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Does noise have a stationary impact on residential values?

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Received April 2009
Accepted June 2009

Abstract

Purpose – Environmental noise has become a major issue in densely urbanized areas. The impact of this externality on the quality of life is reflected by a decrease in the residents' well-being, and subsequently a decrease in property values. A considerable number of studies have used hedonic pricing (HP) to assess the impact of noise on property markets, but few of them have considered the existence of submarkets. Theoretically, it could be expected that the marginal value of 1 dB varies according to the neighbourhood's noise exposure, the property characteristics (e.g. insulation level) and the annoyance experienced by residents. The purpose of this paper is to determine whether noise has a stationary impact on property prices.

Design/methodology/approach – Geographically weighted regression is used, which resolves spatial dependencies (i.e. spatial autocorrelation) and considers "soft borders" between submarkets to study the impact of noise on the value of a sample of multifamily dwellings in Barcelona.

Findings – The analysis suggests that the noise level does matter, although the noise depreciation sensitivity index (NDSI) found (0.08 per cent) is in the bottom decile of the HP studies reviewed by Navrud. However, the NDSI is not stationary throughout the city, suggesting that 1 dB has a different impact in different areas.

Originality/value – Noise impact seems to depend not only on the noise intensity to which dwellings are exposed but also on the nature of the noise source. This may suggest the presence of other externalities that arouse social aversion.

Keywords Pricing, Noise pollution, Prices, Property, Spain

Paper type Research paper

Introduction

Interest in the impact of noise on the quality of life is relatively recent. The Report "Fighting Noise in the 1990s" (OECD, 1991) was the cornerstone of the EU anti-noise policy. Assessing the marginal value of noise is now essential in the cost-benefit framework (Vainio *et al.*, 2001). However, this task is doubly complex: first, the marginal value of noise as a social construction is based on individual perceptions and second, quiet does not have an explicit price, since it has public good characteristics (i.e. no exclusion or rivalry in its consumption).

Annoyance caused by external noise depends on:

- the nature of the source (frequency, intensity, intermittency, duration, etc.);
- exposure level (propagation, isolation and reverberation); and especially
- the residents' sensitivity.

The authors want to recognize the support of Dr Josep Roca and Dr Francesc Daumal for their advice on land economics and acoustics, respectively. They also wish to thank the reviewers for their assertive counsels.

Journal of European Real Estate Research
Vol. 2 No. 3, 2009
pp. 259-279

1753-9269
DOI 10.1108/17539260910999992

Noise sensitivity is related to demographic characteristics, such as age (which correlates with deafness level), and also to cultural and social environment. The socio-cultural conditions, for example, influence the type of sounds that are perceived as noise (Daumal, 2002), and the use of domestic time (reading, talking, listening to music, studying, etc.) determines the disturbance produced by external noise (Kryter *et al.*, 1972). Therefore, although the exposure level is maintained throughout the day, people feel more disturbed during resting-periods, especially at night if sleep disruptions occur and at weekends (Bristow and Wardman, 2006). Kuno *et al.* (1993) have suggested that lifestyle and dependence on sound sources (i.e. cars), also have an influence on the sounds that are interpreted as noise.

Noise nuisance reduces people's well-being since it disturbs their daily life (Cohen, 1980; Evans and Lepore, 1993; Hygge *et al.*, 1998; Haines *et al.*, 1998) and has implications for their physical and mental health (Berglund *et al.*, 1995). In economic terms, this reduced welfare would be equivalent to a damage function (Navrud, 2002). The damage can be expressed in monetary units if it is related to a trade-off on the consumption of other goods necessary to enjoy a quieter environment (Mitchell and Carson, 1989; Freemann, 1993).

From the empirical perspective, most studies have used hedonic pricing (HP) functions to infer the marginal value of silence. However, few of them have considered the existence of submarkets, and when they do, these submarkets have been clearly delimited in space. This could bias the coefficient's function by mixing different submarkets (e.g. in a given assumed spatial submarket there may be small and large dwellings belonging to different submarkets). Moreover, such a clear delimitation does not allow interdependences (i.e. externalities) between the submarkets to be considered.

In this paper, we use geographically weighted regression (GWR) to assess the impact of noise on residential market values. This method is used to:

- prove the existence of submarkets by determining local coefficients that are statistically different over the city;
- consider "soft borders" between different local calibrations, which allows interdependences between them to be considered in a softened way and thus; and
- resolve space dependencies (i.e. autocorrelation).

The rest of the paper is organized as follows:

1. the literature is briefly reviewed to describe the HP methodology and highlight its meaning and limitations;
2. the results of other noise-HP studies are reviewed;
3. the data and models are described;
4. the results are discussed; and
5. the paper ends by summarizing the research and discussing the main findings.

1. HP for noise

The HP method belongs to the revealed preferences family, and assumes that in the value of a given property, the marginal value of its attributes is implicit (Bjørner *et al.*, 2003, 2004). In practice, real estate values are used to econometrically infer the marginal value of silence, after controlling for the rest of the location and structural attributes (Lancaster, 1966). In an urban system in equilibrium, the damage function produced by noise at a given point should be compensated by a reduction in the rent paid for the land, thus equalizing the individual's utility level inside the system, and consequently nullifying the mircromotives that may lead the person to relocate (Bateman *et al.*, 2001). Therefore, in a function such as (1), where P is the price and k is the n structural and location attributes, including the noise, the sign of the coefficient k_r of the noise is expected to be negative:

$$P_i = f(k_1, k_2, k_r, \ldots, k_n) \tag{1}$$

As stated above, the main strength of this method lies in the fact that the marginal price of attributes is directly derived from the observed behaviour of individuals on the real estate market. However, it has some limitations related to:

1. *Damage perception.* It is assumed that when householders buy or lease a property, they are fully aware not only of the noise level that they will be exposed to, but also of the negative effect on their well-being. This assumption is implausible because informational asymmetries in real estate markets are enormous, as properties are not perfectly interchangeable, and it is difficult to assess the impact of an event that has not yet been experienced.
2. *Specificities of the real estate market.* Theoretically, if an individual's expectations of a product are not met they will sell it and replace it with another, so that its price is thus readjusted (Feitelson *et al.*, 1996). However, this is not the case in the real estate market due to the significant transaction costs. The main assumption of the method is that individuals, in order to maximize their welfare, choose the goods whose attributes have a marginal value that coincides with their marginal willingness to pay (WTP) for each attribute (Rosen, 1974). This assumption is frequently challenged by the way in which decisions are made in the real estate market, since individuals do not have enough time, information and alternatives to choose exactly the best option.
3. *Data.* There are also problems related to:
    - data sources (e.g. analyses often use databases designed for different purposes);
    - the lack of socio-demographic data on buyers (which is especially relevant in explaining the demand curve of individual WTP in the HP second phase); and
    - the econometric specification of models and/or omissions of relevant variables (Bateman *et al.*, 2001).

Nonetheless, the HP approach is by far the most widely used method for assessing the value of peace and quiet.

2. The impact of noise on property prices

In the literature the most widely used indicator for measuring the impact of noise on property values is the noise depreciation sensitivity index (NDSI). It was originally developed by Walters (1975), and indicates the price variation in percent terms for each unit of noise exposure[1].

Recently, Navrud (2002) summarized the results of 65 noise evaluation studies (of which 58 per cent were related to vehicular traffic). The index used most in these studies (62 per cent of cases) was the NDSI. The analysis of these results for the case of vehicular noise suggests that the NDSI has an average value of 0.64 per cent (i.e. for each dB that noise increases the property price decreases by 0.64 per cent), with an interquartile range (50 per cent of cases) of 0.26-0.89 per cent; in general, 90 per cent of these studies reported a NDSI lower than 1.23 per cent.

Table I summarizes the NDSIs found in other studies. The significant divergence among results is not surprising, since each NDSI calibration is intrinsic to its specific market. This means that each urban market is characterized by a particular implicit price for silence. Schipper *et al.* (2001) carried out a meta-analysis of 11 HP studies, and

Table I.
The NDSI reported in a selection of HP studies (mainly road traffic noise)

City	Author(s)	Year	NDSI (%)	Index
USA				
Tidewater	Allen	1977	0.15	L10
North Virginia	Allen	1977	0.14	L10
North Springfield	Anderson and Wise	1977	0.18	Leq
Towson	Anderson and Wise	1977	0.43	Leq
NS + TS + BG + RS	Anderson and Wise	1977	0.25	Leq
North Springfield	Bailey	1977	0.38	Leq
Washington	Nelson	1978	0.88	Ldn[a]
Washington	Nelson	1978	0.60	Ldn[b]
Kingsgate	Palmquist	1980	0.48	Leq
North King County	Palmquist	1980	0.30	Leq
Spokane	Palmquist	1980	0.08	Leq
Baton Rouge	Hughes and Simans	1992	8.8	[c]
Canada				
Toronto	Hall, Breston and Taylor	1978	1.05	Leq
Winnipeg	Levusue	1994	1.30	Leq
Australia				
Newcastle	McCalden and Jarvie	1977	1.9	[d]
UK				
Manchester	Pennington	1990	0.47	NNI
Manchester	Collirs and Evars	1994	1.5	NNI[e]
Israel				
Urban areas	Becker and Lavee	2003	1.20	Leq
Suburban areas	Becker and Lavee	2003	2.2	Leq
Switzerland				
Geneve	Baranzini and Ramirez	2005	0.70	Leq
Chile				
Santiago	Aguirre and Ramos	2005	2.36	Leq
South Korea				
Seoul	Kwang Sungi Young-J	2007	1.3	Leq

Notes: NS + TS + BG + RS = North pringfield + Towson + Bogosta + Rosedale; [a]for noise increments above than 50 dBA Ldn; [b]for noise increments above the 39 dBA Ldn threshold; [c]for dwellings located both in the city core and in its periphery in noisy streets compared to quiet streets; [d]price reduction when it exceeds in 17/trucks/hour threshold of 33 trucks/hour equivalent to 60 dBA L50; [e]for detached houses when noise level from 27 to 40 NNI

Sources: Own elaboration using data from ENVALUE (www.environment.nsw.gov.au/envalue) and reported studies found that the significant variables that explain the divergence of the NDSI are time, location (country, and accessibility features of the neighbourhood) and specification of the original models.

If it is logical that the NDSI varies among cities, there are no theoretical reasons to expect that within a single city it should remain spatially constant or stationary. Furthermore, some studies, such as that by Becker and Lavee (2003), suggest that the impact of noise is not linear over space. Based on the analysis of three cities in Israel, their findings suggest that noise has a larger impact on suburban residential prices in areas close to the countryside. They found that for each dB Leq that noise increases, property prices are reduced by 2.2 per cent, while in inner city areas this impact (NDSI) is significantly smaller and equivalent to 1.2 per cent. This suggests that noise is penalized more in areas that are expected to be quite. This conclusion was also reached by Baranzini and Ramirez (2005) for Geneva's rental market, and by Marmolejo and Romano (2009) in a contingent valuation study of the area around Barcelona airport. Collins and Evans (1994), following the research initiated by Pennington (1990) in the area around Manchester Airport, also highlighted the differential impact of environmental noise and air traffic depending on the dwelling typology. Rich and Nielsen (2002), in their study of Copenhagen, reported an NDSI of 0.47 per cent for flats and 0.54 per cent for houses. Likewise, Baranzini and Ramirez (2005) also found structural differences between their public and private rental models. These studies suggest that noise does not have a stationary impact throughout the urban space, since noise might be internalized in different ways among submarkets. Day (2003) reported significant differences in the NDSI in his study. He found that noise had a larger impact in areas inhabited by "young urban professionals" (NDSI = 0.57 per cent) than in areas of "white tenants" (NDSI = 0.23 per cent) and "ethnic minority tenants" (NDSI = 0.46 per cent). In Birmingham, Day *et al.* (2003) and Day (2003) detected eight submarkets. In five of these submarkets, traffic and rail-noise were significantly negative, whereas airport noise was significantly negative in only two submarkets.

3. Case study, model and data

Barcelona (100 km^2 and 1.59 million people) has the second largest metropolitan area in Spain (3.200 km^2 and 4.85 million people). Its compact and diverse urban model has recently received international awards. However, one of the major costs of compactness is the significant level of environmental noise in a city with intense street life, a large mix of land uses, and a relative lack of acoustic greenery. The most recent acoustic map published (1997) suggests that more than two-third of the measuring points are above the highly annoying threshold suggested by the OECD (Table II).

Leq dBA day	Leq dBA night	Points (%)	Classification according to city council	Classification according to OECD
<65	<55	23.40	Good	>55-60 annoying
65-75	55-65	63.80	Tolerable	60-65 highly annoying
>75	>65	12.80	To improve	>65 perturbation on behavior and serve diseases

Source: Barcelona's Acoustic Map (1997)

Table II.
Barcelons's 1997 acoustic map measurements

The model used in this paper is specified in equation (2). Although there is no consensus in the literature on what variables should be considered (Mason and Quigley, 1996), there is certain agreement that four dimensions of variables should be included (Roca, 1988; Fitch and Garcia-Almirall, 2008). In equation (2) the price P of a property i depends on a set of variables related to: S structure; A accessibility; N neighbourhood and E environmental externalities. $\boldsymbol{\varepsilon}$ is a vector representing the random error:

$$\mathrm{Ln}(P)_i = B_i + \sum_{s=1}^{n} B_{is}S_{is} + \sum_{a=1}^{n} B_{ia}A_{ia} + \sum_{n=1}^{n} B_{in}N_{in} + \sum_{e=1}^{n} E_{ie}E_{ie} + \varepsilon_i \qquad (2)$$

The semi-log function (2) was used for three reasons:

1. the transformation of the dependent variable suggested by Cox and Box (Kemp, 1996) suggests that, as λ is close to zero[2], the price is linked in this way to the set of covariates;
2. in the noise HP literature it is the most widely used functional specification because, among other things, it helps to normalize the price and residual distribution and allows the results from different studies to be compared (Bateman *et al.*, 2001; Navrud, 2002; Bjørner, 2003); and
3. since it is calculated as a semi-elasticity, the noise coefficient allows the NDSI to be determined directly (Nelson, 1980, 2004, 2008).

The market values were taken from 3,196 appraisals of multifamily dwellings (flats) carried out in 2005[3]. Table III summarizes the descriptive statistics of the covariates used[4]. In the S dimension, there are covariates and factors related to structural features of flats such as built area and construction quality. The quality of the windows is used as a proxy for the level of soundproofing, since the best-quality windows usually have hermetic seals and double glazing. The A dimension includes accessibility indicators such as underground stations, suburban rail stations, bus stops, journey-to-work time, distance to central business district (CBD), density and diversity[5] of employment and services and an indicator of the residents' perception of accessibility[6].

In the N dimension, there is information related to socioeconomics, such as whether there is a doorman, percentage of the residents with a university education, percentage of unemployed people, percentage of managers, percentage of professionals and average dwelling size. In the E dimension the covariates are related to the environmental quality, which includes the environmental noise level (dB A Leq), the residents' perception of bad smells and the lack of green areas, percentage of dwellings in ruins or bad condition, average year of construction of the buildings in the neighbourhood, land use, percentage of industrial economic activities and diversity of the land use covers (as a proxy for the landscape diversity).

The information sources are detailed above in Table II and the smallest geographical units with available data are:

- *Dwellings*. Individually geo-referenced (3,196).
- *Census data*. Census tracts (1,498).
- *IAE information*. Statistical study zones of the city council (248).

Table III. Descriptive statistics of variables

	N	Minimum	Maximum	Mean	SD	Source
Structural (S)						
Total price (€)	2,498	81,220	1,201,625	279,171	127,200	a
m^2price (€/m^2)	2,498	2,032	8,453	3,052	593	a
Gross area (m^2)	2,498	23	220	84.23	25.76	a
Bedrooms	2,498	1	7	2.88	0.87	a
Bathrooms	2,498	–	7	1.28	0.54	a
Bathrooms/bedrooms	2,498	–	3	0.48	0.23	a
Gross area (m^2)/bedrooms	2,498	11	85	30.88	10.10	a
Windows quality	2,498	1	5	3.05	0.62	a
Bath's finishes quality	2,498	1	5	3.06	0.59	a
Kitchen finishes quality	2,498	1	5	3.06	0.65	a
Age (years)	2,498	–	155	31.81	28.30	a
Individual heating (1 = yes)	2,498	–	1	0.91%	4.40%	a
Central heating (1 = yes)	2,498	–	1	51.24%	49.99%	a
Lift (1 = yes)	2,498	–	1	37.56%	48.44%	a
Accessibility (A)						
Travel to work time (min)	2,498	19	38	27.54	2.92	b
Distance to CBD (m)	2,498	76	5,922	2,885	1,237	e
Percentage of poorly communicated households	2,498	1	67	11.16	13.06	b
Employment and service shannon's diversity	2,498	2	4	3.07	0.28	c
Employment and service density (registers/km^2)	2,498	76	8,723	2,570	1,496	c
Bus stops/1,000 people	2,498	–	96	2.48	4.11	d
Subway entrances/1,000 people	2,498	–	20	0.27	0.69	d
Suburban railway entrances/1,000 people	2,498	–	3	0.01	0.09	d
Neighbourhood (N)						
Percentage of managers	2,498	2	27	8.82	3.92	b
Percentage of professionals	2,498	4	39	17.14	8.61	b
Percentage of technicians	2,498	6	21	16.22	3.05	b
Percentage of clerks	2,498	7	18	13.16	2.02	b
Percentage of salesclerks	2,498	6	27	15.76	3.68	b
Percentage of qualified blue collar (manufacture)	2,498	2	23	11.29	4.62	b
Percentage of non qualified blue collar (manufacture)	2,498	1	20	7.58	3.32	b

(*continued*)

Table III.

	N	Minimum	Maximum	Mean	SD	Source
Percentage of non qualified (other sectors)	2,498	3	23	9.60	4.08	b
Percentage of dwellings with caretaker	2,498	0	59	6.93	8.09	b
University graduate	2,498	3%	43%	16.57%	8.59%	b
Average dwelling's net area (m^2)	2,498	30	144	73.17	13.29	b
Environmental (E)						
Percentage of noise annoyed households	2,498	20	63	43.21	7.20	b
Percentage of smell annoyed households	2,498	8	52	26.43	7.42	b
Percentage of households in a poor greenery area	2,498	6	73	38.88	14.94	b
Percentage of disrepaired dwellings	2,498	0	64	6.28	6.57	b
Percentage of beach and water	2,498	0	10	0.09	0.69	f
Landscape Shannon's diversity	2,498	0	2	1.49%	0.27	f
Percentage of manufacturing activity	2,498	5	41	17.03	5.84	c
Noise (dBA Leq)	2,498	50	80	68.38	5.12	g

Notes: Own estimations using data from: (a) valuation database (2005); (b) dwelling and population census INE (2001); (c) IAE Economic Activity Tax (2002); (d) Metropolitan Transport of Barcelona (2005); (e) GIS own estimation (2005); (f) own remote sensing on SPOT satellilte imagery (2002) further details about remote sensing process can be seen in Alhaddad *et al.* (2006); (g) city council Sonic Map (1997)

- *Land use satellite information.* Census tracts (1,494).
- *Acoustic map.* Individually geo-referenced sonometric points (1,045).
- *Bus, underground, train stops/stations.* Individually geo-referenced (4,565).

The data on the non-structural attributes were transferred to dwellings with a GIS. Therefore, different buffers, 300, 600 and 900 metre in radius (mr), were used as in Acharya and Bennett (2001). The model presented in this paper was built using data from the buffer 300 mr.

As a preliminary step, besides removing 604 flats for which there were no sonometric data, all the flats with extreme attribute values, which could not be considered "standard" flats, were also removed. The Mahalanobis distance (MD) was used in order to consider all the dwelling attributes in the filtering process at the same time. Beyond its statistical robustness[7], according to Li *et al.* (2005), the MD can be used to remove the flats whose price is not explained by the covariates used but rather by other aspects not measured, such as the fact that expensive houses have "finer decorations and fixtures, floor coverings and landscaping" (p. 3), or specific insulation against noise pollution. "Taking out the cases influenced by omitted variables is crucial, since they might bias the model's regression coefficients, and therefore lead to inefficient estimates in the noise hedonic function" (Bateman *et al.*, 2001).

4. Results

Table IV (left) shows the ordinary least squares (OLS) model, which is able to explain 89.5 per cent of the property values. The signs of all covariates are those expected, and their coefficients are significant at the 95 per cent confidence level. According to this model, the *S* structural feature dimension includes – in addition to the built area – the square of the built area (which internalizes the principle of diminishing returns) and certain quality indicators, such as the ratio of the built area to the number of bedrooms, which – in addition to being an indicator of interior space generosity – is a proxy for housing quality. In addition, the dummies which internalize the window quality are also included[8], the coefficient of the dummy "regular quality windows" is -0.043, and as expected, the coefficient of the dummy "low quality windows" is -0.078. This suggests that the flats with aluminium, PVC, double glazed and hermetically sealed windows have a market premium because, among other things, they offer reasonable thermal and acoustic insulation, which directly affects the residents' budget and enhances comfort, both of which affect the implied WTP. Finally, it is significant that a central heating dummy is included. This variable also represents the age of the building since the older buildings do not have it.

The journey-to-work time, with the expected negative sign, and the density of jobs and services (which represents access to shops and services) are included in the accessibility dimension *A*. If the other factors remain the same, for every minute that the journey-to-work increases, the property value falls by 0.57 per cent. Principal Component 1 (PC) originates from a factor analysis based on the percentage of households classified according to the professional occupation of the householder, and is included in the dimension *N*, which represents the socioeconomic characteristics of the neighbourhood. The factorial analysis summarizes the socioeconomic structure of the city in two axes, and explains 84 per cent of the variance of the nine original variables. PC 1 is able to explain 67 per cent of the variance and polarizes, at one

Table IV.
Estimation from the OLS and spatial lag models

OLS model				*Max. likehood spatial lag (SL)*		
R^2	0.896			0.902		
R^2 adjusted	0.895			0.901		
Sigma (SE)	0.116			0.112		
	Unstandarized coefficients			*Unstandarized coefficients*		
Variable	B	*SE*	*Sig.*	B	*SE*	*Sig.*
W-LN total price (€)				0.254	0.020	0.000
Intercept	11.600	0.063	0.000	8.319	0.268	0.000
Gross area (m^2)	0.018	4.1×10^{-4}	0.000	0.018	3.9×10^{-4}	0.000
PC 1 (low income households)	0.081	3.9×10^{-3}	0.000	0.033	5.3×10^{-3}	0.000
Gross area (m^2)^2	-3.6×10^{-5}	1.9×10^{-6}	0.000	-3.9×10^{-5}	1.9×10^{-6}	0.000
Percentage of manufacturing activity	0.308	0.059	0.000	0.161	0.058	0.006
Percentage of beach and water	2.384	0.348	0.000	1.948	0.338	0.000
Central heating	0.029	0.005	0.000	0.024	0.005	0.000
Travel to work time (min)	0.006	1.3×10^{-3}	0.000	0.004	1.2×10^{-3}	0.002
Gross area (m^2)/bedrooms	0.001	2.5×10^{-4}	0.000	0.001	2.4×10^{-4}	0.000
Employment and service density	6.8×10^{-6}	2.5×10^{-6}	0.006	5.9×10^{-6}	2.4×10^{-6}	0.013
Percentage of road surface	0.053	0.020	0.009	0.080	2.4×10^{-6}	0.000
Noise (dB A Leq)	-1.4×10^{-3}	6.0×10^{-4}	0.019	-9.3×10^{-4}	5.8×10^{-4}	0.010
Regular quality windows	0.043	0.008	0.000	0.041	0.007	0.000
Low quality windows	0.078	0.019	0.000	0.079	0.018	0.000
ANOVA						
	Sum of squares	*df*	*Mean square*			
Regression	287.6312681	13	22.13	Threshold dist (m)		375
Residual	33.38968005	2.484	0.01	Log likelihood		1.923
Total	321.0209481	2.497		Lag. Coeff. (RHO)		0.254
	F	*Sig.*				
	1.646	0.000				

Notes: Dependent variable: Ln total price (€); OLS stepwise method extreme (with positive factor loadings) low-income classes (e.g. unskilled workers) and at the other (with negative factor loadings) high-income groups (e.g. managers and professionals). Therefore, PC 1 is expected to have a negative sign:

> Of all the exogenous variables considered, according to the standardized beta coefficient, this location attribute has the greatest influence on the price, which not only indicates the importance of the residents' economic standing, but also the market premium that they are willing to pay for flats located in more socially-prestigious areas of Barcelona (Roca, 1988).

There are four covariates in the environmental dimension E. The first is the percentage of manufacturing activities in the area. The second, with a positive sign, is the percentage of beach and water in the area. This basically refers to homes located in coastal area (i.e. the Villa Olimpica), but thanks to the relatively high resolution (1 pixel $= 2.5$ m) of the satellite imagery from remote sensing, this also refers to nearby swimming pools of luxury developments (e.g. Pedralbes), and to a lesser extent, to fountains (e.g. Plaça Espanya) and public swimming pools (e.g. Vall d'Hebron):

> It is worth pointing out that the waterfront renewal in Barcelona (which has opened the city to the sea) has made a significant impact on the historical structure of residential values of this city (Roca, 1988).

The third is the percentage of streets that surround the houses, with a negative sign; this indicator proxies for other externalities associated with vehicular traffic (smog, vibrations). Finally, the last significant environmental variable is the sound intensity. According to the OLS model and considering data limitations[9], the NDSI is 0.14 per cent, which means that, if the other factors are constant, the value of flats decreases by 0.14 per cent for every dB that noise increases. In addition, the p-value of this covariate is greater than any other, which suggests greater uncertainty in estimating the coefficient; we will return to this issue later.

The residual spatial analysis indicates the presence of autocorrelation (Moran's $I = 0.0507$), which may be produced by externalities mutually produced between properties in an area that have not been successfully internalized by the independent variables (Can, 1992; Nelson, 2008). In an attempt to reduce this problem, the data were analyzed in an autoregressive spatial model (Anselin, 1988, 2006). After the spatial-lag calibration (Table IV right), the model fit increases slightly to reach $R^2 = 90.1$ per cent. All the variables keep their sign but some coefficients vary slightly; for example, the social structure indicator decreases in importance, as do the percentage of manufacturing activity and the percentage of water/beach. The percentage of streets in the environment increases in importance. All other variables "maintain" their coefficients. The relatively high-standard error of noise, which leads to a relatively high significance (nearly 90 per cent confidence) might suggest that this externality does not have a linear impact over the entire city. In the next section this hypothesis is explored in depth.

4.1 Non-stationary impact of noise on the spatial formation of residential prices

In addition to spatial dependence problems (i.e. spatial autocorrelation), spatial heterogeneity is another issue to be resolved when the HP method is used. This may affect the accuracy and significance of OLS estimations, which assume a spatially invariant or stationary set of coefficients (Can, 1992; Fotheringham *et al.*, 2002; Paez *et al.*, 2008). Spatial heterogeneity refers to the unequal influence that intrinsic and extrinsic attributes have on property values in relation to the possible existence of submarkets. It would thus be plausible to expect that noise affects differently the hedonic function of flats that belong to different submarkets, because either they have different building attributes and architectonic characteristics like large terraces or community spaces inherently exposed to noise pollution (Marmolejo and Romano, 2009), or the sensitivity of the users is different (Kuno *et al.*, 1993; Daumal, 2002). Therefore, from the theoretical perspective the implicit price of 1 dB is not necessarily the same in different market segments or in different locations subjected to different noise levels. Consequently, for each submarket there should be a specific hedonic function (Rosen, 1974). However, in practice the HP method yields structurally similar equations since it focuses on the price of the attributes and not on the amount of attributes available (Bourassa *et al.*, 2003). Therefore, although the F-Chow test, which analyzes residuals, and the Tiao-Goldberg F-test, which analyzes coefficients, indicate structural similarity, it may be the case that the dwellings are not actually in the same submarket.

In the literature there are statistical alternatives to the qualitative approaches for identifying submarkets carried out by experts (e.g. realtors or appraisers), such as the quite popular factor analysis (e.g. Dale-Johnson, 1982) followed by cluster analysis (Maclennan and Tu, 1996; Bourassa *et al.*, 1999; Bourassa *et al.*, 2003) for finding areas with homogeneous attributes, and the most recent analyses based on price elasticity (Pryce, 2008) for finding areas with interchangeable dwellings. However, with few exceptions (Bourassa *et al.*, 2003), almost all of these alternatives have failed to conceptualize submarkets with clearly defined borders. This assumption in some cities is as unrealistic as administrative boundaries, which is the particular case of Mediterranean cities (compact and diverse), characterized by "smooth transitions" between different urban fabrics. In addition, from the econometric perspective, the "hard" borders prevent the externalities that one zone exerts on others from being considered (i.e. space dependencies) when models are calibrated separately for each zone. Following the conceptual proposal in Paez *et al.* (2008) it seems plausible that it is possible to consider the spatial interactions between submarkets that have fuzzy borders. One method for dealing with this kind of border is the geographically or locally weighted regression GW-or-LWR (Brunsdon *et al.*, 1996; McMillen, 1996; Fotheringham *et al.*, 2002), which also solves space dependency issues (Paez *et al.*, 2008).

In general, the GWR adjusts as many regressions as there are observations in the analysis. In these regressions, the further away the observations are from the pivotal point, the less weight (i.e. importance) they have in the estimation of the B parameters (one difference for each regression). The weighting matrix is calculated as follows:

$$w_{ij} = \left\{1 - \left(\frac{d_{ij}}{h_i}\right)^2\right\}^2 \quad \text{if } \ d_{ij} < h_i \ \text{ otherwise} = 0 \tag{3}$$

where w is the weighting space matrix, i is the pivotal point of the regression, j is each of the N observations included in the local regression and h is the distance from the Nth j point (Charlton *et al.*, 2005). When the density of the observations is not constant throughout the space, it is advisable to use an adaptive kernel, making it possible to relax the geometry of the analysis area, which may not be isotropic from point i.

The results of the GWR using an adaptive kernel with 628 cross validated cases are shown in Table V. The adjustment increases up to $R^2 = 0.91$. The Akaike information criterion and the reduction in sigma suggest that the locally weighted regression model is significantly streamlined in comparison with the OLS and the Spatial-lag models. The summary of the distribution of the coefficients is expressed in terms of upper and lower quartiles and the Huber's M-estimator provides a robust average (Huber, 1981). Compared to the OLS model, the Huber's M-estimators in Table V are quite similar, with few exceptions; for example, the negative influence of manufacturing activities on residential values decreases, and the positive influence of water and beach decreases. The noise coefficient also decreases slightly (from 0.0014 to 0.00083). According to the average price of the flats in the sample used and the M-estimator of the noise, it is inferred that their value is reduced on average by €232.61 for each dB that the surrounding noise increases.

Table V also shows the percentage of local estimations in which the covariate coefficients are significant at 90 per cent confidence. It can be seen that noise and beach-water show the lowest proportions of significant regressions, which endorses the relatively high *p*-value of noise in the models from Table IV (0.019 for OLS and 0.10 for SL):

> It is worth pointing out that virtually all variables have a non-stationary impact on the property value. This means that the marginal value of each unit of each attribute fluctuates throughout the space.

This is probably the reason for the good performance of the GWR model, since it considers the specific local relationships between the price and localized attributes. A Monte Carlo test was performed to statistically validate the spatial variation of local factors (Fotheringham *et al.*, 2002). The results (Table V right) suggest that all covariates, with the exception of the quality of flats (i.e. built area/bedrooms and window quality) and the accessibility indicator, have statistically different impacts on the price of flats throughout the city.

According to the GWR, noise can have either a negative or a positive impact in different parts of the city. If we only consider regressions in which the noise coefficient is significant at the 90 per cent confidence level the bottom decile of the NDSI is -0.0081, while the top decile is $+0.0054$. That is, in the bottom 10 per cent of the regressions, for each dB that noise increases, the property price decreases by 0.81 per cent, while paradoxically in the top 10 per cent of cases the price increases by 0.54 per cent.

By simply looking at the local noise coefficients and "local knowledge", the nature of this paradox can be hypothesized (Figure 1). First, there is a clear relationship between the noise level and the impact of each dB on residential values. Indeed, the correlation between the noise B coefficient (for significant regressions) and the level of environmental noise is negative ($r = -0.404$) and significant at the 99 per cent confidence level, i.e. the higher the noise level, the larger its negative impact on values per dB. However, this relationship is not continuous, as the (statistically significant) regressions in which the noise seems to have a positive impact are located in areas with intermediate noise levels. Therefore, the average NDSI for the observations located between the intermediate range from 70 to 75 dB is $+0.0026$, while the average NDSI for the observations located in the inferior range of 65-70 is negative -0.0014. For those

Table V.
Estimation from the GWR model

GWR model					*Akaike information criterion*	
R^2	0.915			OLS	3.678	
R^2 adjusted	0.911			GWR	3.935	
Sigma (SE)	0.108					
B distribution statistics				*Significance tests*		
	Lower quartile	*Huber's M-estimator*	*Upper quartile*	*Local regressions with pseudo-p-value < 0.10*	*Monte Carlo test for spatial variability (p-values)*	
Intercept	11.143	11.452	11.687	100%	0.000	*
Gross area (Sq.m)	0.018	0.020	0.021	100%	0.000	*
PC 1 (low income households)	0.018	0.081	−0.053	100%	0.000	*
Gross area (Sq.m)^2	-5.4×10^{-5}	-4.7×10^{-5}	-3.7×10^{-5}	100%	0.000	*
Percentage of manufacturing activity	0.0790	0.261	0.181	58%	0.000	*
Percentage of beach and water	4.320	0.088	1.845	21%	0.000	*
Central heating	0.011	0.018	0.026	41%	0.020	*
Travel to work time (min)	0.007	0.004	−o,001	23%	0.110	n/s
Gross area (Sq.m)/bedrooms	2.4×10^{-4}	8.9×10^{-4}	1.5×10^{-3}	47%	0.240	n/s
Employment and service density	3.0×10^{-6}	9.6×10^{-6}	1.6×10^{-5}	42%	0.000	*
Percentage of road surface	0.122	0.052	0.005	33%	0.000	*
Noise (dB A Leq)	-2.9×10^{-3}	-8.3×10^{-4}	1.4×10^{-3}	17%	0.000	*
Regular quality windows	0.059	0.004	−0.028	74%	0.350	n/s
Low quality windows	0.104	0.074	−0.045	50%	0.460	n/s
ANOVA						
	Sum of squares	*df*	*Mean square*			
OLS residuals	33.38	14		*N* nearest neighbours		628
GWR improvement	6.08	108	0.06	Num. locations to fit		2.498
GWR residuals	27.3	2.375	0.0115			
	F	Sig.				
	4.917	0.000				

Notes: *Significant at: 0.1% level; n/s, not significant, dependent variable: Ln total price (€), GWR Adaptative kernel crossvalidated

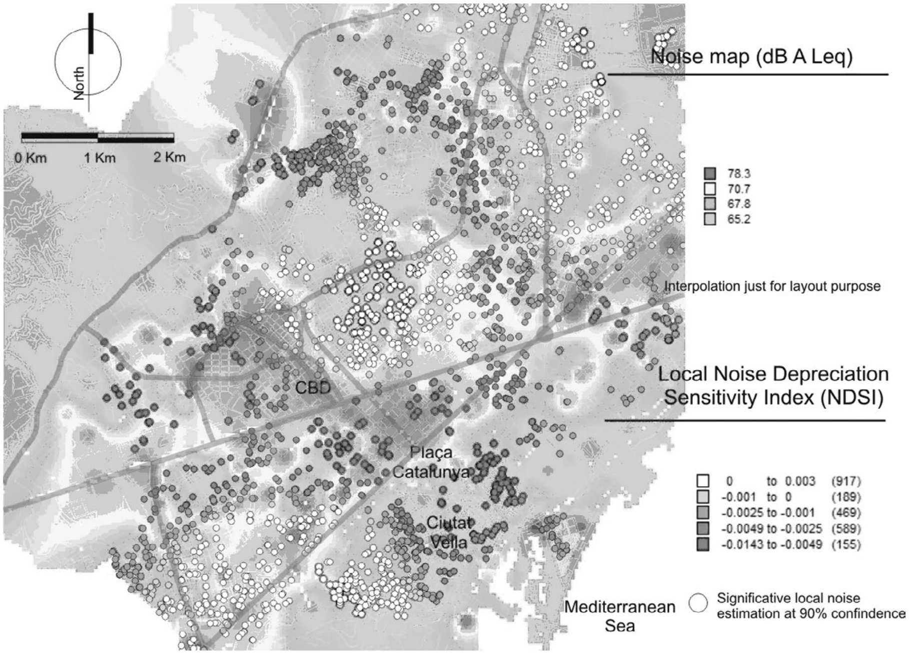

Figure 1.
Noise map and HP of local estimations of noise

located in the upper range of 75-80 dB, the NDSI is even more negative −0.0040. The paradox can be resolved if we consider that the areas of intermediate noise are located near the areas of maximum noise, which are the areas that provide the most transport and services in the city, so the apparent positive correlation may actually be proxying for privileged access to these services. Therefore, it seems there is a market premium in gaining rapid access to services and transport without suffering the highest noise levels from the roads on which these services are located. Day (2003) reached this same conclusion and found a positive sign for the noise in one of the four submarkets identified in Glasgow.

Figure 1 also shows that some pedestrian areas with relatively low-noise levels, like Barcelona's Historic Centre (Ciutat Vella and the Raval), have hedonic functions similar to those vehicular areas with higher noise levels (which is why the NDSI is negative in the lower 65-70 dB range). This suggests that the sonic intensity measured by sonometers is not enough to fully capture the noise dimensions, as they only record one of its aspects: the intensity. Therefore, residents living in urban areas, such as the Ciutat Vella and Raval, where noise comes from pedestrian traffic (mainly leisure), restaurant terraces, pubs and open space public activities, seem to be particularly sensitive to noise (and other externalities), which leads to larger increases in property values for each dB of peace and quiet gained.

5. Conclusions

Several HP studies have assessed the impact of noise on property values (see the excellent reviews by Bateman *et al.*, 2001; Navrud, 2002; Bjørner, 2003; Nelson, 2008). Most of these have successfully proven that welfare lost as a consequence of increased noise negatively impacts property values. This impact can be indexed by means of the NDSI.

Studies conducted in different cities suggest that the NDSI varies greatly. For example, those reviewed by Navrud (2002) for vehicular traffic noise indicate that the NDSI ranges from 0.08 to 2.2 per cent and averages 0.64 per cent (i.e. for each dB that noise increases, the price decreases by 0.64 per cent). From the theoretical perspective this variation among cities is not surprising since each market has its own hedonic schedule that depends on its socio-economic and structural characteristics. However, we can also expect that the NDSI also fluctuates within cities, which have diversified real estate markets characterized by the existence of submarkets. Therefore, studies such as those conducted by Becker and Lavee (2003) and Baranzini and Ramirez (2005) have reported that noise is penalized more in areas where it is expected to be quiet (e.g. suburban countryside areas); however, Collins and Evans (1994) and Rich and Nielsen (2002) reported different penalizations between flats and houses (more penalized for detached houses), and Day (2003) and Day *et al.* (2003) reported statistically significant variations between the NDSIs of different submarkets detected through multivariate techniques. These latter studies considered submarkets clearly demarcated by "hard borders". For Mediterranean cities (compact and diverse) this is unrealistic, because in these cities there are smooth transitions between the different urban fabrics. Paez *et al.* (2008) suggested using moving-window regressions, which can be conceptualized as sliding neighbourhoods (i.e. soft market segmentations) that can incorporate spatial dependency effects. In this paper, we use locally or geographically weighted regression (GWR-or-LWR) (Brunsdon *et al.*, 1996; McMillen, 1996; Fotherigham *et al.*, 2002) to determine whether or not the impact of noise on the spatial formation of Barcelona's residential market is stationary.

The GWR approach is able to explain 91.1 per cent of value variation of a 2,498-flat sample (once it was debugged by means of the MD). The model coefficients suggest that after controlling for the property's structural attributes (e.g. size and quality), neighbourhood (e.g. socioeconomic status) and accessibility (e.g. journey-to-work time), the noise does matter for the spatial formation of real estate values. The adjusted GWR model obtains better results than either the OLS or Spatial-lag model ($R^2 = 0.89$ and 0.90, respectively), which not only suggests that there are spatial dependencies (resolved by the autoregressive model), but also spatial heterogeneity (i.e. an unequal influence of intrinsic and extrinsic attributes on property prices, and consequently, the existence of submarkets).

A Monte Carlo validation confirms that the NDSI has a non-stationary influence on the city. The areas with higher noise levels (e.g. those located along the main avenues) are also those in which the NDSI has a larger negative impact. However, this also occurs in the relatively quiet pedestrian city centre (Ciutat Vella and the Raval), which is characterized by a high presence of bars, restaurants, outdoor cafes and pedestrian traffic. The changes in relative noise intensity during the day-night cycle will probably explain major negative impacts on house prices, especially when noise is substantially higher in the evening and at night when residents are resting. We also hypothesize that in this latter case the negative impact may be associated with the local residents' negative perception of the leisure activities, which produce not only noise, but also other externalities. Therefore, the intensity and nature of the noise source may be behind the non-stationary character of the noise impact on real estate values.

The average NDSI (calculated by means of the Huber M-estimator considering 2,498 local estimations) is 0.083 per cent, which situates Barcelona's market (the submarket) in the bottom decile of all the studies reviewed by Navrud (2002). In monetary terms it can be said that for every dB A Leq that the noise increases in Barcelona the average sale value of flats is reduced by €232.61.

Notes

1. This exposure can be measured by different indices, some of which are composites, such as noise exposure forecast (NEF), ANEF (the Australian version of the NEF), and the British Noise and Number Index (NNI), which combine the tone, intensity (dB), frequency of noise-impacts in a defined interval of time (e.g. take offs and/or landings in airports), duration and time at which they occur (day or night). Other indices are simpler, such as Leq, Ldn and L10.
2. This transformation has been calculated as follows:

$$Y^{(\lambda)} = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda \dot{y}^{\lambda - 1}} \end{cases} \text{if } \lambda \neq 0 \text{ or } \dot{y}\ln(y) \quad \text{if } \lambda = 0$$

   where $\dot{y}$ is the geometric mean. Note that, if λ is 1, then the equation collapses to a linear function (i.e. there is no need to transform Y), while if it approaches zero, the transformation of the dependent variable is the log. In our case, by testing different values of λ to reduce sigma and analyzing the normality of residuals it was found that the logarithmic (i.e. $\lambda \approx 0$) was the best transformation.
3. This information comes from the Appraisal Society CATSA, and is used here for scientific research purposes. In Spain, since there are no comprehensive public or private databases containing the price of real estate transactions, the value stated in appraisals is considered a good indicator of the market price (Roca, 2005). Furthermore, each appraisal was endorsed by at least six "witnesses" of the actual transaction. The bias normally introduced by the real estate cycle and the bias due to appraisers are assumed to randomly affect the entire set of appraisals from the same time period.
4. The descriptive statistics refer to the sample used; for further details see how the sample was selected.
5. The diversity was calculated using Shannon's entropy equation:

$$H = \sum_{i=1}^{n} -1 \times P_i \times \mathrm{Ln}(P_i)$$

   where P is the probability of finding an i activity from the existing n in every zone.
6. This information refers to the percentage of households, at census tract level, which stated in the 2001 national census that their houses were not close to public transport.
7. The MD is calculated as follows:

$$D^2 = (X - M_x)' \sum\nolimits_x^{-1} (X - M_x)$$

   where D is the MD, X is the housing attributes, and M_x and Σ_x are the variance-covariance matrix. In our case we decided to eliminate the upper quintile of the sample (DM $>$ 28.1), since the model streamlined (in terms of sigma and properties (0,1) of residuals) under this threshold.

8. It is important to note the positive correlation of this variable with other variables related to the quality of the finishes of the bathrooms, kitchen and amenities such as central heating. Therefore, the quality of the windows is also a proxy for the overall quality of the dwelling.
9. These results are just an approximation because, despite every effort, it has not been possible to obtain the most recent acoustic map of the city. However, a comparison of the 1990 and 1997 maps suggests that the overall structure of the noise has remained the same despite the large urban transformations, with the exception of the Forum of Cultures area. This reinforces the relative inertia in the spatial formation of property prices (Bateman *et al.*, 2001), and partially supports the results of this research. We want to thank to Marlon Flores for his support in the digital construction of noise map.

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