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Published Version:
D'Orazio D., Montoschi F., Garai M. (2020). Acoustic comfort in highly attended museums: A dynamical model. BUILDING AND ENVIRONMENT, 183, 1-10 [10.1016/j.buildenv.2020.107176].

Availability:
This version is available at: https://hdl.handle.net/11585/771556 since: 2024-09-12

Published:
DOI: http://doi.org/10.1016/j.buildenv.2020.107176

Acoustic comfort in highly attended museums: a dynamical model

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Abstract

High-attendance exhibitions are often uncomfortable, due to too loud background noise. This is due to several factors, primarily the human voice. Moreover, most of the largest museums are housed in historical buildings which cannot be acoustically corrected, therefore the control of human noise is the only way to manage acoustic comfort. Human noise due to visitors is treated as a non-stationary phenomenon, related to flux of visitors/talkers. In the present study, a predictive model is proposed. Markov-chain theory is proposed to study the temporal behaviour of occupancy and generative algorithms are used to analyse the spatial distribution of visitors. The model has been validated by means of measurements in a highly attended museum in Florence during a free-entrance day. Measurement results agree with the predictive model, returning useful information on vocal effort and feedback processes. Results also show that a maximum number of visitors and a maximum visit time should be established in order to keep a proper acoustic comfort. Excess number of visitors or visiting time, may result in an almost two-fold increase in human noise level.

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1. Introduction

Museums are spaces in which education, entertainment and exhibition come together to create the 'visitor experience' in an important cultural environment. Studies concerning physical parameters offer increasing sophisticated indices for comfort control [1, 2] considering thermal and air quality [3], energy consumption [4] and lightning [5, 6]. Many of these parameters are still regulated by technical standards [7] and are included in the indoor environmental quality index (IEQ) [8, 9].

Nevertheless, the control of the acoustic environment is one of the fundamental conditions that improve the well-being of the occupants of interior spaces. Museums, as a matter of fact, can be very noisy spaces wherein the noise level can exceed the tolerance threshold [10]. Most museums are places of silence in which noise disrupts order and distracts attention, hampering the desired connection between the visitor and the exhibition [11]: in the 'silent' museum, sound is not absent, but it does not constitute an organic agent of knowledge during a typical visit. According to Bennet [12], only through silence it is possible for the contemplating visitors to elicit the essential truth of the exhibition. This 'quasi-theological' culture demands that museum space should be regarded as temple of human creativity. This theory is outdated for modern museums that include sound, multimedia or interactive activities in their exhibit experience [13]. However, museum attendees normally expect to enjoy their visit in a non-disturbing environment, motivated by the desire to learn and, indirectly, to find an experience of restoration and an escape to stressful everyday life [14]. Whilst some may still be willing to use extra learning effort during a visit disrupted by unpleasant factors, others may quit it. Given the educational purpose of museums, noise abatement should be a priority for designers, building engineers and operation managers. Some authors focused on perceived parameters of different museum environments relating to physical quantities, in-situ measured [15, 16]. Soundscape-based approaches study the sequential spaces through the correlation between sound level and loudness, intimacy, reverberation, clarity and spaciousness [17, 18, 19, 20, 21].

Few scholars have tried to identify target values of objective and subjective parameters for museums [22]. The identification of these values is sometimes based on direct feedback from visitors, sometimes through a virtual environment. Ideal parameters values, that can characterize a good acoustic behaviour of a museum room, were proposed by Carvalho et al. [23], in 2013. One year later, the same authors proposed an Index of Acoustic Quality in Museums in order to quantify the discomfort felt subjectively as due to the different types of noise present in the museum [24]. In a more recent study, further room acoustic parameters were considered to evaluate an Art Museum in Brasil [25].

Visitors' comfort can be affected by the flux of people: the higher the local attendance , the higher the human noise. Digital technology was used to track the visitors movements. Bluetooth communications were used in the Louvre Museum to examine sequential movements, visitors patterns, time and length of visit [26]. Group-membership trajectories were estimated through Radio Frequency identification readers (RFID), analysing crowded and uncrowded areas inside the Osaka science museum [27]. The relationship between the viewing sequences, the layout of exhibit and the visitors pattern was analysed in eight art museums [28]. Radio-based proximity sensors were used to analyse the time visitors spent for each artwork and the length of stay [29].

The results of the latter studies can be related to the so called *museum fatigue*: the attention effort affecting people during a museum visit [30, 31]. This term was first used by Melton [32] as a determinant human factor influencing the decreasing attention of visitors that become less and less interested the longer they are in the museum [33, 34]. More recent studies on the same topic analyzed the correlation between the effort, the time of stay and the exposition layouts [35, 36, 37]. Environmental causes can increase the visiting effort [38]. When a visitor speaks with another one, the communication quality depends on such comfort conditions. Human task performance such as attention to exhibit, may be influenced in a feedback process by *human noise*. Moreover, the communication quality depends on the distance between talkers. Proxemics [39, 40] may be employed to investigate human behaviour in social interactions.

In the present work a predictive model is proposed that enables to evaluate the human noise in high-attended museums. It is conceived as a dynamical model, generalising the *acoustic capacity* proposed for eating establishments. The visitor flux is modeled by Markov chains, and further parameters of the model are found through parametric software. A highly attended museum in Florence was used as case study to validate this dynamical predictive model.

2. Verbal communication in noisy environments

Noise sources affecting the sound environment of a museum [17] could be classified either as human or non-anthropic. The latter can be traced back to HVAC, or the external contributions mainly due to traffic noise and noise from adjacent halls. Human noise [41] is mainly due to speech, but footsteps, audio guides and everything generated by visitors is included in this category. While non-anthropic noise sources are predominant in low-attended museums, when the number of visitor increases the human noise becomes predominant. Acoustic characteristics of the environment - such as reverberation time, spatial distribution of sound energy - and occupancy conditions, influence noise propagation.

Moreover, this kind of noise rises in a non-linear way with the increase of visitors [42]. This is due to growing vocal effort and loss of concentration as the background noise increases. It has been observed that a decreasing interest in the exhibition results in more people talking to each other [38]. The consequence is that the more people talk, the more the environment is affected by this noise, and ultimately this leads to other people talking.

In 1997, Tang et al. measured the human noise in a staff cantine during lunch time, finding a correlation between the equivalent A-weighted sound pressure level and the occupancy. They used a normal-raised model for the vocal effort, finding a threshold around 69 dBA [43]. Ten years later, Hodgson et al., surveyed ten eating establishments, using a Lombard-slope model on vocal effort [44].

A similar method was used by Rindel in 2010, to analyse the human noise in eating establishments: he proposed the criterion of *acoustical capacity*, i.e.

how many people it takes to produce human noise equivalent to a signal-to-noise ratio greater than -3 dB, 1 m away from the talker [45]. This way, he found a relationship between occupancy, reverberation time, and noise level. Rindel's model agrees with previous studies [46] observing an increase of + 6 dB when doubling the number of people in the room, and a decrease of -6 dB when doubling the equivalent acoustic absorption area of the environment.

3. Modelling human-related sound pressure level in crowded spaces

A visitor's acoustical experience in a museum exhibition is largely determined by the ratio between the useful sound signal (the voice of a guide, of a friend, etc.) and the detrimental noise that, in highly attended museums, is dominated by the human noise. Therefore, a model is needed relating these two competing sounds and taking into account the main parameters, such as the vocal effort of the speaker, the number of people in the hall actually talking, the attenuation of sound propagating in the space, which is a function of the speaker-listener distance and the number of visitors inside the hall. To this extent the latter parameter must be modelled as a dynamic process, because the number of visitors inside the hall varies with time.

3.1. Extending Rindel's model

Visitors increase their vocal effort when their communication is disturbed by noise. The A-weighted sound pressure level of visitors speech at a 1 m distance from the mouth $L_{S,A,1m}$, can be expressed as [45]:

$$L_{S,A,1m} = 55 + c(L_{N,A} - 45) \quad (\mathrm{dB}A) \tag{1}$$

where $L_{N,A}$ is the background noise, in dBA, and c is the Lombard slope, in dB/dB. This adaptation process starts when $L_{N,A} \sim 45$ dBA, but recent studies have shown a reduction of this threshold down to $L_{N,A} \sim 40\,\text{dBA}$ [47]. Below this noise level there is not feedback between speech level and background noise. This is the reason why visitors activity is not a crucial point inside low-attended museums, in which mechanical noises are dominant.

When the number of talkers increases, the background noise ($L_{N,A}$) is only due to them. In a museum hall, the occupation varies in time, following a dynamical process, as will be discussed in the next section. The number of talkers at time t may be expressed in terms of *group size*. The group size (g) was defined, in the context of a cocktail-party [48, 49], as the ratio between the people in the room (N) and the people who are actually talking (N_s):

$$g = \frac{N}{N_s}. \tag{2}$$

In a closed space, the human noise level depends on the acoustic properties of the environment. Eating establishments were analysed, under a diffuse sound field assumption, by Hodgson et al. [50] and by Rindel [45]. As a consequence, the human noise level was assumed as constant over the room, depending on the acoustic absorption of the hall and the occupancy. Tang et al. used a semi-reverberant model of the sound field, taking into account the contribution of the direct field [43].

Instead, in a museum hall, the sound field can not be considered as constant, due to the diffraction effects of display cases, which affect the mouth-ears paths of visitors. The increasing in sound-energy attenuation due to these latter factors, is denoted by $Att_e(r)$, in dB , and depends on the source-receiver distance r. Moreover, the sound energy attenuation is also due and to to the acoustic absorption of people . This is denoted by $Att_p(N)$ which depends on the number of visitors N and on the equivalent absorption area A_0 of the unoccupied environment, in m^2. The overall acoustic attenuation may be assumed as the sum of these contributions:

$$Att(r, N) = Att_e(r) + Att_p(N) \quad (\mathrm{dB}) \tag{3}$$

Being $L_{s,A,1m}$ the speech level of each talkers, its contribution to human noise, at distance r is:

$$L_{N,A,1p}(t) = L_{s,A,1m} - Att(r, N) \quad (\mathrm{dB}A) \tag{4}$$

The contribution of all the active talkers (N/g), at a distance of 1 m is [48]: $L_{s,A,1m} + 10log_{10}\left(\frac{N(t)}{g}\right)$ It follows that the human noise level $L_{N(t),A}(t)$, at each receiver, can be expressed as

$$L_{N(t),A}(t) = L_{s,A,1m} + 10log_{10}\left(\frac{N(t)}{g}\right) - Att(\bar{r}, N) \quad (\mathrm{dB}A) \tag{5}$$

where $\bar{r}$ is the logarithmic mean distance between the visitors. Using eq. 1 into eq. 5:

$$L_{N,A}(t) = 55 + c(L_{N,A}(t) - 45) + 10log_{10}\left(\frac{N(t)}{g}\right) - Att(\bar{r}, N) \quad (\mathrm{dB}A)$$

and rearranging:

$$L_{N,A}(t) = \frac{1}{1-c}\left[55 - 45c + 10log_{10}\left(\frac{N(t)}{g}\right) - Att(\bar{r}, N)\right] \quad (\mathrm{dB}A) \tag{6}$$

where the group-size g and the Lombard slope c need to be found, while the $Att(N, \bar{r})$ value depends on the acoustic properties of the environment and on the occupancy degree.

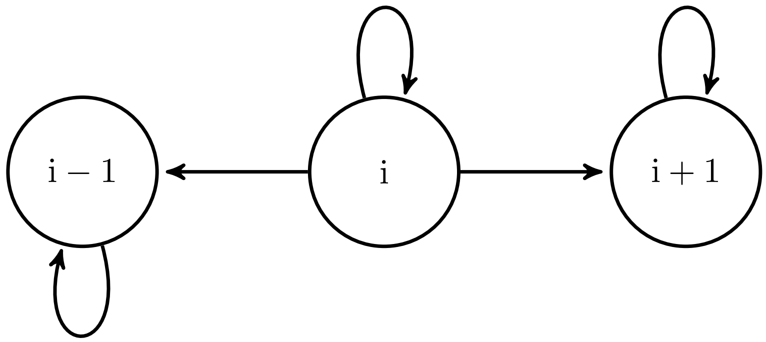


Figure 1: Occupation of a museum hall treated like a Markov chain: the state, i.e. the occupation, can change through adjacent values only.

3.2. Visitors flux modeled as a Markov chain

Visitors move slowly or quickly through an exhibition. Visitors flow has been studied by Serrell in terms of Sweep Rate Index (SRI) [34]. This index is calculated by dividing the total area of the exhibition, in square meters, by the average time spent by visitors within this exhibition area, in minutes. Analysing more than 100 museums and exhibitions, he has come up with an average index value of between 10 sq.m/min and 40 sq.m/min.

Other authors treated the visitors flux inside a museum hall as a k-dimensional Markov-chain [51], being the sequential exhibition the simplest case, for which $k = 1$. A Markov stochastic process is a random process in which the probability of a transition to a new system state depends only on the immediately preceding state and not on how the system came to that state. The occupation of a museum hall, at a given time, can be treated as a logical state, increasing or decraeasing by one unit as a visitor enters or leaves. The model allows to analyse the data with a strict dependence on

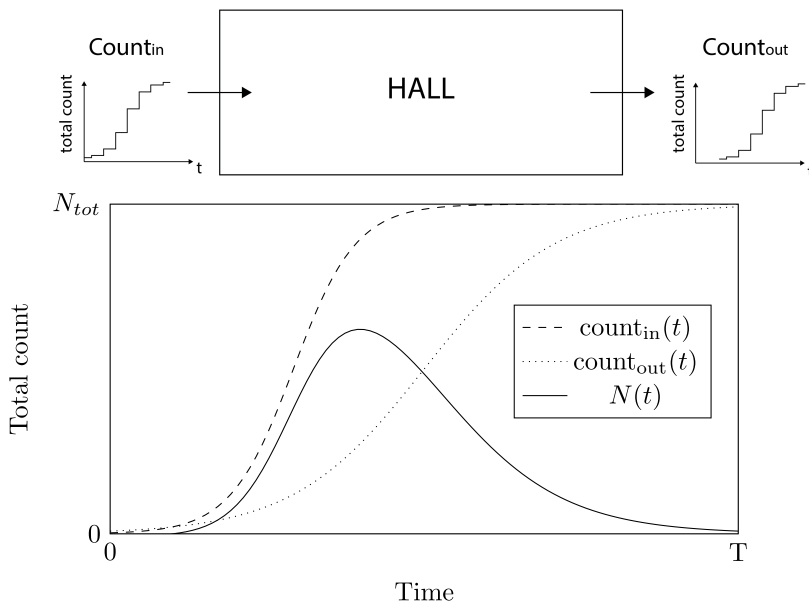


Figure 2: Example of idealised and smoothed cumulative functions of entrances and exits from a museum hall, and relative occupancy of the hall

time. As a matter of fact, this event is a dynamic and discontinuous process, influenced by numerous factors, such as season, time of the visit, visitors age and purpose of the visit. The most significant analysis surely concerns the time spent inside the exhibit hall, influenced by the number of people in the room. Such time increases with the saturation of the room. The passage is obstructed by other visitors and the experience loses fluidity. The problem is also crucial for acoustic comfort, because more occupancy means more background noise.

Let the number of people entering and leaving a museum room be, respectively, two time-dependent variables. If the entrances and the exits are relatively-rare event in time, the probability of having N visitors in a given time interval, considering these time slots occurring successively and independently, may be modeled through a Poisson's distribution.

Fig. 2 shows the smoothed cumulative functions of the number of people enterering and leaving a room, provided by two people counters: the first one at the entrance (count in), and the second one at the exit (count out). Assuming both counters follow a Poisson's distribution, their discrete cumulative function can be fitted by a continuous sigmoid, such as:

$$\mathrm{count}_{\mathrm{in/out}}(t) = \frac{N_{tot}}{1 + \exp(\frac{t}{\tau_{in/out}})} \tag{7}$$

where N_{tot} is the total number of visitors. It can be noted that the time constant τ_{out} value of exit cumulative function is usually higher than τ_{in}, due to different values of crossing time between visitors. The i-th state of the Markov chain is the difference between these to cumulative functions, respectively. It corresponds to the instantaneous occupation of the room, $N(t)$:

$$N(t) = \mathrm{count}_{\mathrm{out}}(t) - \mathrm{count}_{\mathrm{in}}(t) \tag{8}$$

In general, the difference of two Poisson's distributions is a Skellam's distribution [52], which is a more general distribution, depending on two parameters instead of one. When the values of the two parameters are different, the Skellam's distribution looks very similar to the Poisson's one. The Skellam's distribution reduces to the Poisson's one when the expected value of the second Poisson's distribution in the difference is zero. For the sake of simplicity, here it is assumed that $N(t)$ follows a Poisson's distribution. This allows to control the fittings of the data (see Section 5 and Fig. 5.1) with just one parameter, which can be interpreted as the mean visitor dwelling time of the hall..

4. Method

4.1. General method

For the assessment of the reliability of the predictive model proposed (eq. 6), an high-attended museum in Florence was surveyed during a free-entrance day. The analysis was focused on a large room used for temporary exhibitions, which could host more than 130 people at the same time.

The acoustic spatial decay of the room was evaluated through in-situ measurements, and then corrected by occupancy absorption, which shifts-down the spatial decay curve.

The logarithmic mean distance $\bar{r}$ used in the eq. 3, was evaluated from a statistical distribution of distances between visitors. This latter distribution was provided by an algorithm that randomly generates the mutual distances between N visitors, being given the boundary conditions such as the walkable area.

Moreover, the visitor flux varies in time. This can help to study the group size g value, which is defined in eq. 2 and used in eqs. 4 and 6. One-day monitoring of the room was performed, both in occupation and noise levels. The occupancy value $N(t)$ and the sound pressure level $L_{eq,A,1min}$, both averaged over 1-minute windows, were compared a through occurence analysis.

Finally, the communication quality was evaluated as an averaged value over a mean talker-receiver distance, randomly simulated from a subset of close visitors.

4.2. Case study: the Archeological Museum of Florence

The National Archaeological Museum of Florence is one of the oldest and largest in Italy, located in buildings which was property of Medici family. The Museum hosts most of the ancient Medici-Lorraine collections, the Egyptian Museum including a world-renowned Coptic fabrics and the Etruscan section, with the iconic Chimera of Arezzo. Once a month, the free-entrance ticket of the Archaeological museum is joint to that of the Uffizi Museum, the latter being the most visited Italian museum.

The surveyed hall is the *Salone del Nicchio* which is at the same time the first and the last room of exhibition path (see the plan in fig. 3). The room has a rectangular plan (28m x 9.2m) and a volume of 2600 m^3, with stiff plastered walls and characterized by a barrel vaulted roof, 11 m high. Along the side walls there are plasterboards and MDF coatings. In front of the two openings, entrance to and exit from the hall, there are two plasterboard walls 50 cm thick, which allow the place to be separated from the ticket office and the rest of the museum. Along the side wall that overlooks the garden there are large windows and an exit to the garden itself which is temporarily closed to the public.

Table 1: Dimensional data of the room. L, W, H, V respectively the length, width, height and volume of the environment and the mean reverberation time T_M, averaged over the octave bands 500-1000 Hz.

L (m)	W (m)	H (m)	S (m^2)	V(m^3)	Celing	T_M (s)
28	9.30	11	1700	2600	Barrel vault	3.30

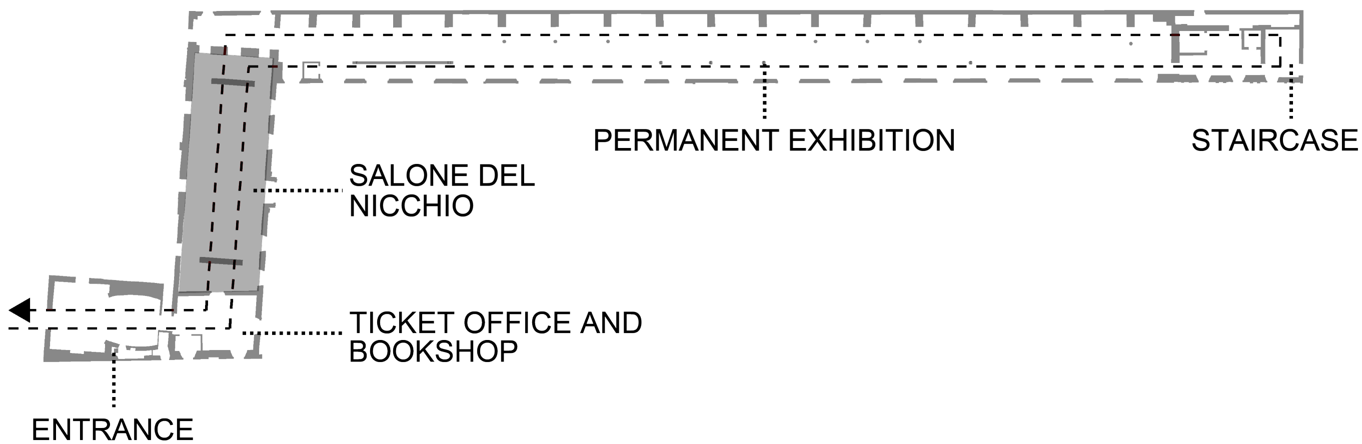


Figure 3: Framing plan of the first floor of the National Archaeological Museum of Florence. The visitors path is shown by dashed black line. The *Salone del Nicchio* is highlighted by grey shading.

In order to take into account the acoustic properties of the environment due to furnitures and different visitors' paths, the impulse responses have been measured through two lines of receivers inside the hall. Receivers were placed at regular distances from the sound source, spanning from 2 to 16 m. A calibrated high-SPL dodecahedron was used as the sound source [54]. Both sound source and receivers were positioned at a height of 1.55 m, assumed as the average height of standing-visitors' ears.

4.3. One-day monitoring

In order to have the largest spread of visitors' activity, the free-entry day was surveyed (see fig. 4). Sound level meters have been placed at 1 m above the display cases to avoid proximity to reflective surfaces (see fig. 5).

Moreover, the visitors' flux was monitored by two counters, placed respectively at the entrance and at the exit of the hall. Each counter had two slots, one increasing when a visitor came in the hall, and the second one when a visitor came out from the hall. The two counters were time-aligned and the data were logged. According to eq. 8 the difference value between the two counters is the state of the Markov-chain.

4.4. Generative simulation of communication distance

Communication distance between visitors changes from place to place and depends on the layout of the exhibition and the type of museum. A parametric model has been developed, with Grasshopper for Rhino 6, in which people were randomly arranged inside the *Salone del Nicchio* hall, in accordance with the occupation range found by measurements.

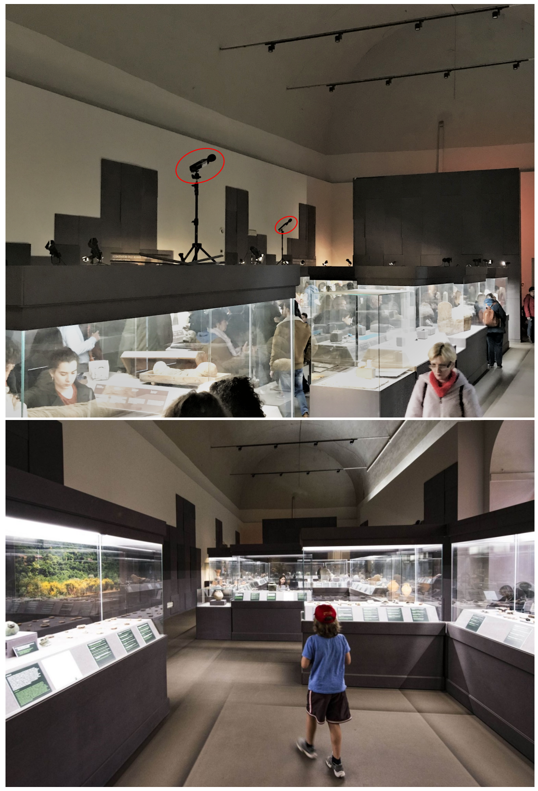


Figure 4: Interior of the *Salone del Nicchio* exhibition hall during the sound level meters measurements.

The algorithm performs the following steps. Starting from the plan of the furnished exhibition hall, it defines the useful area A in which visitors can walk. This is obtained by defining an offset from walls of 40 cm and an offset from display cases of 20 cm. After setting the geometric limits, a random population of points p, representing visitors' positions, is generated. Each point is a bidimensional vector, i.e. a couple of bidimensional coordinates.

Each vector p contains a couples of bidimensional coordinates, representing the visitors which were randomly generated.

The following algorithms return, respectively, the distance-matrix be-

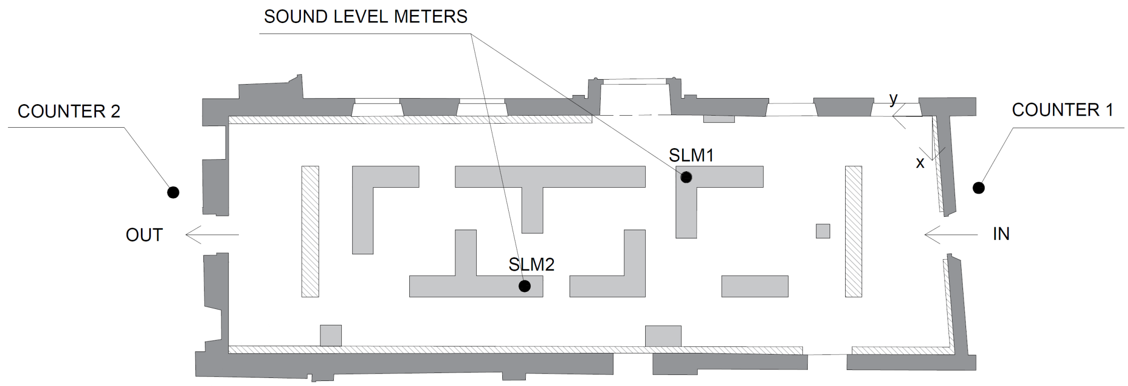


Figure 5: Position of the sound level meters and of the counters.

tween all the N simulated visitors, and the distance-matrix between the five nearest visitors.

Algorithm 1: distances matrix between each visitor and all the remaining visitors

Input: A useful area, N occupancy

Output: r_{ij}; $i = 1, \ldots, N$; $j = 1, \ldots, N$;

```
random N points p in A
for i = 1 : N do
    for j = 1 : N, j! = i do
        r_ij = distance (p_i, p_j)
    end
end
```

Algorithm 2: distances matrix between each talker and the five nearest listeners

Input: A useful area, N occupancy

Output: $r_{near,ik}$; $i = 1, \ldots, N$; $k = 1, \ldots, 5$;

random N points p in A
for $i = 1 : N$ **do**
    for $j = 1 : N, j! = i$ **do**
        $r_{ij} = distance\,(p_i, p_j)$
    end
    for $k = 1 : 5$ **do**
        r_{ik}=min r_{ij}
        clear element (min r_{ij})
    end
end

The distance matrices obtained by the two algorithms, which are respectively $\bar{r}$ and $\bar{r}_{near}$, will be used in eqs. 6 and 16. This method differs to the one proposed by Tang [43] who modeled the enclosure as a rectangular mesh where each occupant occupies one small rectangle of this mesh from which he then calculated the attenuation due to the direct field through geometrical considerations.

5. Results of in-situ measurements

5.1. Visitors' flow

The recorded data may be analysed through the occurrence distribution of visitor's dwelling times, showing a multimodal distribution, see fig. 7(a)

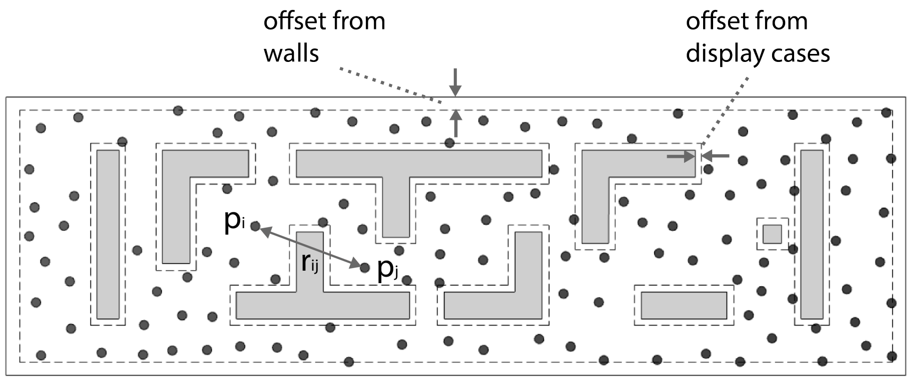


Figure 6: Set of random points generated with the algorithm 1 in order to simulate the distance of communication between the visitors.

and 7(b). The occurrence distribution allows to estimate the crossing time of visitors entering the room for the first time, at the beginning of the museum path, which is found by the differences between the state of the entrances at the first counter and the exits at the second counter; (and also) the crossing time of exiting visitors who visit the room for the second time, at the end of the museum path, calculated from the differences between the state of the entrances at the second counter and the exits at the first counter. According to the hypothesis of Markov chain model, each sub-distribution was fitted through a Poisson's distribution. The mean value of each fitting distribution was assumed equal to the expected crossing time and the exit time. These results could be useful in the analysis of museum performances, like similar studies based on distributed sensors [26]. Crossing times were cropped on three peaks that appear in the occurrence distribution (see fig. 7(a)). Three different distributions were then highlighted. A 'fast' one of about 5 minutes, the most recurrent of about 12 minutes and finally the longest one, with a crossing time of about 23-24 minutes. According to previous studies on visiting dwell time, it is possible to associate these values to different visiting styles: short-stay visitors, medium-stay visitors and long-stay visitors [26].

The same reasoning applies to the opposite flow of visitors, that is to say to the exit from the hall. These showed a more constant trend for all visitors. It should be noted that the exit from the hall, even if it is the first room already visited, is slower than expected (see fig. 7(b)). This is given by the great interest of the temporary exhibition. This crossover of flows, however, greatly increases discomfort and increases the number of people in the room.

5.2. Human noise

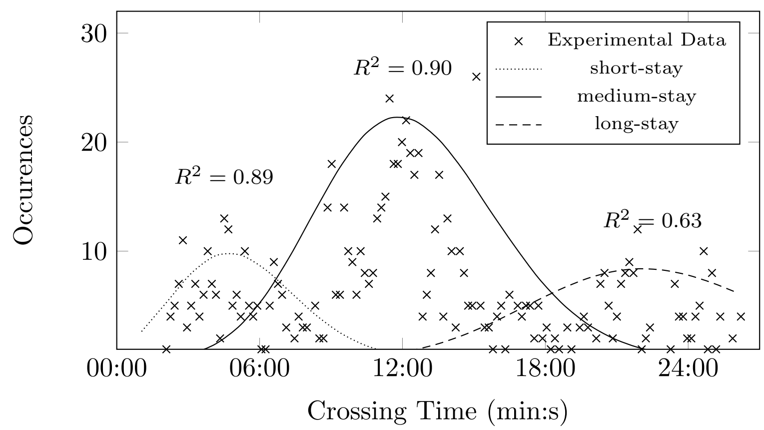
The simultaneous monitoring of the sound pressure levels and the number of visitors in the environment made it possible to understand the impact of visitors themselves on acoustic comfort. In figure 8 the number of people inside the room $N(t)$ and the human noise $L_{N,A}(t)$ are shown.

According to previous literature [43, 50], the integration time of $L_{N,A}(t)$ has been set to 1 minute:

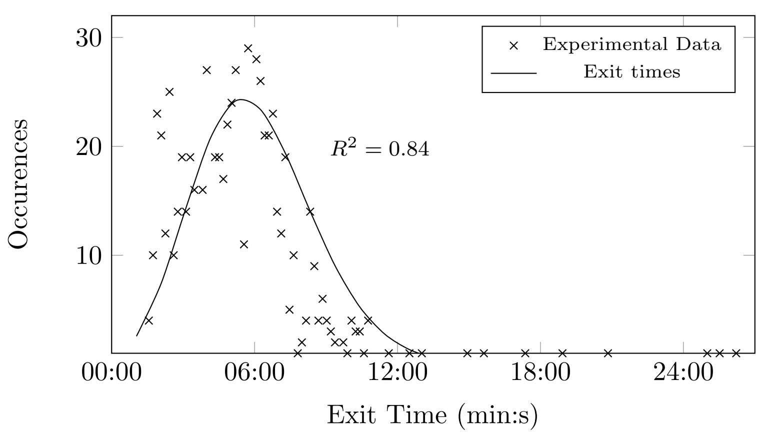
$$L_{eq,A,1min} = 10 \log \frac{t_0}{60} \sum_{i=1}^{\frac{60}{t_0}} 10^{L_{N,A}(it_0)/10} \quad (\text{dB}A) \tag{9}$$

where t_0 is the short-time integration window of the sound level meter, set to 0.1 s.

Being the sound level meters and the counters synchronised, it is possible to know the occupancy N during each 1-minute frame. It is therefore possible to statistically analyse the $L_{eq,1min}$ as a function of occupancy N. The Six-hour measurement return a statistical population of 360 paired samples



(a) Room dwell time of entering visitors



(b) Room dwell time of exiting visitors

Figure 7: Statistical distributions of crossing times and exit times.

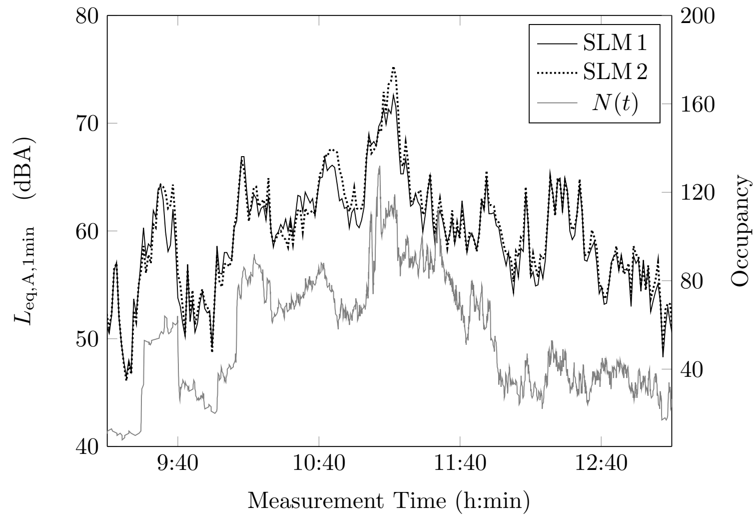


Figure 8: Human noise $L_{eq,1min}$, in (dBA) measured by two sound level meters (SLM1, SLM2), and number of people $N(t)$ inside the exhibit hall during free-entrance day. See the positions of the sound level meters on figure 5.

$L_{eq,1min}$ Vs. N (see fig. 9). The best-fit curve of this trend is:

$$L_{eq,A,1min}(N) \sim 13logN + 38.3 \quad (\mathrm{dB}A) \tag{10}$$

6. Validation of the model

6.1. Attenuation among visitors

The attenuation of sound pressure level $Att(\bar{r}, N)$, in dB, for the exhibit hall under study, depends on the acoustic proprieties of the environment, the mean distance between visitors and on the number of visitors inside the hall. The contribution of spatial attenuation due to the environment – the $Att_e(\bar{r})$ term of eq. 3 – has been calculated as follows.

The measured spatial attenuation (averaged over the 500, 1000 and 2000 Hz octave bands), averaged over two measurement lines, was plotted in fig. 10.

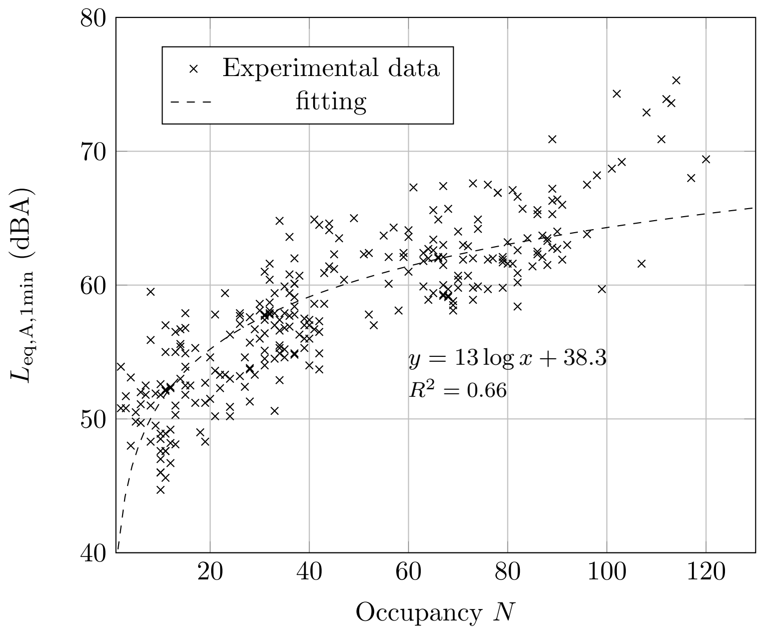


Figure 9: Plot of 1min-frame equivalent level $L_{eq,1min}$ versus the corresponding occupancy.

On the same figure the occurrence distributions of distances between visitors, simulated through the generative algorithm for N=40, 60, 80 and 100 people, are plotted.

The distances between visitors were statistically evaluated thanks to the algorithm 1 of section 4.3. The mean values of log-gaussian fittings of $\bar{r}$ values in high-attended scenarios (cases N=80, 100) are about 6 m, corresponding to an attenuation $Att_e(\bar{r}) \simeq 9\,(\mathrm{dB})$.

In order to estimate the additional contribution to acoustic attenuation due to visitors, the following procedure has been applied. Let's define N_0 as the number of people for which the increase in attenuation due to the acoustic absorption caused by visitors is equivalent to that of the acoustic

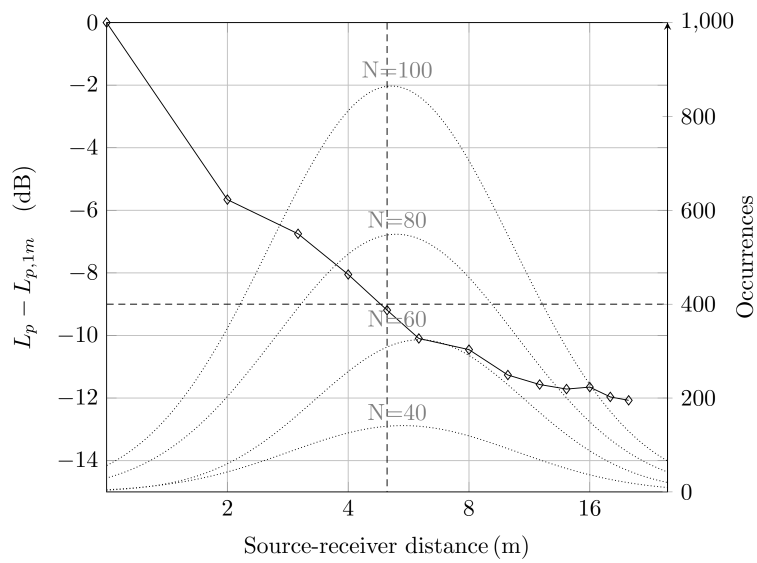


Figure 10: Contribution of spatial attenuation due to the environment ($Att_e(\bar{r})$): the spatial attenuation of sound field is plotted with continuous line, measurements were averaged between 500, 1000 and 2000 Hz; fitting curves of occurrences distribution, calculated through a dynamic algorithm, related to N=40, 60, 80 and 100 people are plotted in dotted lines.

absorption of the environment in unoccupied conditions:

$$N_0 = \frac{A_0}{A_{1p}} \tag{11}$$

where A_0 is the sound absorption area of the room, derived from the acoustics measurements (about 120 m^2), and A_{1p} is the sound absorption area of one standing visitor, assumed as an averaged value in the 500-2000 Hz octave bands of about 1.2 m^2 [53]. It can be estimated that the absorption contribution of Att_p implies an increase of attenuation due to visitors' absorption of 3 dB when $N = N_0$:

$$Att_p(N_0) = x \log N_0 = 3 \quad \text{(dB)} \tag{12}$$

from which, $x \sim 1.5$, and $Att_p(N) = 1.5log(N)$. The full expression of attenuation due to the environment and visitor occupancy is therefore, in the case under study:

$$Att(\bar{r}, N) = Att_e(\bar{r}) + Att_p(N) = 9 + 1.5log(N) \quad \text{(dB)} \tag{13}$$

6.2. Lombard slope and group-size

There are still no well esablished results, to the authors' knowledge, for group-size value g and Lombard slope c inside museums. Both parameters are needed in the formulation of predictive model (eq. 6). Indeed, from eqs. 6 and 13, we have:

$$L_{N,A}(t) = \frac{1}{1-c}\left[55 - 45c + 10log_{10}\left(\frac{N(t)}{g}\right) - 9 - 1.5log(N)\right]. \quad \text{(dB}A\text{)} \tag{14}$$

In order to find the best fit values for group-size g and Lombard slope c, the provisional curve of eq. 14 may be iteratively matched to the measured values of eq. 10, as shown in figure 11. The best-fit process return, respectively, a group-size value $g \simeq 4$ and a Lombard Slope $c = 0.4$. Both these values are within the ranges proposed by previous literature and the technical standard on vocal effort ISO 9921. Using the found values of g and c, eq. 14 becomes, for the case under study:

$$L_{N,A}(N) \sim 36.7 + 14.2 \log(N). \quad \text{(dB}A\text{)} \tag{15}$$

6.3. Communication quality

The signal-to-noise ratio is the difference, in dB, between the useful signal, i.e. the voice of an interlocutor, and the detrimental noise, i.e. the

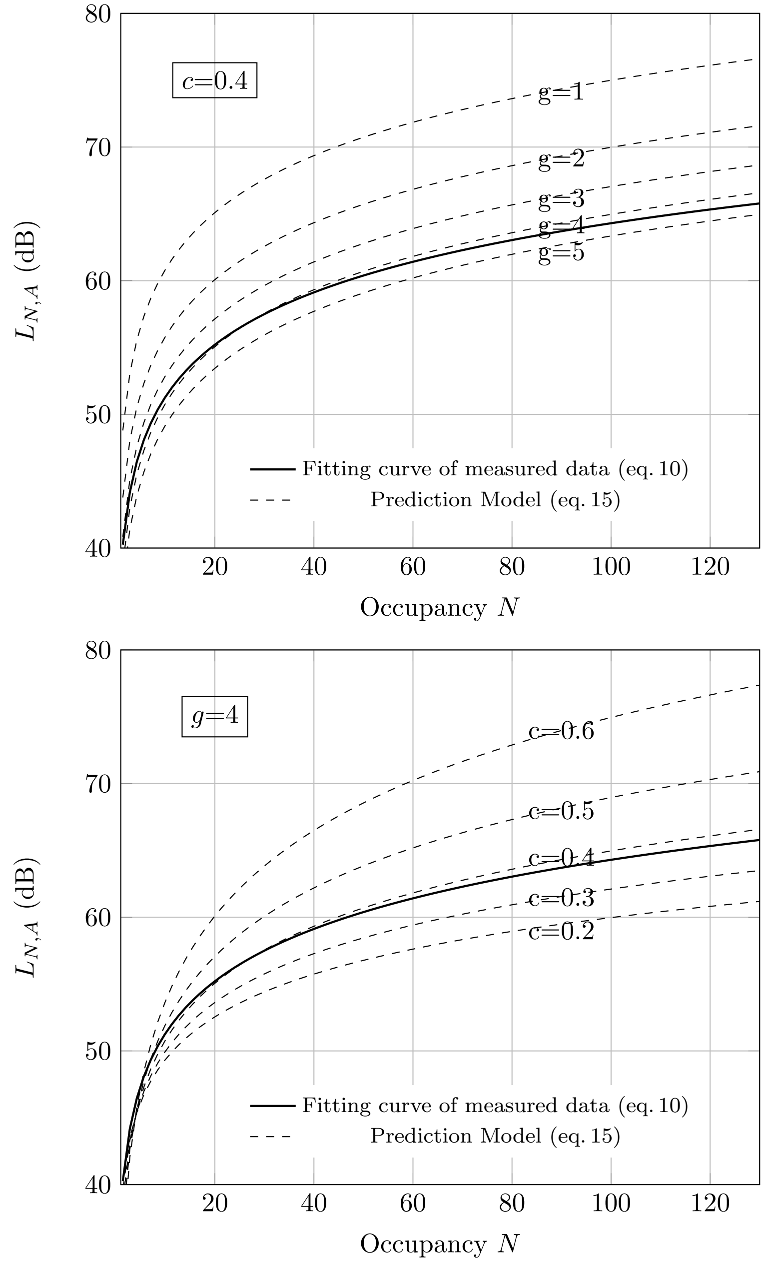


Figure 11: Fitting of the curves of the two models, the measured and the forecast, calibrated through the group-size variable, g, and the Lombard slope, c.

human noise. This criterion can be assumed as a metrics of speech intelligibility. Depending on the attention mechanism and on the type of verbal communication (Interpersonal, Small Groups, ...). Different SNR thresholds - from -3 dB [42] to +6 dB [50] - were proposed in order to achieve a satisfactory degree of transmission. In this study, a minimum value of 0 dB was used. Considering a speaker with 'normal' vocal effort, such as a professional guide, the SNR varies depending on the distance of listeners, according to the expression:

$$SNR(\bar{r}_{near}) = L_{S,\mathrm{normal},A}(\bar{r}_{near}) - L_{N,A} = 60 - 20log\left(\frac{\bar{r}_{near}}{r_0}\right) - L_{N,A} \quad \text{(dB)} \tag{16}$$

where r_0=1 m and $L_{N,A}$ follows the general formulation of eq. 14 or the specific formulation for the case under study of eq. 15.

Depending on the type of verbal communication, the distance between the talker and nearest listeners $\bar{r}_{near}$ should properly set. Algorithm 2 proposed in section 4.3 returns the mean distance between each talker and the five nearest listeners around him. Various attempts of simulations are shown in fig. 12. The results show that the average distance between visitors is in a range between 0.7 m (nearest listener of the group) and 1.8 m (farthest listener of the group). It should be noted that these results agree to proxemics studies [39, 40], which found a mean distance between talkers of about 1-1.2 m for such kind of communication.

Based on the results of fig. 12, the values of SNR as a function of occupancy can be found through the eq. 16. Fig. 13 shows the curves for nearest, mean and farthest case, respectively 0.7 m, 1.05 m and 1.8 m. For each curve,

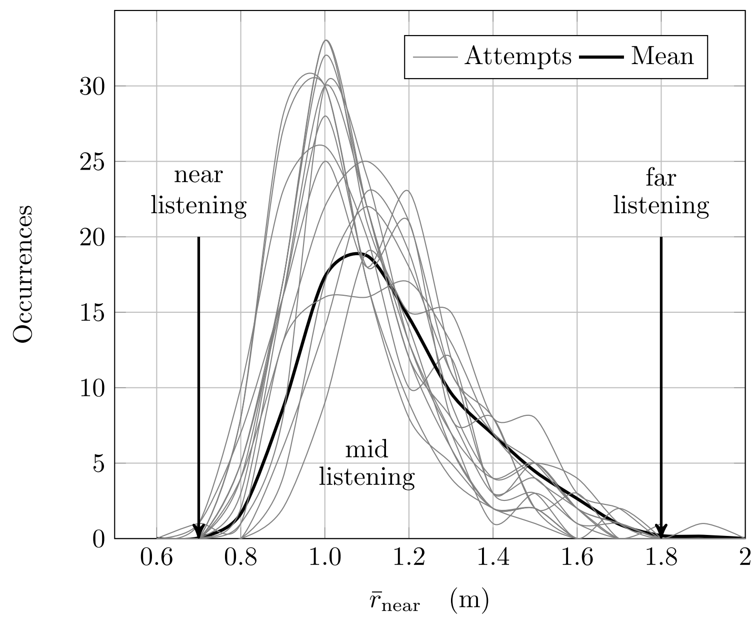


Figure 12: Occurrences of distances for the five nearest persons simulated by algorithm 2 in section 4.3. Gray curves: results of 10 attempts; black curve: mean of the 10 attempts.

the occupancy corresponding to a SNR value of 0 dB is the maximum number of visitors which allows a satisfactory verbal communication.

Once collected all the parameters of the predictive formulations, a final comparison between the present analysis and the previous ones [43, 45, 50] is proposed in table 2.

6.4. Effects on exhibition design

The last figure of the previous section needs further observations. Indeed, here is a relationship between the acoustic conditions of the environment and the maximum number of persons who may visit a museum in a given time interval, if an adequate acoustic comfort has to be ensured.

The first point (the acoustic conditions of the environment) is affected by

Table 2: Comparison between the previous studies on human noise and the present one.

Reference	Place	Model	Lombard slope c (dB/dB)	Group-size g	Talking distance $\bar{r}_{near}$ (m)
Tang et al. [43]	canteen	direct + diffuse field	–	–	
Rindel [45]	restaurants	diffuse field	0.5	3-4	1
Hodgson et al. [50]	cafe, bistros, restaurants	diffuse field	0.69	3	1
Present study	museum	non diffuse field	0.4	4	0-7–1.8

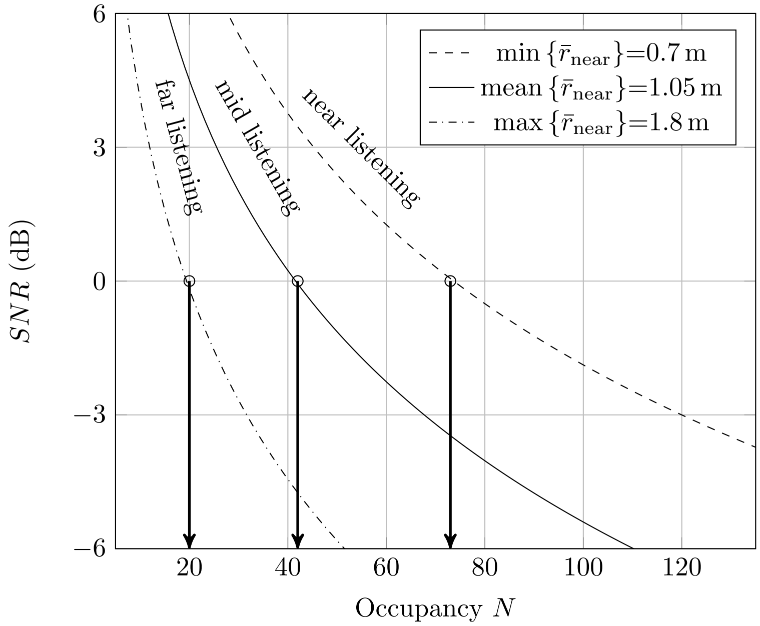


Figure 13: Signal-to-noise ratio (SNR) as a function of occupancy inside of the *Salone del Nicchio* hall. In the case under study the group-size g is about 4, the Lombard Slope c is 0.4 dB/dB, the spatial attenuation is $9 + 1.5\log(N)$, in dB, and the crossing time is about 12 min. The arrows refer to the maximum number of occupants for three scenarios of talker-listeners communication. The talkers' vocal effort was considered as a fixed value, i.e "normal" vocal effort.

the acoustic absorption of the space (in non-occupied conditions) A_0 and the layout and height of the display cases. The latter tactors influence the slope of the curve in fig. 11: the higher the display case and dense the layout, the higher the attenuation. In case of already existing historical spaces or listed buildings, due to heritage constraints, it is not often possible to modify the sound absorption of the space (which is not sufficiently high, for instance in the case of empty halls). However, it has been shown how the presence of display cases can affect the spatial attenuation of sound energy. The cases that are higher than the mouth-ear path and that are arranged in a 'noise-barrier configuration', increase the spatial decay of the sound energy.

Concerning the second point (the maximum number of persons) it is possible to keep under control the average visiting time. Using the Serrell's SRI, as a comparison parameter with the others museum halls, the *Salone del Nicchio* has a SRI value of $15\,\mathrm{m}^2/\mathrm{min}$, considering an average room crossing time (medium-stay visitors) of about 12 min and a walkable area of 180 m^2. Optimal value SRI found by Serrell are higher than this value. [34]. It means that the visitors' flux measured inside of the Nicchio Hall is too low. This can be due to two reasons. First, the surveyed hall is the first room of the museum, which is known to have a higher rate of attention than the rest of the museum. Moreover a very high number of exhibited works makes the room crowded and the visit speed very slow. This factor can constrain the maximum quantity of exhibits to be added in a certain space: more elements lead to an higher visiting time. The longer is the visit time, much more people are, at the same time, inside the space creating discomfort.

This design criterion can be useful to the exhibition designer or to the museum space manager. It should be considered that the verbal communication inside a museum hall has an additional impact on the learning process and attention effort. An appropriate containment of $L_{N,A}$ allows for example to a group of children to have the appropriate distance from the teacher and to maintain a good understanding of words. In case of adult visitors, or even visitors which are not involved in verbal communications, it must be considered that the containment of anthropic noise contributes not to increase the museum fatigue, helping the correct use of the museum space.

Finally, it must be considered that high background noise leads to the triggering of Lombard effect and it has been shown that this lowers the ability to assimilate and/or not to stress out.

7. Conclusions

Museum visitors should be able to learn and discover novel context during their experience, which needs to be interesting, but are also subject to a fatigue that is strongly conditioned by the surrounding environment. While the thermal and visual aspects of this peculiar experience are largely studied in scientific and technical literature, there are few studies on acoustic comfort in museums. In particular, it is a common experience that in highly attended museums, the acoustic comfort is mainly conditioned by the human noise produced by visitors themselves.

In this work a predictive model of human noise is proposed, based on previous ones on eating establishments and generalised in order to take into account the visitors' behaviour. In this model, the display cases act as acoustic barrier for speech propagation, so that the spatial attenuation of the sound field is not negligible as in the case of eating establishments.

While the talkers' walking path and the occupancy variation still depends on each specific context, the temporal evolution of the occupancy can be modelled using the Markov-chain theory. Statistical results of this model have been produced using generative algorithms to simulate the visitors' spatial behaviour.

A highly attended museum in Florence was used to validate the model, choosing to monitor a free-entry day. The comparison between the measured results and the predictive model return a Lombard-slope value of about 0.4 dB/dB, slightly lower than the values proposed in eating establishments, and in the range of vocal effort allowed by ISO 9921. A group-size value of about 4 was found, which is still plausible for the environment under study. Moreover, the proposed model was shown useful to analyse the visitors' spatial behaviour.

It is hoped that the proposed model be a useful tool for museum responsible to plan and implement more effective exhibitions. In fact, giving a closer insight to visitors behaviour, the proposed model can suggest appropriate ways for designing an experience that will increase visitors satisfaction from an acoustical perspective. For example, when a museum is located in an historical building often the halls are not comfortable from an acoustical point of view, but usual acoustic treatments are not allowed due to cultural heritage constraints; in such cases, good visitor comfort could be reached through a proper design solution driven by the dynamical approach proposed here.

Acknowledgements

The authors gratefully acknowledge the direction of Archeological Museum of Florence. The authors would also like to thank Jens Holger Rindel, who provided preliminary suggestions on the group-size, and Laura Anderlucci, who assisted in the statistical analyses. The authors are indebted to Alessia Milo and Michele Ducceschi for suggestions and for proofing the manuscript.

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