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A theory of patterns of passby noise

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Abstract

Some people say they are annoyed by traffic noise. There is rather a lot of evidence to show that where traffic noise is louder, more people say they are annoyed by it. On the basis of this sort of evidence, there is a consensus that road traffic noise causes annoyance, but some studies have detected unexplained peaks of annoyance in quieter places, or a plateau of annoyance in high noise. Such anomalies may especially affect those sensitive to noise. The pattern of alternation of passby noise and background traffic noise explains the positioning in soundspace of anomalies variously reported at 60 dB(A) L_{eq}, 4000 NV and 1800 NHV. Such anomalies occur where there are regular or rapidly alternating patterns of passby noise.

1. Introduction

The noise hypothesis [1] says that traffic noise loudness is the causal agent of the effects of traffic noise. Because decibels are so closely related to traffic volume (flow or density) and its logarithm, these are alternative measures of the causal agent. The consensus is that, with traffic noise measured in decibels, and traffic noise annoyance measured as the rate or frequency of people annoyed, traffic noise causes traffic noise annoyance [2–4]. Schultz' meta-analysis [5] of a substantial number of surveys of annoyance about noise from aerial and surface transport in several countries shows that traffic noise annoyance, measured as proportion of people highly annoyed, is consistently predictable as a monotonically increasing function of loudness, or more strictly L_{10}. However, for all that the analysis upon which Schultz' result is based shows a highly consistent trend of increasing traffic noise annoyance with increasing decibels, there is yet plenty

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of variation around the mean trend and, in regard of noise measurements and interpretation, two criticisms have been levelled at Schultz by Kryter [6, see also 7,8].

Despite the criticism (see below), the upshot of Schultz [5] is the widespread acceptance of L_{10} as the best predictor of traffic noise annoyance. Other measures in use tend to fall into two categories, expressed as sound energy (loudness, intensity or power) or noise events. The peak loudness is not known to be related to any other statistical level [9] but, because of the logarithmic nature of loudness, there is necessarily a correlation between the number of loud events and the overall energy. Consequently, there is some degree of positive correlation between energy and event measures. This paper aims to develop a quantitative theory to account for observations of non-positive relationships between traffic noise and human response.

The development begins with the criticisms of Kryter [6], to illustrate the room for manoeuvre left by Schultz [5], before focussing upon some observations of anomalous response describing non-linear relationships with L_{eq}, daily traffic volume NV and daily heavy vehicle volume NHV. The points of inflection in these relationships are shown to be related via passby duration, allowing an extension of traffic theory to account for the observed non-linearities. The new theory introduces several measures describing the alternation of passby noise and background noise. Two of these measures define an axis deviating significantly from the collinear axes of L_{eq}, L_{10} and counts. The two measures maximize at medium traffic volumes and therefore the theory allows low response from groups exposed to low or high volumes.

This theoretical result, explaining as it does some observed anomalous responses, raises the possibility that there is a second, biologically important axis of noise.

2. Non-increasing responses

In regard of noise measurements, Schultz' [5] meta-analysis reduces aircraft noise measurements couched in L_{eq} and noise-and-number index to L_{dn} ("L day and night", essentially L_{eq} with a 10 dB penalty added for night-time noise). Kryter [6] believes the calculations to be biased by some 5 dB, with L_{dn} overestimated by that amount. Also, the criteria for inclusion of studies in Schultz' meta-analysis depend upon the identifiability of a "highly annoyed" group of respondents. Kryter argues that the selection of surface noise studies for inclusion biases the surface noise result by some -5 dB, underestimating L_{dn}. Thus, where Schultz assumes that the degree of annoyance is independent of the noise source and dependent only upon noise measured by L_{dn}, Kryter finds evidence to show that aircraft noise is more annoying than road noise. Interestingly, a test conducted at that time [10] agrees with Kryter. In consequence, Schultz' curve may underestimate annoyance from aircraft noise and overestimate annoyance from road noise.

In regard of Schultz' interpretation, Kryter suggests that the percentage highly annoyed figure is misleading for two reasons. Firstly, there is a percentage of people who respond with high annoyance even at very low values of noise. Kryter suggests this group exhibiting high annoyance in very low noise provides an estimate of the number of people who respond with high annoyance regardless of the level of noise, and that this percentage should be subtracted from the highly annoyed response at each level of noise. Thus, Schultz overestimates the truly varying percentage highly annoyed. Second, Kryter notes that there is plenty of evidence that the percentage expressing any given level of annoyance increases with increasing noise, so the resort to percentage highly annoyed as a single figure measure of the true situation significantly underestimates the impact of noise in the community.

Although Schultz' result is "the curve which has become the most widely accepted description of the relationship between annoyance and noise level" [11], the theory reported here is motivated by three studies that have generated observations not contemplated by the orthodox noise hypothesis. These observations have inspired hypotheses which seek to explain non-increasing trends of response to increasing noise. One moots a possible physical basis [12], another resorts to psycho-social explanation [13, see also 1,14,4]. The three studies give details about instances of worse health in lower noise or non-increasing ill-health in higher noise: anomalies in terms of the noise hypothesis.

Firstly, an Australian main roads study [12] finds a non-increasing trend of annoyance about noise at the low end of main road noise exposures. Brown's study of noise in the three eastern state capitals (Brisbane, Sydney and Melbourne) focussed on traffic noise annoyance response along freely flowing roads carrying 4000 or more vehicles per day with L_{10} (18 h) ranging from 63 to 80 dB. The study mostly confirms the noise hypothesis. On the basis of linear regressions on group scores, traffic noise annoyance rises as noise rises. A qualification, exposed by fitting a quadratic, is a non-linear, negative trend at the lowest densities—the overall response falls from 63 to 68dB, before the 68-plus dB trend climbs [12, pp. 115–119 and Figs. 6.1 and 6.3]. Brown's synthesis of the three city results speculates that "at low flow rates (say less than 4000 vehicles per day), a noise event inside a dwelling may not be the passage of a heavy vehicle heard over the prevailing traffic noise levels, but the passage of an automobile heard above the ambient noise levels" [12, p. 129]. Thus, there may be more than one maximum in the noise spectrum.

Second, Bjorkman's north European study [15] of freely flowing and congested urban truck routes finds a peak of annoyance about truck noise at a flow of 1800 NHV, with higher flows, ranging up to 10 000 NHV, occasioning no increase in annoyance. The response increases up to some 1800 trucks per day, at which point the response flattens, and even diminishes slightly as volumes increase further. Bjorkman displays the result graphically as two line segments.

Third, a Welsh study [13] finds that psychological distress among people sensitive to noise peaks at medium noise exposures of approximately 60 dB(A) L_{eq}. Stansfeld embedded this study of sensitivity, road traffic noise annoyance and psychological health measured by GHQ within a pre-existing study of heart disease in 2000 middle-aged males. Traffic noise exposures were determined because traffic noise is a suspected risk factor for cardiovascular disease. Sensitivity to noise is determined by the Weinstein test, with subjects classified in three equal sized groups. Overall, the study confirms the noise hypothesis, but the results show the different response patterns of sensitives and tolerants, how the sensitives react most strongly in middle loudness. The study found a just significant association ($p = 0.05$) between sensitivity to noise and noise, "with less highly sensitive men in the noisiest areas. Given that sensitivity to noise is a stable trait this (is) unexpected … but selective migration could mean a tendency for noise sensitive men to move out, or not move into noisy areas" [13, p. 981]. This observation motivates the mobility hypothesis that the noise hypothesis is valid but is obscured in the case of sensitives by nett migration out of low- and high-noise zones. Up-noise migration by sensitives is presumably involuntary, down-noise migration is presumably voluntary. As sensitives are more prone to poor psychological health and road traffic noise annoyance at any level of noise, it is suggested that the mobile sensitives inflate morbidity in less than maximum road traffic noise.

Although these anomalies are expressed in different units (i.e., vehicles, trucks, decibels), they have something in common. A reliable prediction method [16] assures us that traffic flows of 4000 vehicles per day cause a traffic noise level of approximately 60 dB, and that there is no necessary correspondence between 1800 trucks per day and 60 dB. However, there is nothing in the prediction method to suggest whether 4000 vehicles per day and 1800 trucks per day have anything in common. The common factor would seem to be associated with the ratio of 4000 cars to 1800 trucks. What is it about a truck that is about twice as big as the corresponding feature of a car?

Vehicle passbys are audible for a certain amount of time: the passby duration. Pilot observations show that in open countryside, passbys are audible for longer than they are in urban environments, and that in urban environments, truck passbys are audible for about twice as long as are car passbys. Cars can be heard from kerbside for about 20 s and trucks can be heard for about 40 s. Now,

$$\begin{aligned}40\text{ s truck duration} \times \text{(say) } 2000 \text{ trucks per day} &= 20\text{ s car duration} \times 4000 \text{ cars per day}\\ &= 80\,000\text{ s.}\end{aligned}$$

This observation yields two inferences. Firstly, flows of 4000 vehicles per day and 1800 trucks per day seem to be related through taking the product of flow rate and passby duration. Taking this together with the correspondence of 4000 NV with 60 dB relates all three of the anomalies of interest. Secondly, 80 000 s is approximately the number of seconds in a day (86 400). Thus 4000 cars or 2000 trucks which passed in succession so that each was just becoming audible when its predecessor became inaudible would fill up a whole day with (almost) continuous passby sound.

Of course, the real world is more complicated than that. Vehicles are not all the same and they do not pass at regular intervals, so a probabilistic theory is appropriate.

3. Patterns of passby noise

Fig. 1 shows a distribution of little black squares spread along an axis (Fig. 1a). At the left-hand end, the little squares are far apart; if the axis is time, then the squares are infrequent, or sparse, as in Fig. 1d. At the right-hand end, the squares occur so frequently that they overlap almost all the time; there is only the occasional gap. The gaps occur less frequently than in the rapid alternation of Fig. 1f. The gaps are not white squares, they are white gaps or background amongst overlapping black squares. In the middle of the axis, the squares are regularly spaced (Fig. 1e). Just to the right of middle, they alternate as frequently as possible (Fig. 1f). Such patterns may be described through an extension of traffic density theory.

The Poisson distribution is the basis of the simplest model of traffic densities. To extend the Poisson approach from rates to headways, the times between vehicles, it suffices to calculate the probability of no vehicles arriving in periods of varying lengths [17]. The likelihood of observing a headway of longer than a given period decreases monotonically as the traffic volume rises, and as longer headways are sought. As the traffic density rises, headways become shorter. On high-density roads, the average period for which a vehicle may be heard and identified is of approximately the same period as the average headway, each vehicle is heard when the preceding vehicle gets out of the way and ceases to be heard when the succeeding vehicle dominates. As the

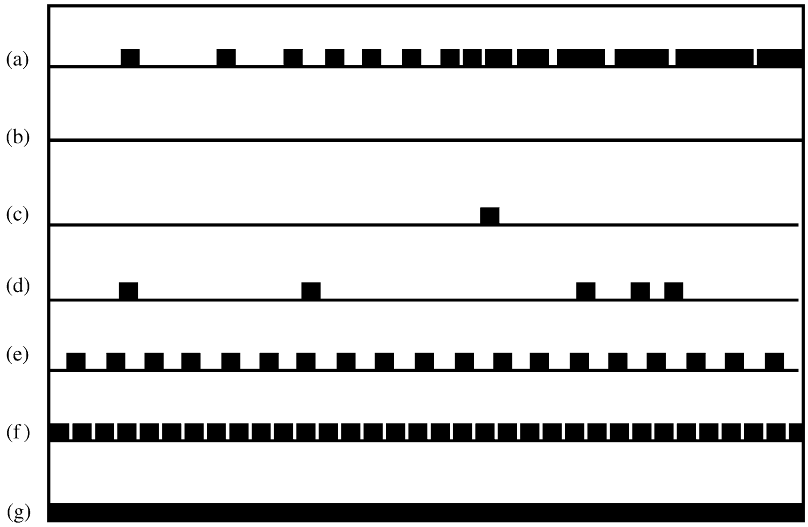

Fig. 1. One-dimensional patterns: (a) template, (b) background, (c) single element or motif, (d) sparse, (e) regular, (f) rapid alternation, and (g) continuous.

density falls, headways increase, until periods occur when no passbys are audible. In such periods the traffic noise background arises from distant roads, or at least from distant traffic. Thus, in low-density environments, when background sound brackets each vehicle passby, the passby duration is easily defined. One simply stands by the road, waits for an approaching vehicle, and measures the time elapsing from when noise definitely emanating from the vehicle can be distinguished until the sound of the vehicle can no longer be identified. This situation occurs relatively frequently in the hinterland of local streets, but infrequently on high-density roads, such as freeways and main roads. In high-density environments, passby duration is approximated by the duration of the most isolated vehicles.

The headway distribution can be extended to predict the distribution of audibility of passbys and background sound. The probability P of passby sound being audible is just

$$P = 1 - \mathrm{e}^{-\rho d},$$

where ρ is the mean time density and d is the mean passby duration. Defining a lull to be a period when no passby can be distinguished from background, a period of passby silence so to speak, when only background sound will be heard, then the probability of a lull is

$$1 - P = \mathrm{e}^{-\rho d}.$$

The rate ρ_p at which passby sound occurs (which is equal to the rate at which lulls occur) may be found from the distribution of headways longer than passby durations:

$$\rho_p = \rho \mathrm{e}^{-\rho d}.$$

For example, for a location at which passby duration is 20 s, Fig. 2 shows the mean daily rate of occurrence of lulls as a function of daily traffic density. The horizontal axis shows daily traffic

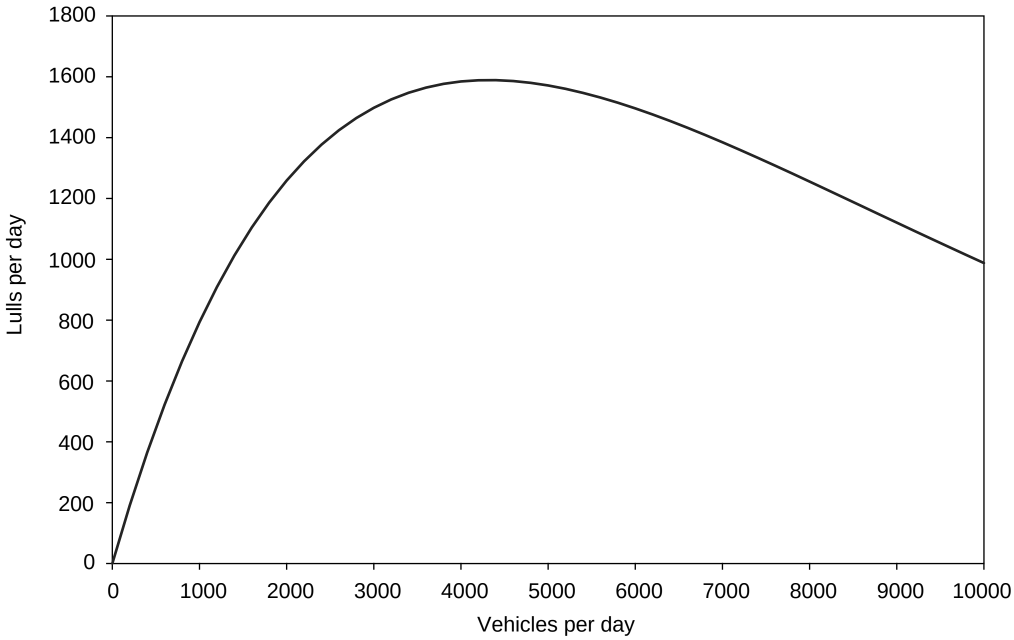

Fig. 2. Rate of lulls as a function of traffic density, when duration is 20 s.

flow. The vertical axis shows the rate at which lulls may be expected to occur on the basis of the Poisson assumptions. The most obvious feature of the lull distribution is the occurrence of a maximum rate of lulls at a traffic density of 4300 vehicles per day, equivalent to approximately 60 dB(A) [16]. The rate of lulls is 0.0184, yielding a lull every 50 s on average. For a duration of 40 s, the maximum would shift to approximately 2200 (heavy!) vehicles per day, with a lull every 110 s on average.

The reason for the occurrence of a maximum depends not just on the rate, but also on the length of lulls. If there is no traffic, then there is one, long, continuous lull. The intrusion of one vehicle interrupts this lull, making two lulls. The extent of each extra vehicle may overlap with the extents of other vehicles, shortening a lull but leaving the number of lulls unchanged, or it may interrupt a lull, increasing the number of lulls by one. As the density rises, the lulls become more numerous and shorter. Eventually, as the maximum rate of lulls is approached, it becomes likely that an extra vehicle will completely fill a lull. In that case the number of lulls decreases by one. Relative to the maximum rate of lulls, for lower traffic densities there are fewer lulls which are longer, and for higher traffic densities there are fewer lulls, which are shorter.

Fig. 3 shows what happens as the passby duration increases. The right front axis shows daily traffic density. The left front axis shows passby durations increasing from 1 s at left to 20 s on the right. The vertical axis shows the daily rate of lulls, which is the same as the rate of passby sound. The graph serves to make clear the trend of rates of lulls. The maximum observed in the previous figure is again clearly visible. However, this graph displays two other features of the lull distribution. Firstly, as passby duration increases, the rate of lulls decreases: ρ_p is monotonic in d. Second, as passby duration increases, there is a decrease in the density at which the maximum rate

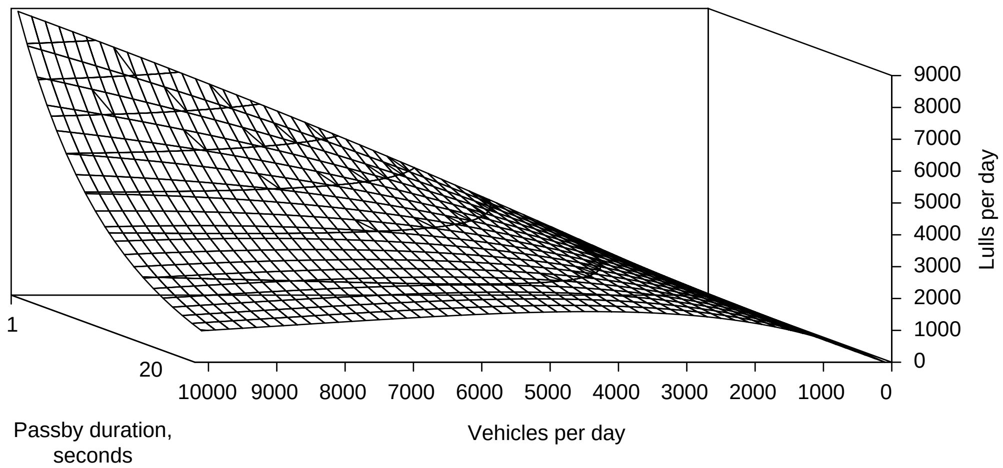

Fig. 3. Rate of lulls as a function of passby duration and traffic density.

of lulls occurs. These effects share the same fundamental reason: longer durations fill up more lulls more quickly than do short durations.

That this is a three-dimensional graph with a curvilinear maximum implies that passby noise is not merely a matter of rates, but also of pattern. Near the maximum, passbys and lulls tend to alternate rapidly. Away from the maximum, either passbys or lulls occupy most of the available time. Thus, two different locations may share the same rate of passbys and lulls, but may display different patterns of alternation of passby sound and lulls, because one location is on or near the maximum and the other is not. In environments with longer durations, a lesser traffic time density (i.e., fewer passbys) is necessary to generate the maximum rate of alternation. In environments with shorter durations, a greater traffic time density is necessary to generate the maximum rate of alternation. Near the maximum the soundscape varies most rapidly between passbys and background. Thus, a crude measure Π of the pattern of alternation of passby sound and lulls for given mean duration and traffic density may be constructed as the quotient of the observed (mean) rate of passby sound above background and the maximum rate of passby sound for that passby duration.

$$\Pi = \rho_p/\rho_{p,max},$$

where $\rho_{p,\,\mathrm{max}}$ is obtained when

$$\mathrm{d}/\mathrm{d}\rho(\rho_p) = 0,$$

which occurs when $\rho d = 1$, and thus

$$\Pi = \rho d \mathrm{e}^{1-\rho d}.$$

This development yields formulae for the probability of lulls, $1-P$, the rate of lulls ρ_p, and the pattern of lulls Π, as functions of traffic density and passby duration.

Thus, on a first approximation assuming the Poisson arrivals, a pattern constructed of identical elements distributed upon a uniform background as suggested in Fig. 1 is described by three variables:

P is the probability of black, which in Fig. 1a varies from zero for a pattern constructed by replicating the white segment from the left-hand end of the line (Fig. 1b) to 1 for a pattern constructed by replicating the black segment chosen from the right-hand end of the line (Fig. 1g). $1-P$ is the probability of white, which varies oppositely. Thus P increases monotonically from Fig. 1b–g.

ρ_p is the density of black segments. Note that this is not the black square density, nor the probability of black; it is equal to the density of transitions from black to white, which equals the density of transitions from white to black. ρ_p is a maximum when black squares are so close together that they almost overlap, as in Fig. 1f. As more black squares are added to Fig. 1f, so that white segments are overlaid, the value of ρ_p falls. Thus, ρ_p attains a maximum to the right of centre of Fig. 1a.

Π is the pattern of alternation of black/white. Π varies from zero at the ends of the Fig. 1a (strictly for no black squares as in Fig. 1b, or continuously overlapped black squares as in Fig. 1g) to 1 just right of centre of Fig. 1a, where black and white alternate as frequently as possible, as in Fig. 1f. Π normalizes the rate of alternation of a pattern, given the motif.

If passby duration is a meaningful concept in urban terrains, then by analogy with Fig. 1a, the pattern of alternation of passbys and background sound which corresponds to 4000 NV, 60 dB or 1800 NHV is something like that to the right of the middle of the axis, where ρ_p is maximal and $\Pi = 1$ (Fig. 1f). This would correspond to (the probabilistic equivalent of) a situation where there is a rapidly alternating or just discontinuous stream of passby sound, where the sounds of successive passbys are punctuated by an instantaneous return to background. Variation in the development could shift the maximum of a redefined Π to the pattern of Fig. 1e, corresponding to a regular alternation of passby and background sound.

4. Discussion

The three studies present localized non-increasing responses to increasing noise. In each case the value of a traffic noise variable is measured, attaching non-increasing response to a point in the broader spectrum of traffic noise. In the context of each study, the departure from monotonicity is an anomaly in the more-is-worse, linear noise hypothesis under test. In context, the departures are by definition random noise injected by untested variables. But pattern is an untested variable which predicts a maximum approximately coincident with the onset of non-increasing response in each case. Such a non-random variable saps the statistical assumption of independence of errors. The truth of these anomalies may be better approximated by some combination of conventional and pattern variables. However, there are difficulties in application and interpretation of a pattern hypothesis. Clearly, the major difficulty in application is the lack of an objective measure of passby duration. Even where there is such a measure, a combined analysis of conventional and pattern variables would suffer from the positive correlation of conventional and pattern variables in low noise.

Even though the peaks in rate ρ_p and degree Π of pattern are putatively associated with the 4000 NV [12], 1800 NHV [15] and ~60 dB [13] anomalous annoyance and sensitives' psychological distress observed in the three studies [18], there is a spread of interpretations. There seem to be three ways in which the role of the variables may be important. They may affect the way we think about the measurement of noise, the measurement of response to noise, or the relationship between noise and response to noise.

Firstly, there is an implication that loudness, or density, or statistical levels based upon loudness, are partial measures of noise characteristics. There is nothing new in this observation. Pattern variables merely suggest how the definition of noise may be extended to quantify the to-date qualitative notions of continuity and intermittency of noise. Generally, the theory describes noise functions with maxima occurring at middle densities determined by characteristic audible durations. Thus, such maxima may differ between vehicles and heavy vehicles, and between different forms of transport. In particular, the theory lends support to Brown's [12] suspicion that at low energies/decibels the sound of a car above ambient may be the operational factor in annoyance causation.

Secondly, there is an implication that the usual questions about traffic noise annoyance may mean different things to different people. Some subjects may interpret traffic noise to mean the number or loudness of audible vehicles, while others may understand it to mean the frequency or pattern of change between background and passing traffic, whether single vehicles or platoons. In relation to the different physical maxima, the heretofore simple question of the form analysed by Schultz [5] is ambiguous. The single question fails to distinguish between the alternative physical stimuli. The result is a response curve plotted on too few axes.

Finally, with regard to the three peak responses reported at 4000 NV, 1800 NHV and ~60 dB(A), and especially because the results of Stansfeld et al. [13] deal with complicated distress and distinguish carefully between subgroups of the sensitivity spectrum, it is possible that there is a causal relationship between the pattern of application of noise and the psychological state of at least some individuals. Most importantly, it is no longer safe to assume that systematic anomalous responses in middle decibels are unrelated to noise. In particular, sensitives' response is possibly related to the patterned aspect of the soundscape.

Despite the difficulties of measurement and analysis and the spread of interpretations, the pattern theory erects a candidate hypothesis in competition with psychosocial explanations of anomalies in medium noise [1,11,13,14]. Thus, assuming that passby duration is a meaningful concept in urban terrains, the conclusion of this work is that there is some evidence, from three studies, to suggest that studies of the noise hypothesis may be biased or confounded by non-recognition of pattern effects. Noise and responses to noise, its effects, may be non-monotonic in the interval contemplated for testing the orthodox hypothesis.

So, the theory described here introduces a new noise hypothesis: the pattern hypothesis. New axes defined by ρ_p or Π quantify the continuity or intermittency of noise. Unlike vehicle and heavy vehicle counts, the new axes measure the rate of alternation of passby and background sounds. Unlike L_{10} and L_{eq}, the new axes count episodes of noise and establish the distribution of noise in time. Thus, the new axes are not everywhere collinear with the bundle of energy and event count axes, so that subjects in high noise and low pattern may exhibit lesser responses than subjects in middle noise and higher pattern. In particular, the pattern hypothesis may explain why subjects experiencing high levels of patterning of noise yield anomalous responses such as are observed in the three studies, responses maximizing at or near 4000 NV, 2000 NHV and 60 dB(A)L_{eq}.

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