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Effects of noise on pedestrians in urban environments where road traffic is the main source of sound

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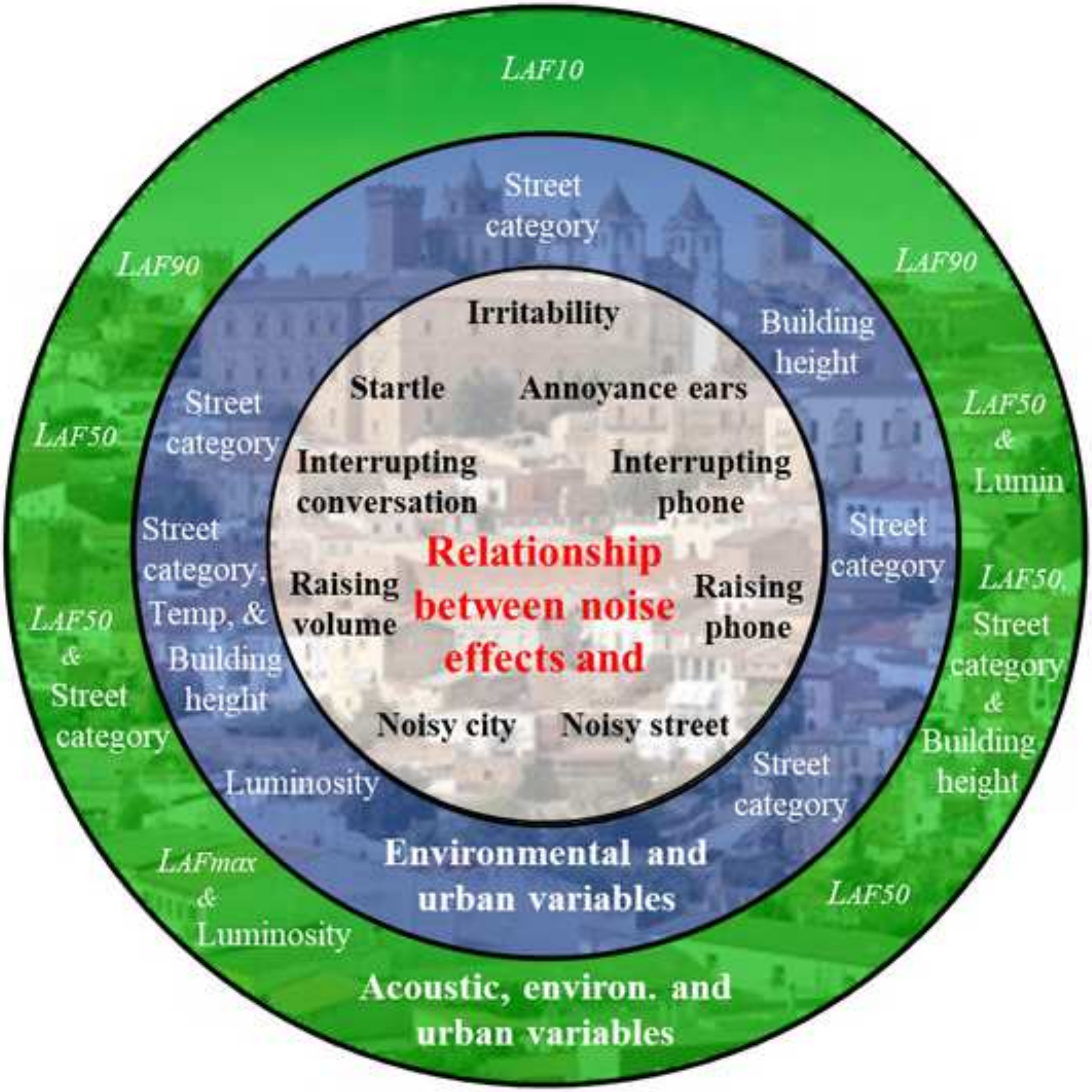
Abstract:	Research combining the measurement of objective variables with surveys of people's perception of noise on city streets is useful in terms of understanding the impact of urban noise on the population and improving the environment. Although previous investigations have analysed the factors that may influence the noise annoyance of citizens, it is usually considered as a global aspect. This paper presents research based on in situ surveys and objective variables (urban, meteorological and noise indicators) to evaluate some specific effects of noise on pedestrians in urban environments where road traffic is the main source of sound. The results show significant relationships of the effects of noise and perceptions of how noisy urban environments are with variables such as building height, road category and temperature, with correlation coefficients ranging from 0.37 to 0.64. Significant correlations between these subjective variables and the acoustic variables were also found, with explanations of variability that reached values of up to 50%. A multivariate analysis revealed that both urban variables (especially the category of street) and environmental variables can be an alternative or a complement to models predicting the effects and perception of environmental noise based only on acoustic variables.
Response to Reviewers:	Reviewers/Editor comments: Reviewer #1: Comment No. 1: After the authors have made corrections and additions, the quality of the article is much better and in my opinion it is suitable for publication. Response to Reviewer #1 comment No. 1: The authors would like to thank the reviewer for the comment. Reviewer #2: Comment No. 1: Authors' response regarding only 105 (sample size) responses/people surveyed does not seems feasible to me. This is very small sample size for a study having 29 locations. It means that only 3 to 4 people/respondents participated in the survey at each selected location. How response of such a small sample can represent the opinion/view of the major/entire population of a city? Authors must state clearly that how many people were surveyed at each selected location? Response to Reviewer #2 comment No. 1: The authors understand the reviewer's concern about the representativeness of a sample of 105 individuals. For this reason, the authors showed in the previous version of the article that the tests they are using (bivariate correlations and multiple regressions) are sufficiently powerful for a sample of 105 individuals. Also, they showed that taking into account the population of Cáceres (96,000 inhabitants approximately) and the variability recorded in previous studies, the error is 0.5 (lines 143-148 in the new version of the manuscript). Indeed, when this study was planned, the aim was to conduct more than 105 surveys. But the declaration of a state of alert due to COVID-19 stopped the study for about 2 years and

Graphical Abstract



Highlights

- Increase in some noise effects perceived by pedestrians with building height
- Significant negative correlation between temperature and some noise effects
- Good explanations of the variability of noise effects from some acoustic variables
- Urban-environmental models to significantly explain the perception of noise effects
- Categorisation method could help to predict noise effects on pedestrians in cities

Effects of noise on pedestrians in urban environments where road traffic is the main source of sound

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ABSTRACT

Research combining the measurement of objective variables with surveys of people's perception of noise on city streets is useful in terms of understanding the impact of urban noise on the population and improving the environment. Although previous investigations have analysed the factors that may influence the noise annoyance of citizens, it is usually considered as a global aspect. This paper presents research based on *in situ* surveys and objective variables (urban, meteorological and noise indicators) to evaluate some specific effects of noise on pedestrians in urban environments where road traffic is the main source of sound. The results show significant relationships of the effects of noise and perceptions of how noisy urban environments are with variables such as building height, road category and temperature, with correlation coefficients ranging from 0.37 to 0.64. Significant correlations between these subjective variables and the acoustic variables were also found, with explanations of variability that reached values of up to 50%. A multivariate analysis revealed that both urban variables (especially the category of street)

and environmental variables can be an alternative or a complement to models predicting the effects and perception of environmental noise based only on acoustic variables.

Keywords: effects of noise, noise annoyance, road traffic noise, *in situ* survey, urban variables, environmental variables.

1. INTRODUCTION

Environmental noise pollution in urban contexts is one of the challenges facing society today, mainly due to its impact on human health and well-being (*EEA*, 2020). Infrastructures for the transport of people and goods are considered to be the main source of noise in this type of environment. In fact, transport noise has become the second most important environmental source of ill health in Europe, after fine particulate matter pollution (*WHO*, 2018). Recent research keeps pointing out a close relationship between traffic noise and different types of diseases and health disorders such as anxiety (Lan et al., 2020) (Hegewald et al., 2020), depression and psychological problems (Eze et al., 2020) (Baudin et al., 2018), obesity (Cai et al., 2020) (Foraster et al., 2018), hypertension and cardiovascular risk (Baudin et al., 2020) (Khosravipour and Khanlari, 2020), annoyance and sleep disorders (Paiva et al., 2019) (Basner and McGuire, 2018), and metabolic diseases (Huang et al., 2020) (Thiesse et al., 2018). Traffic noise is not an isolated issue, and is associated with other aspects such as urban planning (Renterghem et al., 2020) (Barrigón Morillas et al., 2021b) (Yuan et al., 2019), air quality (Silva and Mendes, 2012), socio-economic factors (Xu et al., 2020) (Tong and Kang, 2021) and weather conditions (Guan et al., 2020) (Sánchez-Fernández et al., 2021).

The study of environmental noise levels in cities using the noise indicators for day (L_d), evening (L_e), night (L_n) and day-evening-night (L_{den}) established in the European Noise Directive (*END*, 2002) is often carried out by means of strategic noise maps considering the different sources of noise (Ozkurt et al., 2014) (Paschalidou et al., 2019) (Hinze et al., 2022) and following the guidelines of international guidelines and standards (*WG-AEN*, 2007) (*ISO 1996-2*, 2017). In the specific case of road traffic noise, which is considered to be the main source of environmental noise (*EEA*, 2014), simulations using commercial software are carried out for this purpose taking into account different variables such as vehicle flow (Ascari et al., 2015) (Fiedler and Zannin, 2015), sound power (Barrigón Morillas et al., 2021), vehicle speed (Ögren et al., 2018), and the characteristics of the façades (Calleri et al., 2018). These noise models are validated through long- and short-term *in situ* measurements (Zagubień and Wolniewicz, 2021) (Montes González et al., 2020a) (Aletta et al., 2020) that follow different sampling strategies (Quintero et al., 2019) (Gómez Escobar et al., 2012a) and measurement procedures (Montes González et al., 2020b) (*ANSI S12.18*, 1994). Based on the results of noise maps for the exposure of the population to noise pollution, action plans for the mitigation of environmental noise are then designed (Ögren et al., 2018) (Vázquez et al., 2016). In addition, initiatives related to urban planning that focus on the development and promotion of quiet areas have been proposed in the scientific literature to try to make these types of environments more pleasant for the resident population and to improve the sense of well-being (Calleja et al., 2017) (Rey Gozalo et al., 2019) (Vogiatzis and Remy, 2017) (Hong et al., 2020).

However, there is a growing tendency to complement this type of research based on objective noise indices with studies that allow us to obtain an assessment of people's satisfaction with the sound quality of urban spaces (Koprowska et al., 2018) (Youssoufi et al., 2020) (Aletta et al., 2018). The concept of sound quality can be understood as the degree of adequacy of the acoustic characteristics of a space to the activities carried out in the area. In this regard, conducting surveys on city streets is an approach that provides interesting information for an analysis of the degree of satisfaction and annoyance of residents, not only in relation to the sound environment but also to other features such as cleanliness, air quality, aesthetics of the environment, odours, etc. (Lionello et al., 2020) (Engel et al., 2020) (Jiang et al., 2016) (Ba and Kang, 2019).

Noise indicators such as L_{Aeq}, L_{AFmin}, L_{AFmax} y L_N are commonly used in environmental noise studies (Paszkowski et al., 2018) (Maristany et al., 2016). The effects of noise are generally measured based on indicators that take the equivalent A-weighted sound level as a reference (*WHO*, 2011) (*ISO 1996-2*, 2017) (*END*, 2002), although the maximum sound level is also considered in this regard (*WHO*, 2018). The relationships between objective acoustic indices and subjective variables related to the effects of noise in cities can be studied in order to analyse which aspects can influence annoyance of citizens and their preferences for the use of urban spaces (Bouzid et al., 2020) (Van Gerven et al., 2009) (Estévez-Mauriz et al., 2018) (Ma et al., 2021), so that these can be taken into consideration by urban planners at the design stage. Most previous research has only assessed the overall effect of noise in terms of annoyance, but a consideration of more specific aspects of the effects of noise on people may also be of interest. In addition, it is also interesting to analyse the influence of environmental and urban variables on the perception or effects of noise in the same way as was done with physical characteristics of sound and people-related factors (Ouis, 2001).

This paper presents the results of research carried out by means of *in situ* surveys and measurements in Cáceres (Spain) to assess the effects of noise on people in urban environments in which road traffic is the main sound source and to study its relationships with urban, environmental and acoustic variables.

2. METHODOLOGY

2.1 Survey, sampling and data collection procedure

The methodology followed in this study was based on a process of *in situ* surveys and measurements, carried out simultaneously by four people in the streets of Cáceres (Spain), in which values of both subjective and objective variables were collected. This study was carried out on working days (Monday to Friday) in the time period from 9 a.m. to 7 p.m, during the year 2020 (January and February) before the COVID-19 alarm state. The sampling points were randomly selected on urban roads with different functionality for vehicle mobility. Thus, they were sampled from main city streets, Category 1, used for connection to other cities or interconnection of preferred streets, to Category 5 streets corresponding to residential neighbourhood streets (Barrigón Morillas et al., 2021). The objective was to sample different urban settings with variability in urban and environmental characteristics. For this purpose, 29 different locations were sampled in the city of Cáceres as shown in Figure 1.

Figure 1. Locations of the surveys and measuring points in Cáceres (from Google Earth)

The design of the survey was approved by the ethics and bioethics committee of the University of Extremadura (37//2020), and an informed consent form was filled out by each participant in each survey, according to the Declaration of Helsinki. The effects of environmental noise on people walking down the street was the dimension assessed in the survey using nine questions. An 11-point numerical scale was used for each question (where 0 was "not at all" and 10 "extremely"). The points on this numerical scale are equally spaced and therefore provides a justification for treating the data as continuous in statistical tests (ISO/TS 15666, 2021). This type of scale is more suitable for linear regression analysis (Brink et al., 2016). The 11-point numerical scale is recommended by the International Standardisation Organisation (ISO/TS 15666, 2021) and used in current studies (Brink et al., 2019) (Schäffer et al., 2020) because it also has advantages over verbal scales in its comprehension by people of different nationalities (Fields et al., 2001). Face-to-face was the method used for data collection in the survey. Any evidence of hearing loss detected by the interviewer during the presentation or conduct of the survey led to the exclusion of the responses obtained. In the first seven questions related to effect of noise (see Table 1), respondents were asked to what extent or how often the environmental noise in that street causes them: a) irritability; b) startle; c) annoyance in the ears; d) interrupting a conversation with someone nearby; e) raising the volume of their voice to speak with someone nearby; f) interrupting a phone conversation; and g) raising the volume of their voice on a phone conversation. Respondents were also asked to rate their perceptions of the environment was h) in the city in general; and i) on that particular street. Other demographic characteristics were also collected: age, sex and level of education.

Different aspects have been considered to justify the representativeness of the sample size. Fritz and Mackinnon (Fritz and MacKinnon, 2007) point out the importance of having sample sizes necessary for 0.8 power for the tests to be used. Therefore, the appropriate sample size for correlation and multiple linear regression was determined using G*Power software (Kang, 2021). It was deduced that 100 people were required for a power of 0.95 and a medium effect size according to Cohen (Cohen, 1988). On the other hand, Nunnally (Nunnally, 1978) and Thorndike (Thorndike, 1982) recommend a sample size 10 times the number of items. The present study had 9 items; therefore, the recommended sample would be 90 subjects. However, Kline (Kline, 1994) suggests sampling at least 100 subjects when the number of items is low. Finally, taking into account the number of inhabitants of the city of Cáceres and the variability in the scores registered in preliminary studies ($\sigma \approx 2.8$), the estimate of the population mean for a sample size of 105 subjects would give an error of 0.5 (Rodríguez del Águila and

González-Ramírez, 2014). This error is not high and is similar to the standard error of the mean that would be obtained in the study. A total of 105 people were surveyed (44% of whom were male and 56% female, aged between 17 and 80, with education from primary to university level) despite the low response rate (25%) and the termination of the study due to COVID's state alarm. A similar number of surveys were completed at each sampling point.

It is not unusual to find previous studies with a sample size similar to this study. Fritz and Mackinnon (Fritz and MacKinnon, 2007) show results from a review of the survey literature where more than 50% of the studies have a sample size of less than 200. Douglas (Douglas and Murphy, 2016), Van Reterghem (Van Renterghem and Botteldooren, 2012), Pirrera (Pirrera et al., 2014), Tao (Tao et al., 2020) and Paiva (Paiva et al., 2019) carried out survey studies in highly populated urban areas with a similar number of surveys to show the representativeness of the overall perception in the city where each survey was conducted at a different point/household.

Table 1. Subjective and objective variables registered in the city of Cáceres

Variables			**Meaning**	**Value range**
Subjective variables (survey)		**a)**	Irritability	0 – 10
		b)	Startle	0 – 10
		c)	Annoyance ears	0 – 10
		d)	Interrupting conversation	0 – 10
		e)	Raising volume	0 – 10
		f)	Interrupting phone	0 – 10
		g)	Raising phone	0 – 10
		h)	Noisy city	0 – 10
		i)	Noisy street	0 – 10
Objective variables	**Urban**	**L**	Street length	85 – 1000 m
		W	Street width	9 – 40 m
		H	Average buildings height	0 – 27 m

	H/W	Relationship between building height and street width	0 – 1.6
	SC	Street category	1 – 5
Environ.	**T**	Temperature	9 – 23 ºC
	RH	Relative humidity	19 – 95 %
	AP	Air pressure	1000 – 1013 hPa
	WS	Wind speed	0 – 3.5 m/s
	LU	Luminosity	1 – 94 klux
Acoustic	L_{Aeq}	A-weighted equivalent sound level	48 – 73 dB
	L_{AFmax}	A-weighted maximum sound level	70 – 89 dB
	L_{AF10}	A-weighted 10th percentile sound level	47 – 77 dB
	L_{AF50}	A-weighted 50th percentile sound level	40 – 70 dB
	L_{AF90}	A-weighted 90th percentile sound level	37 – 60 dB

The objective variables were classified into three different groups (see Table 1) and were collected both through a GIS database of Cáceres and with visual inspection on site simultaneously with the surveys. First, a set of urban variables associated with the features of the street were registered, such as the length (L) and width (W) of the street, the average height of the buildings (H), the relationship between building height and street width (H/W), and the category of street (SC). The streets were classified into the following categories (Barrigón Morillas et al., 2021):

- Category 1: Preferential streets for connection with other towns and interconnection of those preferential streets.
- Category 2: Streets that provide access to major distribution nodes in a town or are used as an alternative to category 1 during traffic saturation.
- Category 3: Streets that lead to regional roads, streets that provide access from street categories 1 and 2 to centres of interest in a town (hospitals, shopping malls, etc.), and streets that clearly allow communication between street categories 1 and 2.

- Category 4: All of the other streets that clearly allow communication between the three previously defined types and the principal streets in a town’s different districts that were not included in the previously defined categories.
- Category 5: The rest of a town’s streets except traffic-restricted streets.

Next, a group of variables related to environmental conditions were registered. The temperature (T), relative humidity (RH) and air pressure (AP) were measured at microphone height by a portable weather station, and monitoring was carried out to ensure that the wind speed (WS) did not exceed 5 m/s. The luminosity (LU) at each measuring point was also logged using a luxmeter. Considering that indicated in the Weber-Fechner Law (Dehaene, 2003) (Reichl et al., 2010), the logarithm of luminosity (logLU) was considered to study its relationship with the effects of noise.

Finally, different sound indicators were measured using a type 1 analyser, including the A-weighted equivalent sound level (L_{Aeq}), the maximum sound level (L_{AFmax}) and the percentile levels (L_{10}, L_{50} and L_{90}). For this purpose, a type 1 sound level meter-analyser was used, and the microphone was placed 1.5 m above the ground and at a similar distance (2 m from the nearest point of the sound source) from the main sound source of road traffic (Montes González et al., 2020b). Fifteen minutes sound measurements were made avoiding placing the microphone on reflective surfaces (Montes González et al., 2018). If the microphone was placed at a distance between 0.5 and 2 m from the building façade, a correction of -3 dB was applied following the recommendations of ISO 1996-2 (*ISO 1996-2*, 2017; Montes González et al., 2020a). A verification of the calibration before and after each series of measurements was carried out using a type 1 sound calibrator. The sound measurements were carried out simultaneously with the surveys as indicated above. The researcher conducting the sound measurements was separated at a sufficient distance so that the sound levels registered were not influenced by the interviewers. At least one sound measurement was performed at each sampling point. In addition, sound sources were registered during the measurements. Road traffic was the main noise source with a significant presence at the different sampling points. In fact, total traffic flow explained 83% of the variability of L_{Aeq} (dB).

2.2 Statistical analysis

The average values of the objective and subjective variables registered in the measurements performed at each sampling point (N=29) were used in the subsequent descriptive and inferential analyses. The responses obtained at each sampling point were averaged considering different aspects. The urban variables are static and the environmental and noise variables presented a low variability at each sampling point (see Figure 2 in the Supplementary Material). The responses given to each subjective variable also presented a stable and low variability at each sampling point as shown in Figure 1 in the Supplementary Material. Therefore, similar results are obtained in the per-survey and per-point correlation analyses as shown in Tables 1, 2, 3 and 4. However, the analysis by surveys does not meet the premises of normality, homoscedasticity and linearity (an expected result given the no or low variability of the objective variables) leading to a loss of test power (non-parametric tests have lower power) and the impossibility of performing bivariate and multivariate linear regression analyses. Furthermore, considering the difference in the number of respondents between the different points and the fact that the variability of the variables is due to their different locations, a treatment by surveys would bias the results towards those points with a greater number of surveys.

A descriptive analysis of the average values and their deviation was carried out with the subjective variables, i.e., those related to the effects of noise. This descriptive analysis was complemented by a comparative study of the mean values using the *t*-test. Parametric tests were used since the variables met the assumptions of normality, homoscedasticity and linearity. Next, an analysis of the relationships between the objective and subjective variables was carried out. First, the significance of the relationship between the two types of variables was analysed using Pearson's correlation coefficient, except for the "street category" variable, where Spearman's correlation coefficient was used, given its ordinal nature. Next, a bivariate regression analysis was carried out for those variables that showed a significant correlation. Finally, only those variables that did not show collinearity (variance inflation factor < 5) and which contributed to a significant increase in the explanation of the subjective variables were included in the multivariate regression models. Stepwise regression and the Bayesian information criterion (BIC) were used to choose the best performing model.

3. RESULTS AND DISCUSSION

This section presents an analysis of the results obtained for the effects of noise on people and the relationships between the subjective and objective variables, and is organised into subsections corresponding to the different groups defined for the objective variables.

3.1. Noise and its effects

As a starting point, Figure 2 shows the mean and the error in the mean for the responses obtained in all the streets surveyed for questions a) to i) described in Section 2 in relation to the effects of noise on people. Figure 2 reveals that the only noise effects with mean values of above 3 were irritability (3.6) and startle (3.3). Around the mean value of 3 were the effects of annoyance in the ears (2.9) and raising the volume in a conversation, either with someone present in the environment (3.0) or talking on the telephone (2.8). Below these values, around a mean value of 2.5, the effects of interrupting a conversation were found, with a value of 2.6 when face-to-face and 2.5 on the phone. Although a statistical analysis using *t*-test only showed the existence of significant differences ($p < 0.05$) between the effect of irritability and the effects of interrupting a conversation face-to-face or on the phone, the existence of a consistency can be considered in the mean results. It can be observed for example that for both means of communication, the effect of raising the volume of the voice reaches higher mean values than that of interrupting a conversation.

When analysing the values for the participants' perceptions of how noisy is the city or street in which the survey was conducted, it can be noted that the city was rated at a value of 5.5, that is, above the average value of the employed scale. While the street was rated at 4.8, very close to the average value of the scale. If comparing these results for the noise perception of an environment with the values obtained for the specific effects of noise, it can be found that there is a significant increase in the average values. In fact, a statistical analysis using *t*-test revealed significant differences in both values of the perception with respect to all the values of the effects. For "noisy city", a significant difference with $p < 0.001$ was found in all cases. While for "noisy street", a significant difference with $p < 0.05$ was obtained for irritability and startle and $p < 0.001$ for the others. No significant differences were detected between "noisy city" and "noisy street".

Given that this study considered a number of specific noise effects, it was difficult to find previous research in the scientific literature that treated these effects in the same way in order to establish a direct comparison and discussion. In the particular case of annoyance, some authors have reported ratings of the general perception of noise annoyance that would somehow cover all the specific noise effects addressed in the present study (Öhrström et al., 2006) (Gómez Escobar et al., 2012b). Taking this into account, it would be expected that in general, the rating of overall perceived annoyance in similar urban environments would be higher than for each of the effects analysed separately. Other research also analysed the annoyance perceived by people in green areas and urban parks considering various types of sound sources, and distinctions have been drawn, for example, between annoyance caused by construction, screams, animals and road traffic (Rey Gozalo et al., 2019).

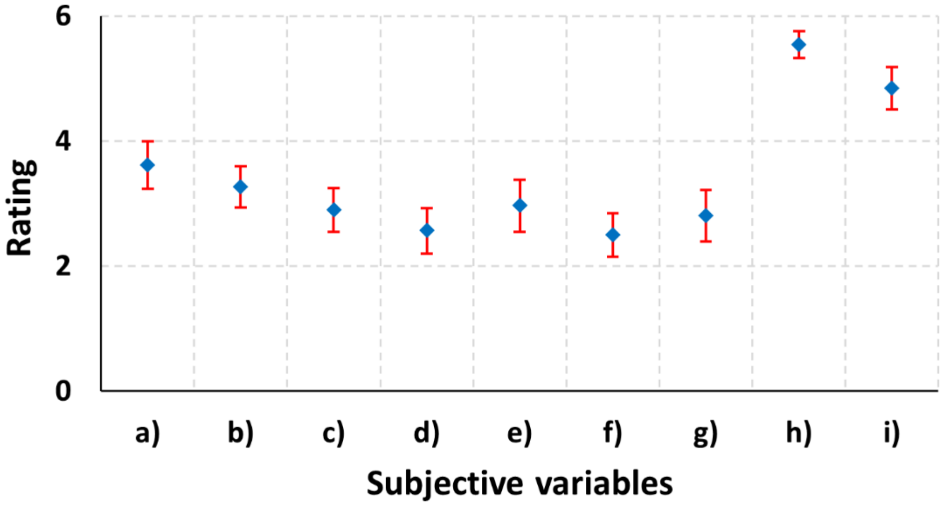

Figure 2. Mean and standard error of the ratings given for all the streets surveyed for the subjective variables related to effects of noise on people.

3.2. Analysis of the relationships between subjective and objective variables

The outcomes obtained from the analysis of the correlations between subjective and objective variables are shown in Table 2. With regard to the urban variables, only two of the variables considered in this group (average building height and street category) showed significant correlations with the subjective variables related to noise and its effects. The L, W, and H/W did not show any significant correlation with the subjective variables ($p > 0.05$). Both urban variables (H and SC) differ in the number of subjective variables with which they have significant relationships and in the intensity of these relationships. While the height variable is strictly geometric, the street category is based on the functionality of the street as a means of communication. According to the results reported in previous studies, road categories significantly stratify noise, so that noise values decrease from Categories 1 to 5 (Barrigón Morillas et al., 2021). The subjective variables analysed here with respect to the effects and perception of noise show a significant negative correlation with respect to the road category, except for items c) and h) . The degree of association between the type of road and the subjective variables related to raising the voice showed associations with a degree of significance of less than 0.001, which are comparable to those found for the noise indicators. Concerning the environmental variables, the temperature showed the greatest number of significant relationships with the answers given by the respondents. In addition, the variables of atmospheric pressure and luminosity showed only one significant relationship, in these cases with the perception of how noisy the environment was in the street and city, respectively. The RH and WS did not show any significant correlation with the subjective variables ($p > 0.05$). Finally, the acoustic variables generally showed significant negative relationships with all or almost all of the subjective variables studied with a greater or smaller degree of association. This indicates that, as expected, there is a close relationship between the sound indicators and the effects of noise. It can be noted that the L_{Aeq}, L_{AF10} and L_{AF50} indicators are associated with all the subjective variables analysed here; the L_{AF90} indicator is associated with almost all of them, while L_{AFMax} is the indicator that shows the weakest relationship with the subjective variables.

Table 2. Correlation coefficient between objective and subjective variables

		Subjective variables								
		a)	**b)**	**c)**	**d)**	**e)**	**f)**	**g)**	**h)**	**i)**
Urban variables	**H (m)**	0.37^{*}	0.41^{*}	0.44^{*}	$0.19^{\text{n.s.}}$	$0.08^{\text{n.s.}}$	$0.02^{\text{n.s.}}$	$0.02^{\text{n.s.}}$	$-0.13^{\text{n.s.}}$	0.41^{*}
	SC	-0.44^{**}	-0.48^{**}	$-0.20^{\text{n.s.}}$	-0.62^{***}	-0.58^{***}	-0.49^{**}	-0.64^{***}	$-0.29^{\text{n.s.}}$	-0.53^{**}
Environ. variables	**T (ºC)**	-0.41^{*}	-0.39^{*}	$-0.32^{\text{n.s.}}$	-0.43^{*}	-0.48^{**}	$-0.18^{\text{n.s.}}$	$-0.32^{\text{n.s.}}$	0.43^{*}	-0.44^{*}
	AP (hPa)	$-0.30^{\text{n.s.}}$	$-0.23^{\text{n.s.}}$	$-0.26^{\text{n.s.}}$	$-0.11^{\text{n.s.}}$	$-0.24^{\text{n.s.}}$	$-0.13^{\text{n.s.}}$	$-0.22^{\text{n.s.}}$	$0.09^{\text{n.s.}}$	-0.38^{*}
	logLU	$-0.21^{\text{n.s.}}$	$-0.32^{\text{n.s.}}$	$-0.22^{\text{n.s.}}$	$-0.06^{\text{n.s.}}$	$-0.32^{\text{n.s.}}$	$0.12^{\text{n.s.}}$	$-0.13^{\text{n.s.}}$	0.52^{**}	$-0.29^{\text{n.s.}}$

Acoustic variables	**L_{Aeq} (dB)**	0.69^{***}	0.61^{***}	0.46^{*}	0.63^{***}	0.65^{***}	0.54^{**}	0.64^{***}	-0.38^{*}	0.63^{***}
	L_{AFmax} (dB)	0.57^{**}	0.41^{*}	$0.26^{\text{n.s.}}$	0.44^{*}	0.50^{**}	$0.28^{\text{n.s.}}$	0.42^{*}	-0.50^{**}	0.47^{*}
	L_{AF10} (dB)	0.71^{***}	0.66^{***}	0.49^{**}	0.62^{***}	0.65^{***}	0.54^{**}	0.63^{***}	-0.38^{*}	0.64^{***}
	L_{AF50} (dB)	0.71^{***}	0.69^{***}	0.59^{***}	0.66^{***}	0.70^{***}	0.60^{***}	0.69^{***}	-0.38^{*}	0.66^{***}
	L_{AF90} (dB)	0.64^{***}	0.71^{***}	0.66^{***}	0.61^{***}	0.64^{***}	0.57^{**}	0.62^{***}	$-0.30^{\text{n.s.}}$	0.64^{***}

$^{\text{n.s.}}$ Non-significant correlation ($p > 0.05$).
* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.001$.

3.2.1. Urban variables

Table 3 shows the values of the different parameters of the regression analysis between the subjective variables and the average building height (H) that showed a significant correlation in Table 2. The values of this independent variable ranged between 0 and 27 m for the studied streets as shown in Table 1.

Table 3. Regression parameters among all subjective variables and the objective urban variable of average building height (H)

		Subjective variables			
		a)	**b)**	**c)**	**i)**
Average building height (H)	**Slope**	0.11	0.11	0.13	0.11
	Intercept	1.83	1.55	0.92	3.09
	Determination coefficient	0.14^{*}	0.17^{*}	0.20^{*}	0.17^{*}

* Significant at $p \leq 0.05$.

When the results obtained for average building height (H) are analysed, it is possible to see that this variable can explain between 14% and 20% of the variation in the subjective variables related to the effects of noise on the population in urban environments, such as irritability (14%), startle (17%), annoyance in the ears (20%) and the perception of how noisy the street is (17%). Considering results obtained in previous studies, the explanation of the variability of subjective variables by the predictor H is not low. It should be noted that these previous studies used multiple predictor variables and acoustic variables. This study has the novelty of analysing the perception of specific noise effects and the specific contribution of predictor variables based on urban and environmental features. Average building height and other building characteristics are also used as independent variables to predict noise annoyance in multivariate models. Although these models may have a better explanation of the variability than the one obtained in this study, it must be considered that they are models with many independent variables. Preisendörfer et al. (Preisendörfer et al., 2022) obtain explanations of the variability for road traffic annoyance between 23% and 31% using multivariate models that include 17 factors, including some related to building characteristics. Another recent study obtained a McFadden's pseudo r-squared value of 0.263 for the multivariate noise annoyance model including seven independent variables (Chung et al., 2022).

Table 3 also shows that most the values of the slope coefficient for the four subjective variables are similar and positive; that is, the noise effects related to these variables that respondents report to perceive increase as the average height of the buildings increases. When the average building height (H) rises from the minimum to the maximum values of the range studied here (0–27 m), irritability (a) ranges between 1.8 and 4.8; startle (b) increases from 1.6 to 4.5; annoyance in the ears (c) rises from 0.9 to 4.4; and the perception of how noisy the street is i) increases from 3.1 to 6.1. Although the maximum height of the streets under evaluation was 27 m, corresponding to buildings of approximately nine storeys, there are large cities in which the height of buildings is greater than this. It would therefore be interesting to continue this line of research by expanding the study to cities containing streets with larger average building heights.

3.2.2 Environmental variables

The results of the regression analysis between the subjective variables and the environmental variables with significant correlations in Table 2 are shown in Table 4. The values of the slope, intercept coefficient, coefficient of determination (R^2) and significance level are given for the variable of temperature (T). Since in the case of air pressure (AP) and luminosity (logLU), a significant correlation was only found for one of the subjective variables, the results are shown in Eq. 1 and Eq. 2 for air pressure (AP) and luminosity (logLU), respectively. The ranges of these independent variables were approximately 9–23 °C for temperature, 1000–1013 hPa for air pressure and 1–94 klux for luminosity as shown in Table 1.

Table 4. Regression parameters between the subjective variables and the environmental variable of temperature (T).

		Subjective variables					
		a)	**b)**	**d)**	**e)**	**h)**	**i)**
Temperature (T)	**Slope**	-0.22	-0.18	-0.22	-0.28	0.13	-0.21
	Intercept	6.83	5.93	5.78	7.05	3.6	7.94
	Determination coefficient	0.17^*	0.15^*	0.18^*	0.23^{**}	0.18^*	0.20^*

* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.

$$i = 211.82 - 0.21 \cdot AP\ (R^2 = 0.14) \quad \text{(Eq. 1)}$$

$$h = 44.31 + 1.58 \cdot logLU\ (R^2 = 0.27) \quad \text{(Eq. 2)}$$

Among the environmental variables in Table 2, temperature (T) shows significant relationships with several subjective variables such as a), b), d), e), h) and, i). In this regard, temperature can explain between 15% and 23% of the variability of these subjective variables. In contrast, the remaining two environmental variables only showed a significant relationship with one of the objective variables. This was the perception of how noisy the street is (i) for the case of air pressure (AP), which explained 14% of the variation, while for luminosity it was the perception of how noisy the city is (h), with a 27% explanation of its variation. If these results are compared with those of previous studies analysing the relationship between meteorological variables and noise annoyance from different sound sources, they are satisfactory. For example, Miedema et al. (Miedema et al., 2005) found a R^2 less than 0.19 but for multivariate models that did not only include meteorological variables. L_{den} (dB), aircraft and railway variables were also considered in the multivariate models. Only sound indicators show a high correlation with noise effects as shown in Table 2.

Regarding the variable of temperature (T), the values of the slope coefficient with respect to almost all of the correlated subjective variables were similar and had a negative sign, indicating that the values given by the respondents for the subjective variables decrease as the temperature increases. In contrast, a positive value was obtained for the subjective variable of perception of how noisy the city is (h). In the case of the significant relationship between air pressure (AP) and the perception of how noisy the street is (i), the slope coefficient was negative, meaning that the rating of this variable decreases as air pressure increases. However, for the relationship between luminosity (logLU) and the perception of how noisy the city is (i), this coefficient had a positive value. Hence, of the environmental variables considered, temperature showed the highest number of significant relationships with the different effects of noise and the perception of how noisy is the environment. The negative slope suggests that people may perceive the effects of noise as being of lower intensity in environments with softer temperatures.

Another aspect of interest in Table 4 is the analysis of the values of intercept coefficients. For the significant relationships of temperature and luminosity with the subjective variables, all values were positive and within the interval of the 0–10 rating scale used in the surveys. This gives an idea of the base value when temperature and luminosity tend to zero.

The values of the subjective variables resulting from applying these equations remained within the scale of 0–10 for ranges of approximately -9–25ºC for temperature, 983–1025 hPa for air pressure and 0–105 klux for luminosity. These ranges of environmental variables are wide and include a great range of environmental conditions in which these regression models could be considered valid.

3.2.3. Acoustic variables

The values for the different parameters of the regression analysis between the subjective dependent variables and the acoustic independent variables that showed significant correlation in Table 2 are presented in Table 5. For each of these five variables, that is the A-weighted equivalent sound level (L_{Aeq}), maximum sound level (L_{AFmax}) and percentile levels (L_{10}, L_{50} and L_{90}), the values of the slope, intercept, determination coefficient (R^2) and significance level are given. For the streets studied, these independent variables took values in the range 48–73 dBA for L_{Aeq}, 70–89 dBA for L_{AFmax}, 47–77 dBA for L_{10}, 40–70 dBA for L_{50} and 37–60 dBA for L_{90} as shown in Table 1.

Table 5. Regression parameters among all subjective variables and the objective acoustic variables L_{Aeq}, L_{AFmax}, L_{10}, L_{50} and L_{90}.

		Subjective variables								
		a)	**b)**	**c)**	**d)**	**e)**	**f)**	**g)**	**h)**	**i)**
L_{Aeq}	**Slope**	0.24	0.18	0.15	0.21	0.25	0.18	0.24	-0.08	0.20
	Intercept	-11.49	-8.24	-6.49	-10.61	-12.63	-8.43	-12.20	10.42	-7.54

	R^2	0.47***	0.37***	0.21*	0.39***	0.42***	0.29**	0.41***	0.15*	0.40***
L_{AFmax}	**Slope**	0.22	0.14	--	0.16	0.21	--	0.17	-0.11	0.16
	Intercept	-14.17	-7.98	--	-10.65	-14.16	--	-11.23	14.54	-8.17
	R^2	0.32**	0.17*	--	0.19*	0.25**	--	0.17*	0.25**	0.22*
L_{AF10}	**Slope**	0.20	0.16	0.13	0.17	0.20	0.14	0.19	-0.06	0.16
	Intercept	-9.60	-7.34	-5.59	-8.50	-10.21	-6.81	-9.78	9.62	-5.82
	R^2	0.50***	0.44***	0.24**	0.39***	0.42***	0.29**	0.40***	0.14*	0.42***
L_{AF50}	**Slope**	0.20	0.17	0.16	0.18	0.22	0.16	0.21	-0.06	0.17
	Intercept	-7.81	-6.29	-5.82	-7.55	-9.38	-6.37	-9.12	9.08	-4.68
	R^2	0.50***	0.47***	0.34***	0.43***	0.49***	0.36***	0.48***	0.15*	0.44***
L_{AF90}	**Slope**	0.22	0.21	0.21	0.20	0.24	0.18	0.23	--	0.19
	Intercept	-7.53	-7.31	-7.67	-7.59	-9.17	-6.65	-8.67	--	-5.03
	R^2	0.41***	0.50***	0.43***	0.37***	0.41***	0.33**	0.38***	--	0.41***

-- Non-significant correlation ($p > 0.05$).
* Significant at $p \leq 0.05$.
** Significant at $p \leq 0.01$.
*** Significant at $p \leq 0.001$.

Most of the relationships between the subjective variables related to the effects of noise on people and the acoustic variables are significant (Table 4). These relationships have a higher level of significance in the case of L_{Aeq}, L_{10}, L_{50} and L_{90}, which can explain up to 50% of the variation in some variables such as a) and b). The variation had a value of between 47% and 29% for the other effects of noise on the population, such as c), d), e), f), g), i). In the case of the acoustic variable L_{AFmax}, the results for the significant correlation explain variations in the subjective variables of between 32% and 17%. The explanations of the variability of the studied variables related to the effects of noise reach high values in the case of some acoustic variables taking into account that they are subjective variables. The L_{Aeq} is the indicator most commonly used in previous studies to study its relationship with noise annoyance. A Spearman´s rho less than 0.24 was found in the correlation between noise annoyance and L_{den} by Dzhambov et al. (Dzhambov et al., 2017) and Felcyn et al. (Felcyn et al., 2018). A similar value of Pearson's correlation coefficient (r = 0.26 - 0.30) was also found by Paviotti et al. (Paviotti and Vogiatzis, 2012) and Tao et al. (Tao et al., 2020). Therefore, the explanation of variability does not exceed 9% in these previous bivariate analyses. In multivariate studies using different sound indicators or combinations of them, R^2 values similar to those in this study are achieved (Nguyen et al., 2012) (Lee et al., 2021).

It is interesting to see how the capacity of the sound indices analysed here to explain the annoyance in the ears (c) increases as the value becomes more representative of the background noise level at the site. The L_{AFmax} index is not significant and L_{Aeq} is significant at 95%, while L_{AF50} and L_{AF90} are significant at 99.9%. The last of these explains the highest variability (43%). The statistical sound variables are therefore better than the energetic sound variables in this respect, in relation to the variable c). Note that the case of the variable b) is similar in terms of the explained variability, while the variable a) does not follow the same pattern. In the cases of the variables d), e), f), g), and i), the index L_{AF50} seems to be the best predictor of their variability, which is an indicator of average values over time. Finally, it is also interesting to note that that the capacity of the sound indices analysed to explain the variability of the perception of how noisy is the city (h) is low or not significant in all cases. It can be observed that L_{AF90} is not significant, while L_{AFmax} is significant at 99%, the only variable for which this is seen.

Another noteworthy point in relation to Table 5 is that for each acoustic variable, the slope of the linear regression equation is positive for all issues related to the effects of noise or the perception of the studied environment; that is, the value indicated by the respondents for the subjective variables increases as the sound indicators take on a higher value. However, this is not the case for the subjective variable perception of how noisy the city is (h), where the negative value of the slope reflects an inversely proportional linear relationship. The value of the subjective variables resulting from applying these equations remains within the scale 0–10 for a range of sound levels of approximately 51–87 dBA for L_{Aeq}, 68–101 dBA for L_{AFmax}, 52–98 dBA for L_{10}, 44–86 dBA for L_{50} and 39–

79 dBA for L_{90}. These ranges for the acoustic variables, over which the subjective variables remain within the scale used in the survey, cover a wide range of urban environments in which road traffic is the predominant source of noise, meaning that the linear equations obtained in this study relating the subjective variables to the acoustic variables could be considered valid for many other cities of different sizes.

3.3 Multivariate regression analysis

In addition to the bivariate regression analysis presented in the previous sections for each group of objective variables, a multivariate analysis was also carried out using stepwise regression. The street category (SC) was recoded as a dummy variable in order to include it as an independent variable in the regression analysis. Consequently, the five different street categories were grouped into main streets (Categories 1 to 3) and neighbourhood streets (Categories 4 and 5). Neighbourhood streets were considered as the reference level (value = 0) for this binary variable (SC_b).

Since Table 1 revealed that the acoustic variables are those that individually explained a higher percentage of the variability of the subjective variables related to the effects of environmental noise and the perception of noisy urban spaces, a stepwise regression was first proposed in this section considering only the urban and environmental variables. The aim was to study the extent to which combinations of these objective variables would allow for a prediction of the effects of environmental noise and its perception in urban environments with no need for *in situ* acoustic measurements and, therefore, reducing the production costs of carrying out this type of research associated with acoustic measurement equipment. Table 6 shows the results from the stepwise regression between the subjective variables and the urban and environmental variables, where *B* is the regression coefficient and R^2 (coefficient of determination) shows the percentage of explanation of the variability of the subjective variable.

Table 6. Regression parameters among the subjective variables and the urban and environmental variables.

Subjective variables	**Objective variables**	**Constant**	***B***	***R*²**
a)	SC_b	3.05	1.82	0.18
b)	SC_b	2.74	1.68	0.20
c)	H	0.92	0.13	0.20
d)	SC_b	1.85	2.29	0.30
e)	SC_b T H	8.83	2.82 -0.31 -0.13	0.63
f)	SC_b	1.87	1.98	0.25
g)	SC_b	1.85	3.08	0.44
h)	logLU	4.31	1.58	0.27
i)	SC_b	6.28	-2.08	0.29

Although all urban and environmental variables were initially considered in the multivariate regression analysis, the resulting models have only one independent variable in most cases (see Table 6). In this regard, bivariate models obtained from a stepwise regression, based essentially on urban variables, provide explanations of between 18% and 44% for the variability in the effects and the perception of environmental noise. This explanation of variability is similar to that provided by sound indicators for some effects (c: annoyance ears, and f: interrupting phone). It is also interesting to note the effect of the street category on the prediction of most of the subjective variables, which suggests that this categorisation method could also be useful for predicting the effects of environmental noise on people and their perceptions of noise in urban spaces.

Table 6 also reveals that in the case of the subjective variable raising the volume of the voice (e), models based on a combination of urban and environmental objective variables allow for a high explanation of its variability. For this noise effect, a model containing only the urban variable SC_b explains 45% of its variation. When combined in a multivariate model with an environmental variable such as temperature (T), a significant increase in explanation of up to 54% is found. Moreover, when the urban variable of average building height (H) is included, the explanation of the variability of raising volume (e) reaches a value of 63%. This percentage of variability is much higher than that found for any of the sound indicators shown in Table 5. Hence, reliable predictions for some variables related to the effects of environmental noise in urban environments can be obtained from a combination of urban and environmental variables, and this offers a possible alternative to models based on acoustic variables. In this context, the urban variable related to street geometry, i.e. the average building height (H), also showed a relationship with the perception of the sound environment (Prida et al., 2019).

After the analysis considering only the urban and environmental objective variables, a new multivariate regression analysis between the subjective variables and all the objective variables (urban, environmental and acoustic variables) was carried out. The hypothesis was to analyse whether the use of both urban and environmental variables could complement the predictions made by acoustic variables with respect to the effects and perceptions of noise. Thus, in addition to looking for possible alternative models containing only urban-environmental variables, the aim was also to develop models that complement the predictions made by the acoustic variables. The results presented in Table 7 show that for the variables: raising volume (e), interrupting phone (f), raising phone (g) and noisy city (h), the inclusion of urban and environmental variables improves the prediction. In these models, the acoustic index L_{AF50} provides an explanation of variability of 49% for raising volume (e), 36% for interrupting phone, and 48% for raising phone (g) (see Table 5), which increases to 59%, 48%, and 65%, respectively, with the variables

SC_b, logLU, and H. For the perception of how noisy is the city (h), a model is obtained in which the acoustic index L_{AFmax} explains 25% of its variability (see Table 5), reaching a value of 41% with the environmental variable luminosity (logLU). The percentage explanations for the variability of the different effects and perceptions of noise are high compared to results obtained in recent studies (Chung et al., 2022) (Lee et al., 2021) (Preisendörfer et al., 2022) (Tangermann et al., 2022). Chung et al. (Chung et al., 2022) consider that a Pearson's r of 0.60 is strong in view of the subjectivity of the variables analysed. Furthermore, these multivariate models have a high efficiency given the low number of independent variables. Lee et al. (Lee et al., 2021) use 12 independent variables to achieve a 60% explanation of the variability of noise annoyance.

Table 7. Multivariate regression parameters between subjective variables and urban, environmental and acoustic variables.

Subjective variables	Objective variables	Constant	*B*	R^2
e)	L_{AF50} SC_b	-5.88	0.15 1.88	0.59
f)	L_{AF50} logLU	-9.71	0.19 1.81	0.48
g)	L_{AF50} SC_b H	-6.11	0.17 1.82 -0.09	0.65
h)	L_{AFmax} logLU	11.63	-0.09 1.28	0.41

4. CONCLUSIONS

An analysis performed of the relationships between the responses of surveyed pedestrians in urban environments about some specific effects of noise and their perceptions of noisy environments with those values registered for urban, environmental and acoustic variables led to the following conclusions.

Concerning the urban variables, an increase in the average height of the buildings increases some related perceived noise effects. In fact, a significant positive correlation was found for the subjective variables irritability (a), startle (b), annoyance in the ears (c) and perception of how noisy the street is (i) with the average height of the buildings on the street, with explanations of the variability ranging from 14% to 20%. When the environmental variables were taken into account, a significant negative correlation was found only between temperature (T) and several variables related to the effects of noise and the perception of noisy environments. This finding suggests that the values assigned by the respondents for these variables tended to decrease as the temperature increased. This study makes an initial approach to the analysis of the possible effects that urban and environmental variables have on the annoyance or effects of noise, and presents a methodology that can be applied in other urban environments with different characteristics and conditions. The considered ranges of environmental variables allow to cover a great range of environmental conditions, but it would also be interesting to extend this research to cities in which streets have a wider range of average building heights.

The explanations of the variability in the subjective variables related to the perception of the effects of noise reach noteworthy values in the case of some acoustic variables. The indicators L_{Aeq}, L_{10}, L_{50} and L_{90} explained up to 50% of the variation of irritability (a) and startle (b) and values of between 29% and 47% were found for other effects of noise on the population and the perception of noisy environments. It is also interesting to highlight the capacity of some sound indices such as L_{AF50} and L_{AF90} to explain the variable ear annoyance (c), which increases as the index becomes more representative of the background noise level at the site and reaches an explanation of variability of 43% in the case of $\mathrm{L}_{\mathrm{AF90}}$. For the variables interrupting a conversation with someone nearby (d), raising the volume of the voice to talk with someone nearby (e), interrupting a phone conversation (f), raising the volume of the voice on a phone conversation (g) and perception of how noisy is the street (i), the index L_{AF50} was the better predictor of their variability. In the case of the perception of how noisy is the city (h), L_{AFmax} was the only variable that showed a significant correlation at 99%.

A stepwise regression analysis showed that if only urban and environmental variables are considered, models with a single urban or environmental variable provide explanations of between 18% and 44% of the effects and perception of environmental noise. Furthermore, the efficient combination of these urban and environmental variables in multivariate models can lead to an increase in the explanation of subjective variables provided by acoustic variables. In this vein, increases in the explanation of the variability of between 10% and 17% were found for some subjective variables. In the case of the subjective variable raising volume (e), a model based on the combination of variables as SC_b, average building height (H) and temperature (T) was able to provide explanations of up to 63% of its variability. The variable SC_b again provided an increase of about 10% in the explanation of the subjective variables in these models. Therefore, the results suggest that the categorisation method, in addition to being useful in stratifying road traffic noise in cities, could also be valuable in terms of predicting the effects of environmental noise on people and their perception of noise in urban spaces.

The specific analysis of each urban and environmental variable recorded in this study has shown those that have a significant relationship with the specific effects of noise and therefore those that can be used as an alternative or complement in future prediction models of noise effects.

The number of respondents in this study implies a limitation, as the sample size of 105 individuals, being an adequate number to be representative of the population studied, is at the lower limit. In addition, the presence of the same or similar values for the objective variables recorded in the different surveys carried out at each sampling point precluded the use of bivariate and multivariate linear regression analysis by surveys as they did not meet the assumptions of normality, homoscedasticity and randomness. For this reason, the study was limited to studying the mean values obtained at each sampling point which, due to the also low and constant variability of the subjective variables at each sampling point, the results obtained by points were similar to those obtained by surveys. The variability of the objective and subjective variables was mainly due to their different locations and, therefore, using a survey analysis would bias the results of the overall perception of the city because the same number of surveys were not carried out at each point. Despite limitations in the sample size (105) due to the emergence of the pandemic and in an analysis based on values by location (29), the careful methodology and, fundamentally, the novel design of the questions asked in the survey can serve as a guide for future studies to validate the results obtained in this study.

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Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author contributions statement

David Montes González: Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Juan Miguel Barrigón Morillas**: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Guillermo Rey-Gozalo**: Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition.