at the national and international levels. The primary reason for this is that, in the absence of a generally agreed upon environmental noise descriptor, establishing long range goals for reducing environmental noise is progressing slowly. Yet, such goals are essential if noise control and abatement programs are to be both relevant and cost-effective. For example, various industries have little guidance on how to expend limited funds for noise control research and development programs. Such expenditures are meaningful only if there is a knowledge of future noise abatement requirements within a country, and, for products sold internationally, of future noise abatement requirements in other countries.

An accurate understanding of the response of people to noise will provide the means to develop a unified metric to measure all noise exposures, in order that various noise exposures may be pooled to arrive at the total noise exposure experienced by people. Thus noise exposure produced by various sources could be characterized in a consistent manner and in a way that accounts for the integrated effects of noise on people. Then criteria of acceptibility could be chosen, for all noise sources, that included other, non-acoustic factors (e.g., economic factors, feasibility, and a particular community's aspirations) in the decision making process.

Table 5. Examples of Environmental Noise Descriptors Currently Used in Several Countries.

Country	Noise Descriptor	Application
United Kingdom	L_{10}	Traffic Noise
	Maximum A-weighted Sound Level	Railway Noise
	NNI	Aircraft Noise
United States	L_{10}	Highway Noise
	L_{dn}, L_{eq}	General Environmental and Highway Noise
	NEF	Aircraft Noise
Switzerland	L_{50}	Traffic Noise
	NNI	Aircraft Noise

4.1 General Descriptors for Environmental Noise

A number of investigators have attempted to derive general descriptors for rating environmental noise. These attempts are summarized below.

Many descriptors that attempt to predict the effect on people of noise exposure are in terms of a weighted equivalent sound level. Such an approach implies that exposure to equal equivalent sound levels over a given time period should produce equal subjective effects. Most of these descriptors are of the form

$$L = K \log_{10}\left[\frac{1}{T}\int_0^T 10^{L(t)/K} dt\right], \tag{4.1}$$

where

L(t) = the weighted noise level at time t (typically A-weighting is used),

T = period of time over which the levels are averaged, and

K = a selected constant

In the United States, K is set equal to 10, thus yielding the average sound level, L_{eq}. K is also assigned the value 10 by the International Organization for Standardization. However, values other than 10 are embodied in indices used in other countries. The Noise and Number Index (NNI) used in the United Kingdom uses a value of 15 while the German Stör Index, Q, uses a value of 13.3.

The value of the constant K determines the trade-off relationship between the level of a metric and the number of noise events that occurs within a fixed period of time. When K = 15, the trade-off relationship between the sound level and doubling the number of events is -4.5 dB; when K = 13.3, this trading relationship is -4 dB; and it falls to -3 dB when K = 10.

None of the indices based upon equivalent sound levels take into account the extent of the variation in sound levels, the rate of change in sound level, or the intermittency of individual events -- characteristics that have been observed to contribute to subjective response.

In an attempt to explain some of the differences observed by Griffiths and Langdon [78] in human response to traffic noises recorded at different locations, Robinson [51] re-analyzed Griffiths and Langdon's data and proposed the Noise Pollution Level (NPL). This environmental noise rating procedure is derived from L_{eq} by adding a correction term that is proportional to a measure of the extent of the variability in sound levels over time:

$$NPL = L_{eq} + k\sigma , \tag{4.2}$$

where

L_{eq} = the average sound level,

k = an empirically determined constant, and

σ = the standard deviation of the sound level about the mean value, as shown in the following equation

$$\sigma = \left[\frac{1}{T}\int_0^T [L(t) - \bar{L}]^2 dt\right]^{1/2} , \tag{4.3}$$

where

$$\bar{L} = \frac{1}{T}\int_0^T L(t)dt. \tag{4.4}$$

Robinson argues that, unlike the Traffic Noise Index (TNI), which also takes the range of variability of levels into account, the Noise Pollution Level applies to a variety of environmental noises. Robinson [53] suggested using the value k = 2.56; with this choice, NPL = L_{eq} + (L_{10} - L_{90}) for a Gaussian distribution of noise levels.

In a later paper, Robinson [52] suggested modifying the Noise Pollution Level. He pointed out that the use of a standard deviation that corresponds to a long integration time, T, is not reasonable, since people respond differently to short-, medium-, or long-term fluctuations in sound levels and the Noise Pollution Level does not take this into account. He suggested that σ be based primarily upon sound level fluctuations having durations of approximately one minute with fluctuations having longer and shorter durations being given less weight. No validation for this modified version of the Noise Pollution Level has been published.

In 1971, Muller [79] suggested that the rate of change of a time-varying signal is an important factor in terms of human response. He pointed out that none of the previously-existing rating schemes accounted for this parameter. Accordingly, he proposed a new descriptor based upon the equivalent sound level, plus a correction term that is a function of the root-mean-square value of the rate of change of sound level with time:

$$L_{eq}' = L_{eq} + f(\sigma') , \tag{4.5}$$

where

$$\sigma' = \left[\frac{1}{T}\int_0^T (dL/dt)^2 dt\right]^{1/2} , \tag{4.6}$$

in which dL/dt is the rate of change in the A-weighted sound level with respect to time.

Muller [79] proposed that f(σ') be tentatively defined as:

$$f(\sigma') = 10 \log_{10}(1 + 15\sigma') , \qquad (4.7)$$

which implies that a doubling of an already large σ' will increase f(σ') by 3dB.

More recently Matschat, Müller and Zimmermann [80] argued that, in the development of a general noise index, both the rate of change of level with time and the differential sensitivity of people to short-, medium-, or long-term fluctuations of the noise levels must be accounted for. Accordingly, they introduced a new general descriptor, L_B, which is described in the appendix. A particular case of this general descriptor is

$$L_B = k \log_{10}\left\{\frac{1}{T}\int_0^T \left[1 + \tau^{*2}(dL/dt)^2\right] 10^{L(t)/k} dt\right\}, \qquad (4.8)$$

where

L(t) = weighted noise level at time t (typically A-weighting is used),

T = period of time over which the levels are averaged,

k = an empirically determined constant,

τ^* = "time constant which determines the limit beyond which rates of change of the level, dL/dt, contribute significantly to the noise index value."

On the basis of data from an aircraft noise survey, Matschat, et al. suggest that τ^* be of the order of 0.5 s. For eq. (4.8), this means that rates of change of level on the order of 1-2 dB/s, or higher, contribute significantly to L_B.

Bennerhult, Lundquist, Nilsson, and Voigt [81] have proposed a new noise index -- the Fluctuation Level, L_{fl}. This general noise index is also purported to account for the sensitivity of people to modulation of noise signals. It is defined as follows:

$$L_{fl} = 20 \log_{10}\left[\frac{1}{T}\int_0^T |p(t)|^k dt\right]^{1/k} + C \log_{10}(FR), \qquad (4.9)$$

where

p(t) = A-weighted sound pressure, as a function of time, normalized by dividing by the reference sound pressure of 20 μPa,

T = the duration of the time sequence studied,

k = a constant, empirically determined,

C = a constant, empirically determined,

FR = a rating number related to the frequency-weighted Fourier transform of the A-weighted time history.

The leading term on the right hand side of eq. (4.9) is an equivalent sound level, and can be put in the form of eq. (4.1) by noting that $|p(t)|^2 = 10^{L(t)/10}$ and k = 20/K. The second term in eq. (4.9) is a correction intended to account for amplitude fluctuation in the A-weighted time history. It is obtained by a frequency analysis of the detected (or squared and low-pass filtered) A-weighted sound pressure and comparing the resulting curve of spectrum level versus frequency (0.01 to 10 Hz), with a series of rating curves (see fig. 2) derived from laboratory studies of human perception of amplitude-modulated signals.

The noise indices discussed above have been developed as tools for characterizing environmental noise. They are essentially independent of the noise source, and are expressed in terms that are purported to be relevant to human response.

Matschat, et al. [80] argue that in order for a noise index to be used as a general purpose index for time-varying noise, it must meet a specific requirement for consistency: "the noise index for the total reference time period remains unchanged if the noise exposure L(t) within a sub-interval of the reference time period is replaced by an equally annoying exposure (i.e., an exposure having the same index value for that sub-interval)." The Noise Pollution Level, L_{eq}', and indices such as the Traffic Noise Index do not meet the requirement postulated by Matschat, et al. On the other hand, L_{eq}, L_B, and the statistical descriptors (i.e., L_{10}, L_{50}, etc.) do fulfill this consistency criterion. It may be argued, however, that the necessity for the consistency requirement postulated by Matschat, et al. has not been established. Conceivably, the same noise presented at different times could produce different adverse responses, depending upon the preceding noise exposures and the conditions of a particular situation. If this were indeed the case, then the consistency requirement may not be a necessary condition.

4.2 Differences in Predicted Annoyance as a Function of the Environmental Noise Descriptor Used

Each of the general noise ratings discussed above emphasizes different aspects of time-varying noise. Thus the predictions of human adverse response given by each descriptor are generally different. L_{eq} is based on the idea that the adverse response increases as the average sound level increases. Use of both the Noise Pollution Level, NPL, and Traffic Noise Index, TNI, is based on the assumption that the general human response to noise grows with the average sound level, as well as with increases in the extent of the variability in the noise levels. However, neither L_{eq}, NPL, nor TNI differentiates among noises differing in their rate of fluctuation as opposed to their extent. Independent of whether one noise has rapid fluctuations in noise level and another has

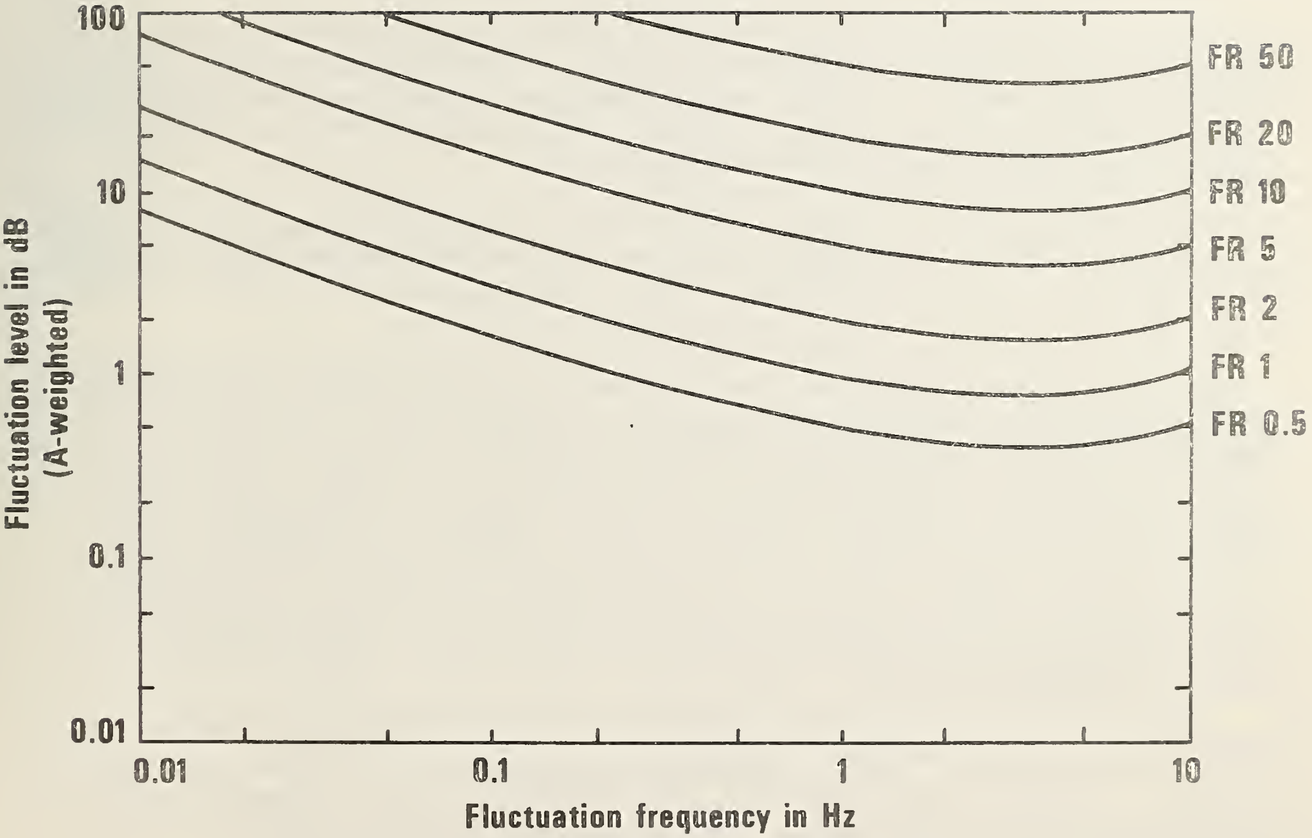

Figure 2. Rating curves for the perception of noise fluctuations for fluctuation frequencies between .01 and 10 Hz, as proposed by Bennerhult, et al. [82].

slow fluctuations, if both noises have the same average sound level and equal overall variability, the ratings for the two noises would be identical if L_{eq}, NPL or TNI were used to rate them.

The two time-derivative-based indices, L_{eq}' and L_B, were proposed with the goal of taking the rate of change in levels into consideration. Each rating scale increases as a function of both the rate of change in noise level and the average sound level of the noise. They differ, however, in the way in which the rate of change is handled in the computations. Accordingly, the two indices yield different predictions of human response and are not equally sensitive to various rates of change in levels. The Fluctuation Level, L_{fl}, [81] was proposed to account for human sensitivity to amplitude modulation, but this is dependent upon the frequency of modulation. Accordingly, different noises will be rated differently depending upon the frequency of modulation of the noise. Similarly, the modified NPL also differentiates among noises, depending on the frequency at which a particular noise fluctuates.

4.3 Relationship Between Predicted and Measured Annoyance

In several studies [27,39,41,42,54,81,84,87] both data available in the literature and new experimental data were used to compare predictions based on several indices (in particular, L_{eq}, NPL, L_{eq}', L_B and L_{fl}) to subjective responses measured by jury tests. A brief description of these experiments and a comparison of the results are presented below.

Rice required subjects to listen to aircraft [39] and traffic noise [27] while performing a task. Upon completion of the task, and following noise exposures lasting 25 minutes to one hour, the subjects were asked to fill out a questionnaire designed to assess their feelings about the noises.

In a review article prepared by the International Organization for Standardization [82], several noise ratings computed from previously published data were compared to subjective responses obtained in studies reported by the Society of Automotive Engineers (SAE) [83] and by Voigt [84]. In the SAE study [83], jury data were collected by having subjects adjust the level of a "pseudo-flyover signal" until it was equal in annoyance to 60 seconds of a recorded aircraft flyover. In the Voigt study [84], subjects were exposed to 12-minute segments of traffic noises differing in rate of fluctuation. Following each exposure, subjects were asked to rate the annoyance of the noise. From these data an annoyance rating was derived.

Bennerhult, et al. [81] exposed subjects to the same set of nine traffic noises used in the Voigt [84] study, and derived an annoyance scale from the subjects' judgments. Andrew and May [54] presented traffic noises to subjects while also presenting a taped radio program. The subjects judged the annoyance of the traffic noises. From these data an annoyance scale was derived.

In other studies of traffic noise, Jacobsen [41] had subjects rate the annoyance caused by 45-minute samples of traffic noise and Rasmussen [85] had subjects rate 30-minute samples of simulated traffic noise. Powell [42] exposed subjects to combinations of aircraft flyover and backgrounds of traffic noise. Subjects were asked to rate the annoyance of these mixed aircraft and traffic noises after exposures of 15 minutes.

The correlation coefficients between human response data and expected responses, based on various noise indices explored in the studies described above, are summarized in table 6. It is seen that L_{eq} had the highest correlation coefficient in five of the nine studies. The exceptions were the ISO recalculations [82] of the SAE data [83], in which the correlation coefficient for L_B was highest, the Bennerhult, et al. study [81], in which L_{eq} and L_{f1} were about equally high, the Jacobsen [41] study in which L_{eq} and L_{eq}' were equal, and the Rasmussen [85] study where all correlations were high. In seven of the eight relevant studies the Noise Pollution Level, NPL, had the lowest correlation coefficient, although in the aircraft studies of Rice [27,39] it still compared favorably to L_{eq}, as it did in the Rasmussen [85] study of simulated traffic. (It should be noted that the correlations reported for L_{eq} and NPL in the ISO study of Voigt's data were not recalculated, but were taken directly from Voigt's original study [84].)

The two time-derivative based indices, L_{eq}' and L_B, do approximately as well as L_{eq} and the other indices; in one case L_B had a higher correlation coefficient than L_{eq} when predicting jury ratings of noise annoyance [83]. However, given the increased complexity involved when using L_{eq}' or L_B, one would want to see the predictive abilities of these indices established more firmly before adopting either one for general use. The data base available for evaluating either index is still scant. Similarly, in the one test of L_{f1} [81], both L_{eq} and L_{f1} predicted human response very well, and little improvement appeared to be obtained by the increased complexity of the L_{f1} index.

The relationship between laboratory-measured annoyance and predictions based on the several indices is high as seen in table 6. However, several factors could contribute to a better understanding of the relationship between annoyance and noise. These include defining the dose-response relationship between annoyance and the number of discrete noise events [27,37,39,40], determining the effect of background noises on the response to the overall noise environment [10,33,42,58-60], indicating the role of the activity of the respondent as a modulator of annoyance [3,4,6,8,9,13,23-25,45,49,50,55,61], and determining the dose-response relationship between annoyance and the rate and amount of fluctuation in noise level [20,21,27,39,43-45,54-57]. Research that increases the knowledge about any of these topics could improve the ability to predict adverse response from physical measurements of time-varying noise.

Table 6. Correlation Coefficients Observed Between Measured and Predicted Average General Adverse Response to Noise as a Function of Noise Descriptor*.

Study	Type of Noise Source or System	Noise Descriptor				
		L_{eq}	NPL	L_{eq}'	L_B	L_{f1}
ISO-SAE [85]	Aircraft	$.79^{+}$	$.54^{+}$	$.77^{+}$	$.84^{+}$	---
ISO-Voigt [82]	Traffic	.98	.79	.96	.95	---
Rice [39]	Aircraft	.95	.92	---	---	---
Rice [27]	Aircraft	.97	.93	---	---	---
	Traffic	.94	.81	---	---	---
Andrew and May [54]	Traffic	.70	.63	---	---	---
Bennerhult, et al. [81]	Traffic	.98	---	---	---	.99
Jacobsen [41]	Traffic	.98	$.77^{\neq}$	.98	.98	---
Powell [42]	Aircraft & Traffic	.86	.62	---	---	---
Rasmussen [85]	Traffic	.94	.97	.93	.93	---

* All correlation coefficients shown are significant at the .001 level unless otherwise stated.

$^{+}$ Significant at the .01 level

$^{\neq}$ Significant at the .05 level.

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APPENDIX

This appendix contains a compilation of the calculation procedures for the noise rating indices included in the main text, and is intended to assist the reader in understanding these indices. It is not intended to be a compendium of all published rating indices nor a complete documentation of the noise ratings which are described.

In this appendix, $L(t)$ is the A-weighted sound pressure level as a function of time.

6.1. L_n (e.g., L_1, L_{10}, L_{50}, L_{90}, L_{99}) [6-1].* L_n is the A-weighted sound level re 20 μPa, in decibels, exceeded n percent of the time, where

$$n = 1,\ 10,\ 50.... \quad (6.1.1)$$

6.2. Traffic Noise Index (TNI) [6-2].

$$\mathrm{TNI} = L_{90} + 4(L_{10}-L_{90})-30. \quad (6.2.1)$$

6.3. Average Sound Level (L_{eq}) [6-1].

$$L_{eq} = 10 \log_{10}\left[\frac{1}{T}\int_0^T 10^{L(t)/10}dt\right], \quad (6.3.1)$$

where T is the total time of observation and $L(t)$ is the A-weighted sound level at time t.

6.4. Stör Index ($\bar{Q}$) [6-3].

$$\bar{Q} = 13.3 \log_{10}\left[\frac{1}{T}\int_0^T 10^{L(t)/13.3}dt\right], \quad (6.4.1)$$

where T and $L(t)$ are as in eq. (6.3.1).

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*Numbers in brackets refer to the references presented at the end of the appendix.

6.5. Day-Night Average Sound Level (L_{dn}) [6-1].

$$L_{dn} = 10 \log_{10}\left\{\frac{15}{24}\left[10^{(L_d/10)}\right] + \frac{9}{24}\left[10^{(L_n+10)/10}\right]\right\}, \quad (6.5.1)$$

where L_d is the average sound level (L_{eq}) for the daytime period (i.e., 0700-2200 hours) and L_n is the average sound level for the nighttime period (i.e., 2200-0700 hours).

6.6. Noise Pollution Level (NPL) [6-4].

$$NPL = L_{eq} + k\sigma , \quad (6.6.1)$$

where L_{eq} is as in eq. (6.3.1), σ is the standard deviation of the population of A-weighted sound levels observed during the period of observation, and k is an empirical constant selected to be 2.56.

6.7. Modified Noise Pollution Level (Mod-NPL) [6-5].

$$NPL = L_{eq} + ks , \quad (6.7.1)$$

where k is an empirical constant, L_{eq} is as in eq. (6.3.1), and s is a standard deviation computed from

$$s = \left\{\frac{1}{T}\int_0^T\left[\frac{1}{\tau}\int_t^{t+\tau}(L_p-\bar{L}_p)^2dt\right]dt\right\}^{1/2}, \quad (6.7.2)$$

where T is the total observation time, τ is an averaging time of the order of 5 min,

$$\bar{L}_p = \frac{1}{\tau}\int_t^{t+\tau} L_p dt , \quad (6.7.3)$$

and

$$L_p = 10 \log\left[\frac{1}{\Delta t}\int_t^{t+\Delta t} 10^{L(t)/10}dt\right], \quad (6.7.4)$$

where Δt is an averaging time of the order of 5 s.

The integration in eq. (6.7.4) averages out components with fluctuation frequencies larger than about 0.03 Hz. The expression in the curly brackets in eq. (6.7.2) corresponds to the variance, in the L_p values, over a period of about 5 min; it therefore discriminates against components with fluctuation frequencies less than about 0.0005 Hz. The modified standard deviation, s, is obtained from the average of this variance over the entire period of observation.

6.8. L'_{eq} [6-6].

$$L'_{eq} = L_{eq} + f(\sigma) \ , \tag{6.8.1}$$

where L_{eq} is as in eq. (6.3.1) and $f(\sigma')$ is a function of the root-mean-square value of dL/dt, the rate of change of sound level with time. That is,

$$\sigma' = \left[\frac{1}{T}\int_0^T (dL/dt)^2 dt\right]^{1/2} , \tag{6.8.2}$$

where T is the observation time.

Muller postulates that

$$f(\sigma') = A \log_{10}(1 + B\sigma') \ , \tag{6.8.3}$$

assumes A = 10, and takes B = 15.

6.9. L_B [6-7].

$$L_B = k \log_{10}\left[\frac{1}{T}\int_0^T p_B{}^2(t)dt\right], \tag{6.9.1}$$

where k is a constant, T is the observation time of observation, and

$$p_B(t) = \int_{-\infty}^{\infty} g(t-\tau)p(\tau)dt \ , \tag{6.9.2}$$

in which $p(t) = 10^{L(t)/2k}$ and g is the Fourier transform of a weighting function $G(\omega)$.

For $G(\omega) = 1$, $L_B \equiv L_{eq}$.

For $G(\omega) = 1 + i\omega\beta$, Matschat, et al. obtain

$$L_B = k \log_{10}\left\{\frac{1}{T}\int_0^T \left[1 + \tau^{*2}\left(\frac{dL}{dt}\right)^2\right] 10^{L(t)/k} dt\right\}, \tag{6.9.3}$$

where $\tau^* = (\beta/2k)\log_{10} 10$, "is a time constant which determines the limit beyond which rates of change of the level dL/dt contribute significantly to the noise index value," and is estimated to be about 10 to 25 s.

6.10. Fluctuation Level (L_{fl}) [6-8].

$$L_{fl} = \left(\frac{20}{k}\right)\log_{10}\left[\frac{1}{T}\int_0^T 10^{kL(t)/20} dt\right] + C \log_{10}(FR), \tag{6.10.1}$$

where k and C are constants and FR is the "Fluctuation Rating," obtained by frequency analysis of the history of sound levels and comparisons of the resultant spectrum to a family of rating curves.

If k = 2, the leading term in eq. (6.10.1) becomes the average sound level, L_{eq}.

Bennerhult, et al. adjusted the values of k and C to optimize the agreement with subjective response data.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report summarizes the literature dealing with the adverse response of people to time-varying noise, and identifies both the acoustical and non-acoustical factors that influence the relationship between time-varying noise and annoyance. An examination of the laboratory research concerned with the functional relationship between annoyance and the temporal and acoustic parameters of noise shows the tenuousness of such relationships. The adequacy of currently used and/or proposed rating procedures for predicting subjective response to time-varying noise is examined. Critical gaps in current knowledge are identified.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

duration; general adverse effect of noise; intermittency; loudness; noise criteria; time-varying noise

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