

The importance of long-term hygrothermal assessment of museum spaces: method and application in a permanent exhibition in a historical building

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Abstract

This paper presents the analysis of the hygrothermal conditions of a museum space hosted in an 18th century building, in Coimbra (Portugal). This historical building, which houses the Science Museum of the University of Coimbra, is located in the historic centre of the University of Coimbra, officially declared a World Heritage Site in 2013 by UNESCO. The methodology proposed in EN 15757:2010 was applied to two monitoring campaigns carried out at a distance of 4 years, in two of the rooms of the permanent exhibition. The results of the monitoring periods are presented and discussed. The findings unveil the necessity for long-term monitoring of the indoor environmental conditions of museum spaces, towards the support of grounded based-evidence guidelines for the conservation of objects and quality of environment for exhibits conservation.

Keywords

Microclimate
Preventive conservation
Hygrothermal assessment
Building Heritage

Da importância da avaliação higrotérmica de longo prazo de espaços museológicos: método e aplicação numa exposição permanente num edifício histórico

Resumo

Neste artigo são analisadas as condições higrotérmicas de um espaço museológico situado num edifício do século XVIII, em Coimbra (Portugal). Este edifício histórico, que acolhe o Museu da Ciência da Universidade, localiza-se no centro histórico da Universidade de Coimbra, declarado oficialmente como Património Mundial em 2013 pela UNESCO. A metodologia proposta na norma europeia EN 15757:2010 foi aplicada em duas campanhas de monitorização realizadas a uma distância de 4 anos, em dois dos espaços da exposição permanente do MCUC. São apresentados e discutidos os resultados dos períodos de monitorização. As conclusões mostram a importância da monitorização das condições ambientais internas dos espaços museológicos a longo prazo, no sentido da elaboração de diretrizes de conservação de objetos e da qualidade do ambiente interior para a conservação de exposições, suportadas e baseadas em evidências.

Palavras-chave

Microclima
Conservação preventiva
Análise higrotérmica
Património histórico edificado

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Introduction

In many European cities, differentiated cultural spaces, such as museums, exhibition galleries or libraries, are housed in historical or heritage buildings [1-2] whose visit also enhances an intangible cultural heritage experience – e.g. in the Florence district (Italy), 90 % of the museums are housed in historical buildings [3]. In many situations, an existing building has been adapted into a museum, and a compromise between objects conservation and visitors' comfort is required [4]. For the same reason, this type of buildings offers different challenges to conservators and curators. Unlike new buildings that are specifically designed to accommodate museums and are provided with building management systems, most of those historical buildings run on natural ventilation conditions and are sometimes absent of any kind of heating and cooling system. In such cases, the indoor-outdoor climate relation is normally very strong [3]: the air temperature and humidity inside respond in a faster or smoother way to the variations of the outdoor ambient conditions. Furthermore, there is usually a strong relation between air temperature and relative humidity – typically these two parameters behave symmetrically in face of short term variations [5-6].

Besides the indoor-outdoor relation and its influence on the indoor environmental conditions in historic buildings, it has also been recognized the meaningful consequence of the interactions that occur between the indoor environment and the objects housed in such spaces. In fact, when not properly controlled, these effects might lead to irreversible damages [7-8]. Since the beginning of this century, more emphasis has been given to preventive conservation [9-12]. As advocated by Corgnati & Filippi, “monitoring is an essential tool to develop an actual preventive control programme aimed at maintaining the optimal microclimatic conditions for preservation” [13]. One significant contribution on this subject is the indoor environmental quality protocol for preventive conservation in museums developed by D’agostino et al. [14]: herein, apart from the acoustic evaluation, it is foreseen the measurement of lighting, the hygrothermal parameters, the concentration of gaseous pollutants and particle matter. As prompted by these authors, strategies of monitoring and controlling the environmental conditions are often neglected and the conservation of the exhibited works is put at risk.

The importance of microclimatic monitoring of museum rooms has been previously praised [15]: on one hand, it is important to drive direct actions to reduce the risk of degradation of exhibited objects; on the other hand, it is important to specify adequate environmental conditions in which those objects should be exhibited [3, 16]. The following study is focused on the second premise. As such, a discussion on the current conservation standards is proposed, grounded on long-term hygrothermal analyses – seasonal and short-term fluctuations, performed on data collection from the

permanent exhibition of a museum located in a historic heritage building.

It is well known that the hygrothermal conditions are fundamental factors for the conservation of exhibited goods in museums and spaces alike. Several standards, guidelines and technical regulations can be found in the literature addressing this issue: (i) in some cases, strict “safety intervals” are defined, such as in UNI 10829 [17]; (ii) in other situations, less restrictive approaches have been presented, such as in ASHRAE:2015 [18]; (iii) in EN 15757:2010 [19], the acclimatization process of the exhibited collections to the spaces historical climate is reflected.

Moreover, significant new indices have been developed to assess the quality of a museum environment [17, 20]. Although the European standard is not so recent, the applications found in the literature are relatively scarce. As such, accounting on the recorded data in the Science Museum of the University of Coimbra (MCUC) and also on its physical condition and the absence of any heating, ventilation and air conditioning (HVAC) systems, an evaluation of the monitored hygrothermal conditions according to EN 15757:2010 was performed on data collected over more than 24 months, between 2011/12 and 2015/16. Additionally, data were also analysed according to ASHRAE’s design parameters for Museum spaces [18].

Methods and materials

Case-study presentation and rooms description

The MCUC was created in 2006 by the junction of the Physics Museum and the Natural History Museum (zoology, mineralogy and geology, botany and anthropology sections) [21]. It is a university museum, whose collections were initially collected and bought for use in classes context. The MCUC has exhibition spaces open to the public in two nearby facing buildings: the *Laboratorio Chimico* and the ancient Jesus College. The measurements treated in this article are from Jesus College rooms.

The Jesus College is an old building that began to be erected by the Jesuits in 1747 and then remodeled after 1772, during the important education reform initiated by the Prime Minister of Portugal, Marquês de Pombal. All the exhibition rooms of the museum are large and have high ceilings (about 7 m). The rooms are decorated with 18th and 19th century original cabinets where the collections are displayed, and this is one of the main riches and highlights of this university museum.

The museum does not have any heating, cooling or mechanical ventilation system. The studied exhibition rooms, the Vandelli Hall and the Portugal Hall, are integrated in a carriage-type gallery (Figure 1) [22]. The museum has defined a touristic circuit where the exhibition rooms are interconnected by keeping the doors opens. The two exhibition rooms studied in this work

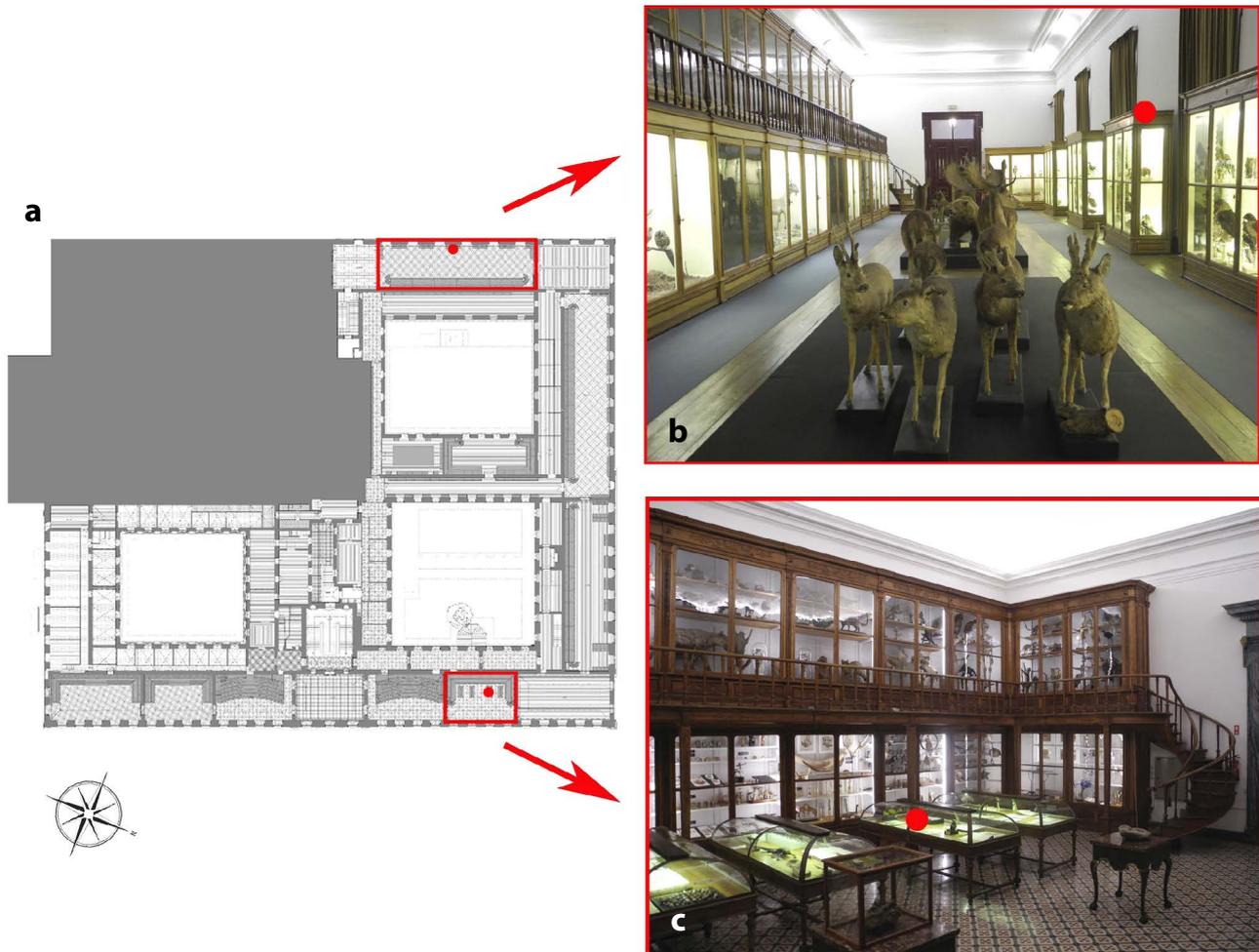


Figure 1. MCUC: a) plan of the first floor and location of the data loggers on the studied rooms [22]; b) Portugal Hall; c) Vandelli Hall.

correspond to the first and last rooms of the Natural History exhibition, and are separated and distant from each other, since they are situated on opposite sides of the building. Besides opposite solar exposure, these rooms are located at different construction phases of the building (e.g. the building envelope properties differ between construction periods).

Currently the museum is open every day of the week (closed only for three holidays per year), but during the time of this study, the museum opened only by prior appointment.

The first room, the Vandelli Hall (VH) – named after Domingos Vandelli (1730-1816), Italian scientist who was the first professor of Natural History and Chemistry at the UC –, contains samples of the most important and oldest collections of the acquies. In this space we can find, among others, the collection that Vandelli himself sold to the university, as well as the ethnographic objects collected by Alexandre Rodrigues Ferreira in Brazil (between 1783 and 1792) [23]. There is a great blend of collections of different types. We can find birds, fishes, reptiles and embalmed mammals, skeletons, teeth and horns, minerals and rocks, ceramics, fossils, paper mache models, watercolors,

books, etc. There is naturally a considerable diversity of materials present in these objects (vegetable fibers, wood, paper, leather, feathers, bone, ivory, metals, glass, etc.), a situation that often causes conservation problems. In the VH, the data logger was placed inside a relatively tight display case made of wood and glass, provided with LED lighting.

The second room, the Portugal Hall (PH), is dedicated to the fauna of the Iberian Peninsula. In this case, the collection is not so diverse as in VH. It is composed mostly of embalmed birds and mammals. The last bear caught in Portugal stands out. In PH, the data logger was placed about 3 m high, on top of a display case in the centre of the room. The main data concerning the exhibition rooms' characteristics are presented in Table 1.

Microclimate measurements

Taking into account the various approaches and methodologies to assess the indoor environmental conditions of museum spaces currently in practice [13, 17-19, 24-25], the data analysis and results discussion in the next sections are settled essentially following EN

Table 1
Room characteristics and equipment

		Vandelli Hall	Portugal Hall
Room dimensions	Floor surface (m ²)	118	263
	Volume (m ³)	888	1645
Windows	Orientation	East	West
	Number	4	6
	Type	Sash windows	Casement windows
Exhibited objects		Natural History	Fauna of the Iberian Peninsula
Equipment	Number	1	1
	Location	Inside a display case (c. 0.80 m from the floor)	On top of a display case (c. 3 m above the floor)

Table 2
Summary table of all registered values on the exhibition rooms

Space	Period	Parameter	Maximum value	Average \pm standard deviation	Minimum value
Vandelli Hall (VH)	29 Aug 2011 – 26 Sep 2012	<i>T</i> (°C)	27.0 ^a	19.2 \pm 5.4	8.7 ^b
		<i>RH</i> (%)	86.3	56.6 \pm 8.5	28.6
	23 Feb 2015 – 8 Mar 2016	<i>T</i> (°C)	26.5	18.7 \pm 4.7	11.1
		<i>RH</i> (%)	71.2	58.4 \pm 5.7	28.6
Portugal Hall (PH)	29 Aug 2011 – 26 Sep 2012	<i>T</i> (°C)	29.7	19.3 \pm 4.8	8.5 ^c
		<i>RH</i> (%)	81.8	58.5 \pm 8.4	29.9
	23 Feb 2015 – 23 Mar 2016	<i>T</i> (°C)	30.2 ^d	18.6 \pm 4.7	9.2
		<i>RH</i> (%)	92.0	65.0 \pm 9.3	33.3

Notes:

^a Registered at 2012/07/25, 16:50 (outdaily mean = 22.1 °C). ^b Registered at 2012/02/13 at 09:40 (outdaily mean = 7.2 °C). ^c Registered at 2012/02/05 at 10:10 (outdaily mean = 4.7 °C). ^d Registered at 2015/06/20 at 18:40 (outdaily mean = 29.1 °C).

15757:2010 [19]. As early stated, not so many applications of this European standard can be found in the literature. Moreover, the MCUC is an historic building without any HVAC system; therefore, the current condition of the permanent exhibition corresponds to an acclimatized context. Nonetheless, the obtained results are compared with those obtained through other guidelines and/or methodologies, e.g. ASHRAEs' method [18].

Environmental monitoring campaigns

Until 2011, no hygrothermal study had ever been carried out inside the MCUC. By then, it was decided to have an initial representativeness of all the rooms (at least one data logger per room). Currently some rooms are provided of more than one sensor – though this issue might be hereafter addressed, it is out of the scope of the current study.

As it was intended to measure the conditions to which the exhibited items were exposed (and not the thermal comfort of visitors, for example), in the VH, since all the items are exhibited inside cabinets and/or display cases, the logger was herein placed. In the PH, since a significant number of the exhibited embalmed animals is not in display cases and is directly subject to the room air conditions, it was decided to monitor the room's hygrothermal conditions – suspected to be less favourable to the preservation of the items. We make notice that that until nowadays no significant building intervention has occurred and the hygrothermal conditions of the room are subject to the direct influence of the building envelope. The precise location of the loggers is presented in Figure 1.

According to EN 15757:2010 [19], data from over one year should be considered for a proper analysis (395 days, to be precise: one year plus one month). Intending

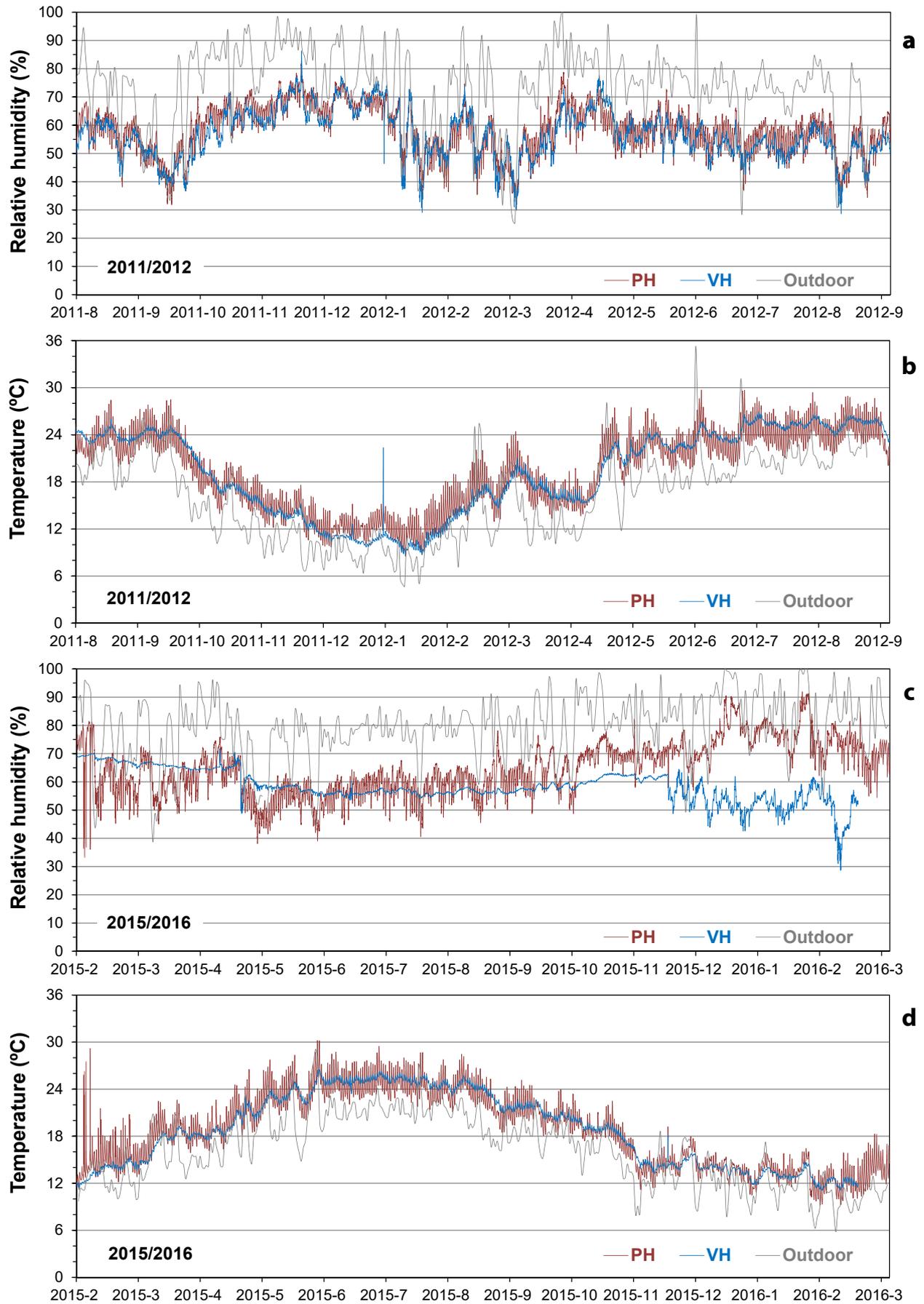


Figure 2. Indoor (Vandelli Hall - VH and Portugal Hall - PH) and outdoor hygrothermal parameters recorded in 2011-12 and 2015-16.

to enlarge our study, as suggested in [15], indoor air temperature (T , °C) and relative humidity (RH , %) were registered every 15 minutes using Tinytag View 2 (TV-4501) data loggers [26], at a distance of four years, during two main periods: (1) 29/08/2011 to 26/09/2012, and (2) 23/02/2015 to 23/03/2016. Specifications on the TV-4501 can be found on Tinytag [26] and include an unobtrusive grey case and monitors temperatures from -25 to +50 °C and relative humidity from 0 to 100 % using built-in sensors, with T sensor logger resolution 0.02 °C or better and RH sensor with an accuracy of ± 3.0 % RH at 25 °C.

Results and Discussion

Global hygrothermal overview

The overall data collection is shown in Figure 2 and Table 2. The analysis of this figure immediately unveils the importance of indoor and outdoor monitoring of the environmental conditions of the museums space, towards a hypothetical hygrothermal rehabilitation, enhancing deep information of the building behaviour.

From data observation, various inferences can be pointed out.

- Nonetheless the outdoor conditions unquestionably influence the indoor ones, the data logger placed in PH shows far more dependence on the external climate. Both hygrothermal parameters were much more stable in VH than in PH. Although this difference may suggest a single influence from the different location of the loggers in the rooms – inside/outside the display case –, please consider also the observation in point 3.

- RH values outdoors were generally higher than indoors and the opposite was verified for T .
- The influence of the thermal inertia of the building construction, as earlier suggested by Dias Pereira et al. [5], seems to have a clear influence in differences found among the two rooms: the pictures clearly disclose that VH and PH were built in different construction phases of the Jesus College, and that VH construction is heavier. In fact, the building in the VH zone was better executed, as the construction occurred during a richer period of the Portuguese kingdom.
- When comparing the autumn/winter periods of 2011/12 and of 2015/16 (e.g. September-March periods), the RH during the second period in VH showed a different behaviour, detaching from the outdoor conditions. The same was not verified in the indoor T records.
- Outdoor RH seems to have a stronger impact indoors than the outdoor air temperature (T). During both winter periods (December-March), for example, RH values indoors varied much more than indoor T (besides considered more stable, T slopes are less abrupt and less pronounced).

Concerning Table 2, some other readings were drawn:

- Maximum indoor temperatures registered in both rooms were above many of the international guidelines maximum temperatures (roughly ≈ 24 °C [17, 27-28]). Moreover, in PH (2015/16) the maximum air temperature (30.2 °C) surpassed the upper limit determined by ASHRAE (though these specifications determine a temperature set point between 15 and 25 °C, seasonal adjustments are accepted [± 10 °C] but not above 30 °C).

Table 3

Summary of daily variations of the hygrothermal parameters during both monitoring periods

Room	Year/ Period	Parameter/ Guideline	ΔT (24 h) (% compliance)	ΔT (24 h) (°C) (max - min)	ΔRH (24 h) (% compliance)	ΔRH (24 h) (%) (max - min)
PH	2011/12	ASHRAE B	97.5	10.3 - 1.0	97.5	20.6 - 2.2
		UNI 10829	3.6		2.2	
	2015/16	ASHRAE B	97.8	6.9 - 0.3	97.3	24.0 - 1.1
		UNI 10829	16.4		34.8	
VH	2011/12	ASHRAE B	99.7	11.3 - 0.1	98.9	24.6 - 1.3
		UNI 10829	97.3		70.1	
	2015/16	ASHRAE B	100	4.3 - 0.1	100	18.1 - 0.0
		UNI 10829	98.6		98.9	

Note 1: The authors opted by ASHRAE's class B as it is appropriate for most historic buildings and presents "a very small risk for most artifacts"; "Classes B and C [...] are the best that can be done in most historic buildings" [5]. ASHRAE B reference values: ΔT (24 h): ≤ 10 °C; ΔRH (24 h): ≤ 20 %.

Note 2: UNI 10829 (1999)[17] is supplemented with D. M. 10 Maggio 2001 [27]. In certain cases/materials, as specific woods and papers, the recommended daily fluctuation of RH reduces to 2 and 5%, respectively. T fluctuations remain at 1.5 °C in the case of wood and might reach 3 °C in the case of paper. UNI 10829 reference value: ΔT (24 h): ≤ 1.5 °C; ΔRH (24 h): ≤ 6 %.

- It is also worth mentioning that very low air temperature values were registered during both monitoring campaigns: in both rooms T values lower than 9 °C were recorded. Both records corresponded to particularly cold days in Coimbra: in 1-15 February 2012, mean outdoor temperature (MOT) varied between 4.7 and 11 °C. The coldest day was February 5th (the day when the lowest temperature was registered in PH). The lowest temperature record in VH was registered on February 13th (MOT = 7.2 °C), after a very cold day, February 12th (MOT = 5 °C). Although *ASHRAE Handbook* states “cold winter periods double life” of objects [18], indoor air temperature values below 10 °C are particularly uncomfortable in terms of the occupants (workers and visitors), considering the relatively low metabolic rate (1.2-1.6 °C [29]). Even more recent and *flexible* standards, such as those considering an adaptive thermal comfort behaviour (ASHRAE’s 55 [30] or EN15251 [31]), accounting on the outdoor conditions, do not consider acceptable indoor operative temperatures lower than 17 °C [30] or 19 °C [31].
- RH mean values were generically between 55 and 60 %. In PH, during 2015/16 this value was slightly higher.
- Extreme values of RH were particularly worrying (maximum values higher than 80 % and even 90 %, and lowest values lower than 30 % were registered).
- The higher stability of the hygrothermal parameters in VH is also confirmed by the annual RH mean values, which was the same in both monitoring periods.

Short-term fluctuations

The definition of fixed and universal optimal values for all types of exhibited objects and materials in museums is a rather difficult task. This is why different reference values and intervals are found in the literature [17-18, 28]. More consensual is the significance of short-term fluctuations of the hygrothermal parameters, namely T and RH daily cycles.

Object deterioration depends not only on the absolute values of each of these parameters but also on their fluctuations in time. Depending on the object, RH fluctuation can be as significant as T fluctuation [3]. In Table 3, for both monitored periods in both rooms, maximum daily amplitude of temperature (ΔT_{\max}) and of RH (ΔRH_{\max}) are reported, as well as its percentage of compliance according to two different technical regulations.

As it can be observed, in both periods, VH performed significantly better than PH, especially if considered its performance according to UNI 10829 [17], a much stringent reference. Besides the effect of building quality, the aforementioned buffering effect of the display case (were the logger in VH was placed), recommends

a complementary study – as stated by Scurpi et al., “showcases are of key relevance in the conservation and are widely used in not HVAC equipped museums” [3].

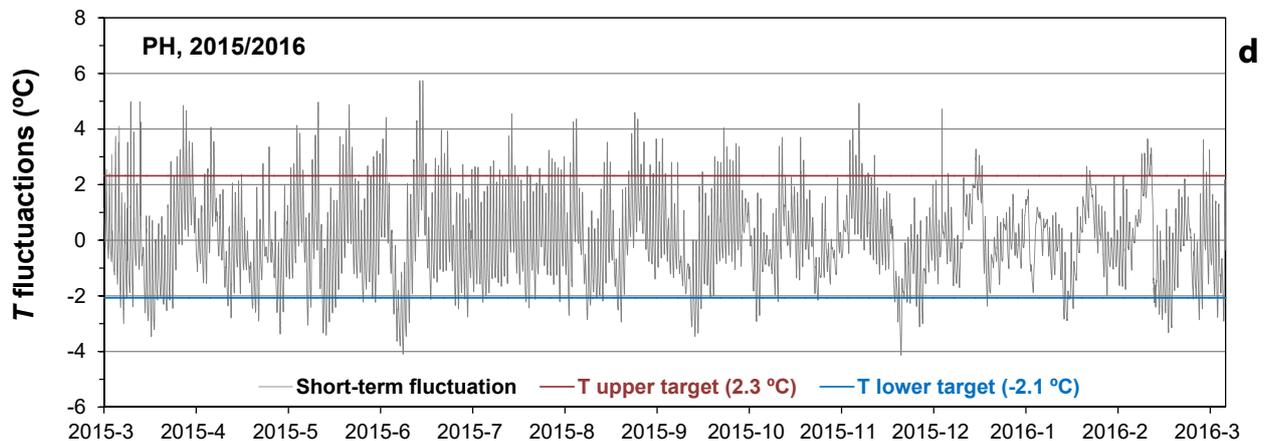
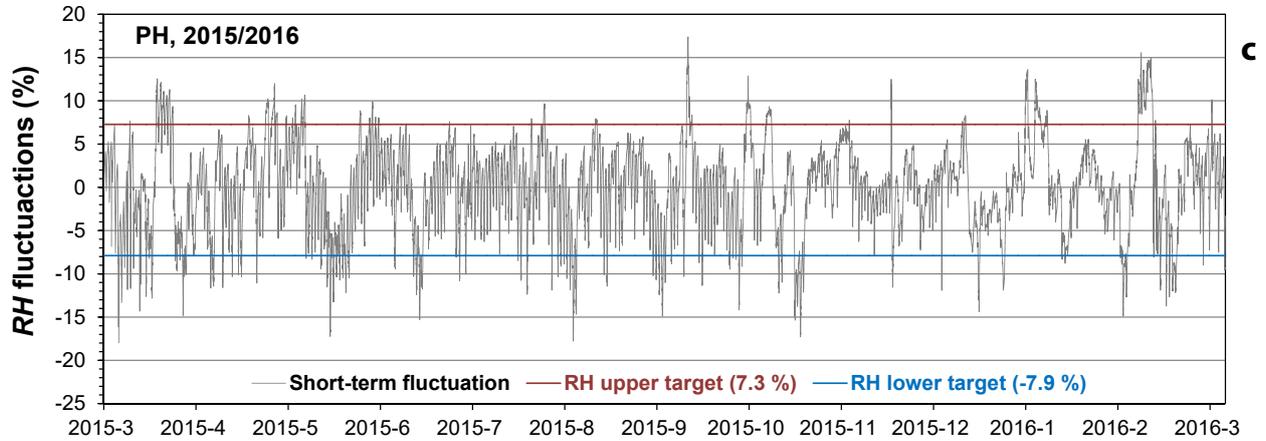
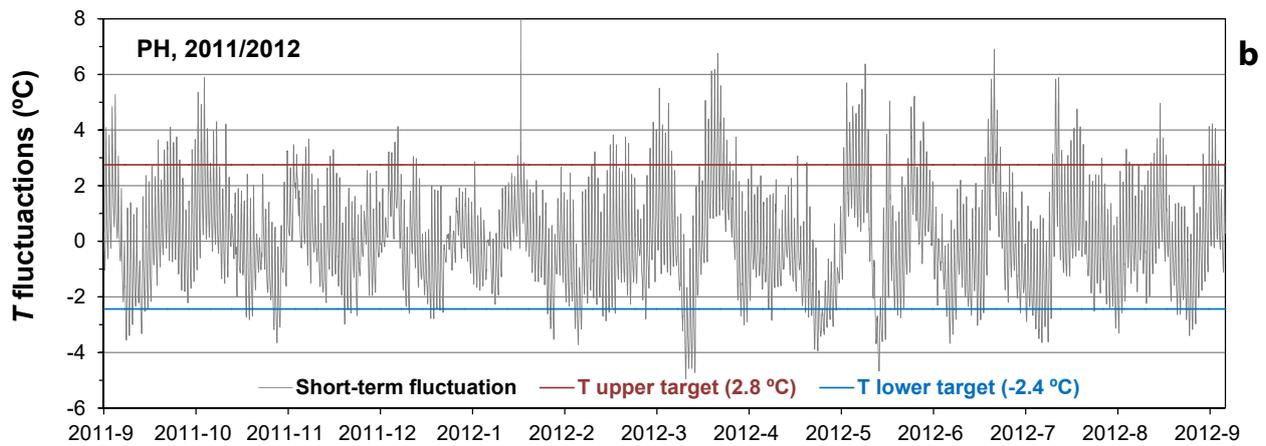
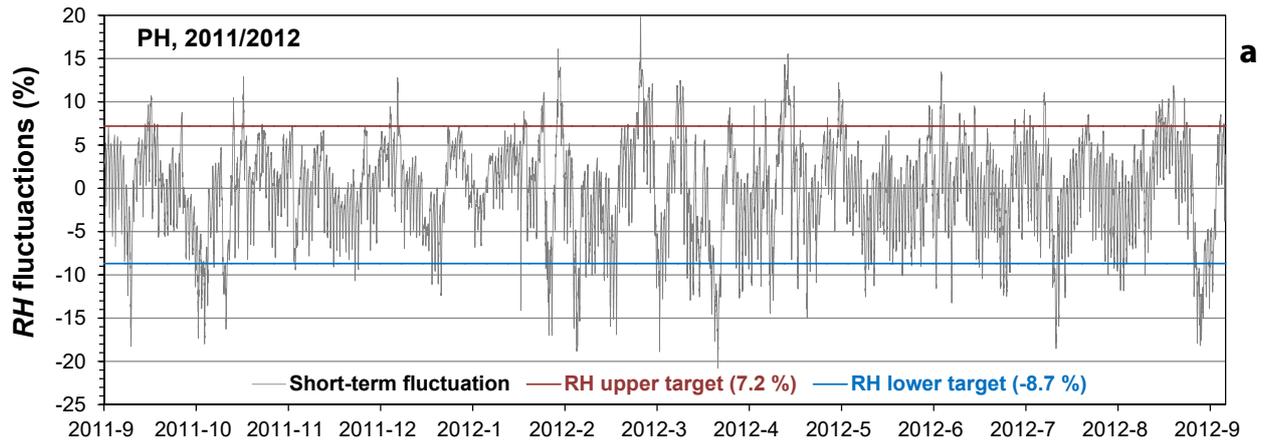
Contrarily to the UNI 10829 guidelines, EN 15757:2010 [19] does not define fixed intervals for daily fluctuations: daily cycles can vary and they are estimated for each computed value by subtracting the moving average from the instantaneous value. In this case scenario, the intervals depicted in Figure 3 were obtained. From the observation of the obtained data, several observations can be pointed out:

- Looking individually at each room, for both analysed years, the upper and lower limits of each hygrothermal parameter vary.
- Considering a yearly analysis (e.g. 2011/12), in VH the daily fluctuations are smaller, and so are the “safety intervals”.
- When looking at 2015/16’s data, the obtained fluctuation limits are quite disturbing – e.g. in VH the obtained RH interval is stricter than UNI 10829 limits.

This analysis brings up the importance of pursuing a continuous long-term monitoring (more than just one year) of the indoor environmental conditions of museum spaces, towards the support of grounded evidence guidelines for the exhibition conservation. Otherwise, erroneous conditions of conservation of objects might be taken for granted. This suggestion is reinforced by previous researches on the subject [9, 32-35], which pointed at learning from the historic indoor climate conditions and also at the history of building itself and its different construction phases.

In addition, a comparison of the obtained results with similar case-studies available in the literature (e.g. museums housed in historic buildings) was attempted, but this has proved a difficult mission. Firstly, many of the most recent *in-situ* studies conducted in museums refer to air-conditioned spaces; secondly, in many occasions the comparison would be biased due to the different type of exhibited items, the type of room usage or even the state of conservation of the building itself.

One of the most divulged Portuguese case-studies is that of Museu Nacional de Arte Antiga (MNAA), located in Lisbon, in a Palace of the 17th century, in which Silva et al. analysed “two air-conditioned and one uncontrolled rooms, [...] to understand the general response of the building” [36]. Unluckily the last space corresponds to the chapel, which, on its turn, was closed to visitors during the study (conducted in 2014). In another study, developed by Ferreira et al. on the Museum of the Faculty of Fine Arts of the University of Porto (FBAUP Museum), installed in a palace of the 19th century, the focus was addressed to the museum storage rooms “visited sporadically by the technical staff” [37], which are mechanically ventilated. Moreover, the comparison with the data collected in the exhibition gallery would be unreasonable due to the recent rehabilitation of the building and its buildings physics (between 2009 and 2010 the FBAUP Museum



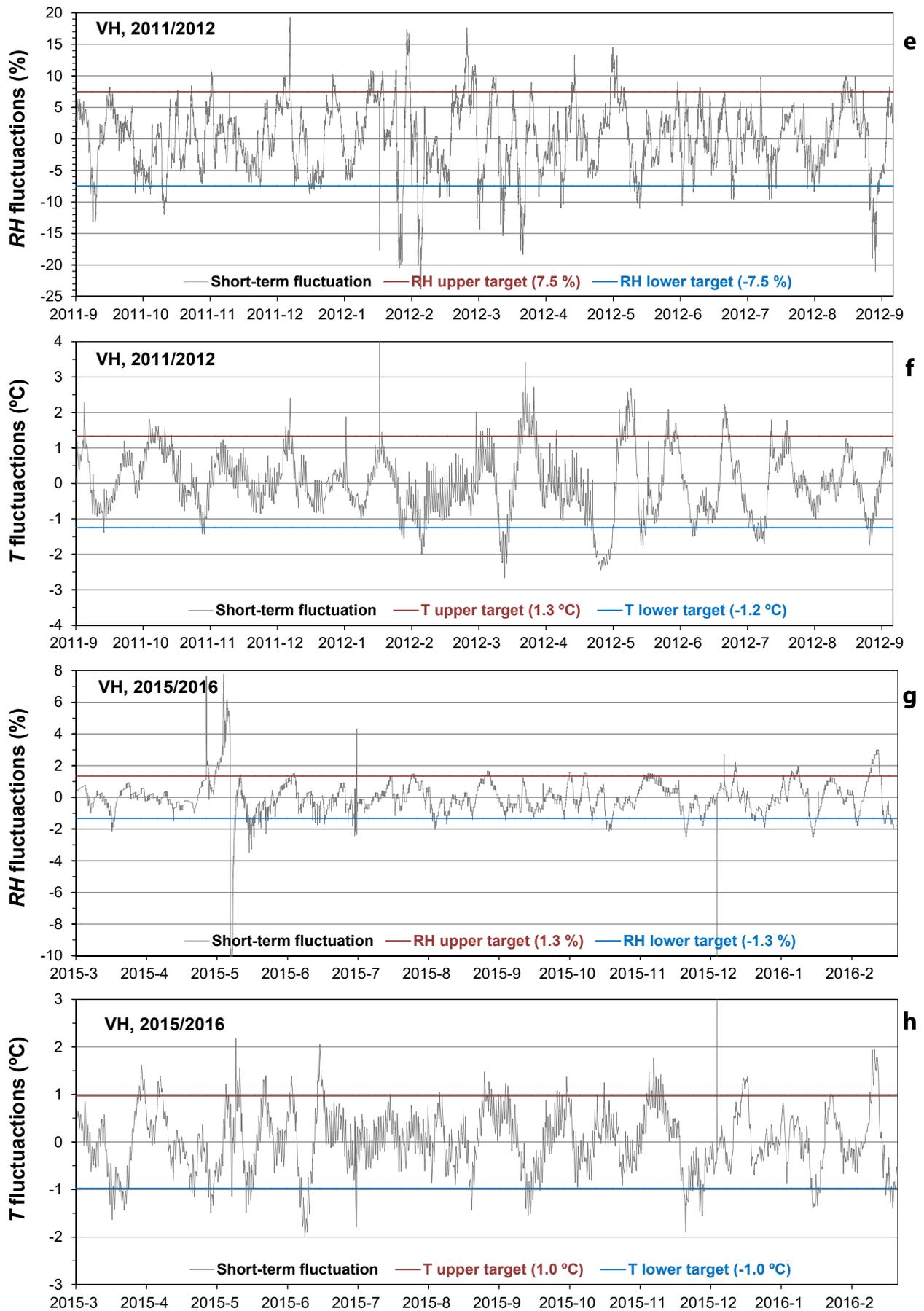


Figure 3. Short-term fluctuations of temperature and relative humidity, determined in PH and VH for 2011/12 and 2015/16.

has undergone a significant intervention in terms of the energy efficiency improvement: the addition of thermal and waterproofing insulation of the envelope, improvement of the windows and the installation of a ventilation and air-conditioned systems; moreover, its original building physics is typical of the 1950's – consisting of granite masonry and reinforced concrete slabs, [38] in [39]).

In short, the singularity of the MCUC makes it hard to be compared. Nonetheless, the international study developed by Sciarpi et al. in the “La Specola” museum in Florence (built in the 18th century) [3] is rather similar to the one herein presented. To begin with, this is considered the first European scientific museum and it is known for its famous zoological collections; then, the experimental monitoring of the environmental parameters was conducted in representative rooms inside and outside showcases whose characteristics do not significantly differ from those in the MCUC; finally, the authors performed a similar data analysis (using EN 15757 and one-year data collection). One of the evidences from this study is that the hygrothermal parameters trend from the uncontrolled rooms (i.e. absent of HVAC systems) was similar and the data followed the outdoor climate, just like in the MCUC. Other inferences concerned the daily variations of such parameters, specifically the difference between the values registered inside and outside the display cases. Globally, the display-cases “reduce *RH* variations respect those of the rooms” [3], i.e. the buffering effect of the display-cases was confirmed, giving further support to the same effect in the MCUC. Despite the similarities, some differences can be pointed out: *i*) at the MCUC, in VH the maximum ΔT (24 h) varied between 4.2 and 11.3 °C and the maximum ΔRH (24 h) varied between 18.1 and 24.6 %, while in “La Specola” museum these values were equal to 3.6 °C and 7 %, respectively; *ii*) on the other and, when comparing the hygrothermal fluctuations of the rooms conditions, in PH the maximum ΔT (24 h) varied between 6.9 and

10.3 °C and the maximum ΔRH (24 h) varied between 20.6 and 24.0 °C, while in the analysed rooms in Florence museum these values were 4.7 °C and 20 %. Generally, the daily variations of the hygrothermal parameters inside the display cases in “La Specola” museum were more satisfying. Moreover, though indoor air ΔT (24 h) were more significant in the MCUC (in the PH), the daily variation of *RH* was quite similar (≈ 20 %).

Beyond short-term fluctuations

It is generally accepted that high *RH* levels endanger collections. In fact, *RH* values above 80 % are known for empowering mould growth and risk of condensation [40]. In ASHRAE Handbook, 75 % is stated as a critical value [18]. On the other hand, when *RH* levels are low, materials release some water molecules decreasing the moisture content enhancing their shrinking [40-41]. Besides a daily cycle analysis, Kalamees et al. suggests that for studying wood cracking caused by *RH* fluctuations in an unheated church, “one month would be a more appropriate time interval” [40].

Nonetheless the potential impact of high *RH* levels on the original cabinets housing the exhibition in the Museum, for the current analysis our study looks deeper into the seasonal analysis. As such, this section examines the seasonal variations of the recorded data, following EN 15757:2010 instructions (e.g. the calculation of a 30-day moving average and 7th and 93th percentiles – determination of the sustainable limits) and also ASHRAE’s class B recommendations.

As previously suggested, contrarily to other norms or guidelines, the EN15757 is less demanding, i.e. does not recommend fixed values, allowing a daily and season variation of the hygrothermal parameters (though the proposed methodology in this norm is mainly addressed at the *RH*). Figure 4 results from the application of this methodology, defining the upper and lower limits of

Table 4

Summary of the hygrothermal parameters target bands (i.e. tolerable fluctuations) according to the EN 15757 methodology

Parameter	Values	Year/ Period	Portugal Hall	Vandelli Hall
Relative humidity (%)	Yearly average	2011/12	58.6	56.8
		2015/16	64.7	61.5
	Extreme values	2011/12	40.3–77.0	39.5–76.6
		2015/16	45.1–87.0	54.5–70.9
Temperature (°C)	Yearly average	2011/12	18.9	18.8
		2015/16	19.0	19.3
	Extreme values	2011/12	9.5–27.6	8.9–26.8
		2015/16	10.0–27.3	11.5–26.3

Note: It is generically assumed that *RH* values above 75 % are dangerous for conservation purposes, including biological degradation. As such, though estimated according to EN 15757:2010, *RH* upper limits above 75 % should be disregarded.

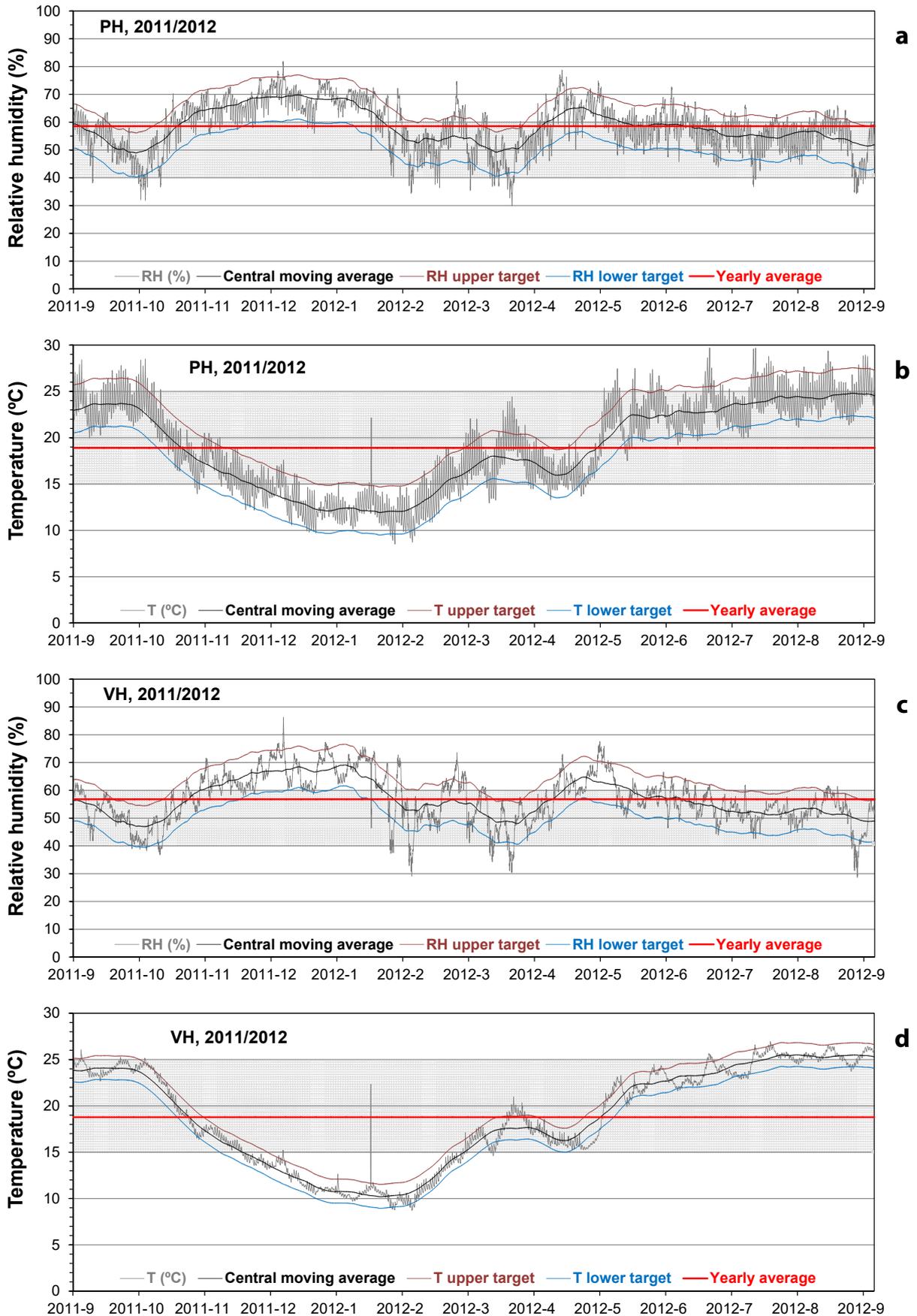


Figure 4. Target bands of tolerable fluctuations compared to the monitored values. Continuous lines represent EN15757 safety targets (defined by the upper and lower limits, the 7th and 93rd percentiles excluding 14 % of the more dangerous fluctuations) and the shaded areas represent the T range 15-25 °C and the RH range 40-60 % defined by class B of ASHRAE.

the acceptable fluctuation band (i.e. 7th and 93th percentiles). For the sake of brevity, only 2011/12's data are graphically represented (Figure 4) and both these results and the 2015/16's results are summarized in Table 4. Based on these data and Figure 4, some comments are due:

- A temperature peak is noticeable in 2011/12's January data in both rooms. This was a day of data collection from the data loggers and the peak was probably due to equipment handling.
- Generically (e.g. looking at the yearly averages), relative humidity is the parameter that changes the most, either between rooms and/or years.
- Monitored RH values are broadly high. Consequently, upper *safety targets* determined by EN 15757 are also much higher than those determined by most of conservation guidelines. Special attention is due to the calculation for PH during 2015/16. In this case, 89 % of RH was achieved as a *safety target*.
- The strong relation/dependence of these two parameters is reinforced by the obtained results: in PH, both RH and T *safety targets* are more extreme than in VH.
- Though significant fluctuations were registered in both rooms and observed periods, the yearly averages were not so far from the recommended guidelines. Namely ASHRAE's class B: in this case either 50 % or "historic annual average for permanent collections" can be used as reference.

In the same way, "temperature set between 15 and 25 °C". Herein, yearly averages have varied between 18.8 and 19.3 °C.

Grounded on this analysis, the collected data was also analysed according to ASHRAE's class of control B. Figure 5 synthesizes this analysis. Ideally, data recorded in both exhibition rooms should fit the intervals 15-25 °C (T) and 40-60 % (RH). According to these criteria: (i) none of the exhibition rooms presents satisfying conditions regarding the conservation of the displayed heritage; (ii) both rooms performed better in 2011/12 than in 2015/16; (iii) RH increase (>60 %) in between years is very significant and particularly disturbing in PH – in 2015/16, RH monitored data were above 60 % more than 67 % of the time.

Moreover, as recommended for this conservation class, temperature values below 30 °C were investigated in both exhibition rooms (PH and VH): this sub-criterion was achieved almost 100 % of the monitored time (both 2011/12 and 2015/16).

Besides the fixed RH interval 40-60 % (average 50 ± 10 %), data were explored according to the historic

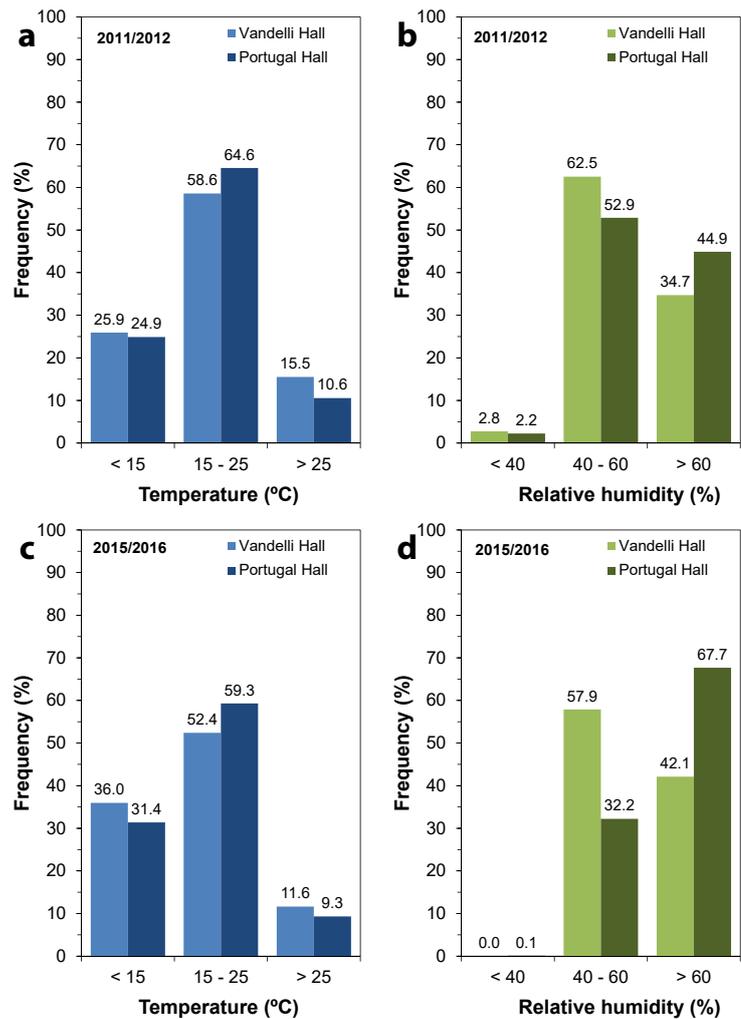


Figure 5. Distribution (%) of the monitored data according to the ASHRAE recommended intervals for conservation, class B., in 2011/12 and 2015/16.

annual average. In this case, a different percentage of compliance in seasonal adjustment, i.e. according to the distribution (%) of the monitored data according, is shown in Figure 6.

When compared with the previous distribution (%) of the monitored data, namely Figure 5, both halls perform significantly better than initially anticipated. In fact, in 2015/16, VH percentage of compliance is almost 100 %. Once more, it is emphasized the significance of performing careful data analysis, "towards the support of grounded based-evidence guidelines for the exhibits conservation". The definition of proper conservation targets cannot be dissociated from cautions and strategic analysis of the monitored data.

Conclusions

Besides a growing attention towards the conservation aspect of exhibited items in museum spaces, a greater focus has also been addressed to the energy consumption

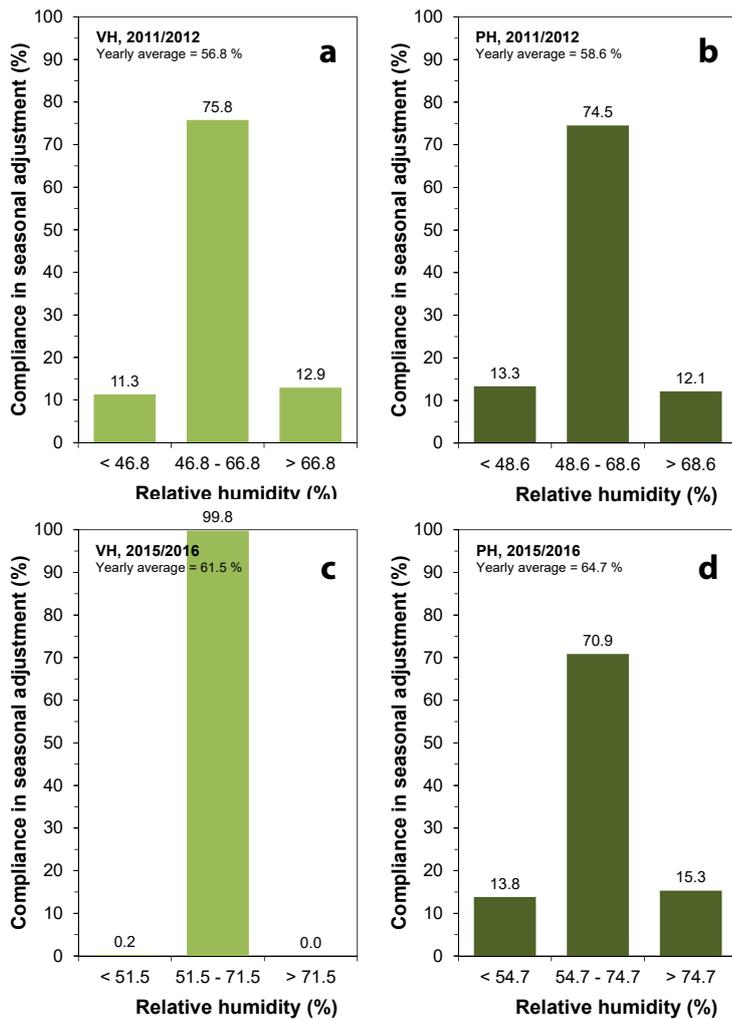


Figure 6. Relative humidity percentage of compliance in seasonal adjustment (yearly average \pm 10%), according to the distribution (%) of the monitored data in both rooms.

of such buildings [42-44], particularly in Cultural Heritage spaces [45]. As reported by Celenza et al., thermal heating energy is a determinant factor in such buildings, its proper management plays a key role in the global energy efficiency and enhances potential energy savings [46]. This concern becomes even more relevant with the recent publication of EN 16883:2017 *Conservation of Cultural Heritage – Guidelines for Improving the Energy Performance of Historic Buildings* [47], which should have been implemented in each European member state by November 2017 at the latest. As such, a correct definition of the interval of the hygrothermal parameters is a fundamental step forward. Improper targets of temperature and relative humidity may put collections at risk and will lead to misuse of energy.

Avoiding rapid or extreme fluctuations minimizes artefacts deterioration. As observed, in this historic museum, the thermal mass of the building positively helped to avoid sharp short-term fluctuations, and monitored data, though not optimal, were generically satisfying – the potential buffering effect of the display case

(where the logger in VH has been placed) can also not be neglected and suggests additional study on this matter, as reinforced by the comparative study by Sciarpi et al. in the “La Specola” museum [3].

The same cannot be said about extreme values of air temperature and/or relative humidity. Data showed the necessity to introduce some control aiming at minimizing the impact of the most extreme values, e.g. $RH > 75\%$ and $T > 30\text{ }^\circ\text{C}$, so that during the year, when excluding 14 % of data beyond the *safety targets* as defined according to EN 15757:2010, the peaks are minimized and the extreme limits respect this maximum values (instead of the estimated 89 %, Figure 4).

As pointed out by Richman et al. [32] and Timusk [48], many solutions exist to *reduce condensation potential*, namely: (i) reducing indoor RH by providing more ventilation, (ii) air-tightening the building envelope, and (iii) depressurizing the interior during cold periods. In the present case, the authors believe that by accurately (de)humidifying the air during the critical periods would immediately improve the obtained results. Another option could be warming up the indoor air when RH is higher. Additionally, in order to enhance a more stable environment, some other measures could be implemented: sealing of windows and/or placing a windbreaker in the entrance/exit doors of the museum; adding a layer of hygroscopic materials to the walls or ceilings increasing the hygroscopic inertia of the rooms [49].

As it is not possible to define optimal values for all materials in all rooms (as suggested in [17], since the exhibition rooms are inter-communicating and integrated in a carriage-type gallery), according to the various analyses carried out in both rooms (VH / PH) and in both years (2011/12 and 2015/16), mostly grounded on Figure 4, the following intervals were broadly defined as being optimal values for the MCUC rooms:

$$40\% < RH < 75\%;$$

$$15\text{ }^\circ\text{C} < T < 27.5\text{ }^\circ\text{C}.$$

These hygrothermal ranges are quite broad and far from the most demanding international guidelines. In this regard, it is therefore recommended that data analysis should continue, so that these intervals, grounded on the historic climate of the MCUC, are defined with more confidence. For an immediate and more self-assured decision, it is recommended that the hygrothermal parameters would be conditioned by the annual average (55-60 % and 18.5-20 $^\circ\text{C}$, Table 2) and closer to human thermal comfort boundaries.

In conclusion, this paper provides a detailed insight on the significance of long-term hygrothermal assessment

of museum spaces. The presented methodology (mostly grounded on EN 15757 – based on two periods of 395 days of monitored data distanced in time, in the present case at a four-year distance), starting from a global assessment of data and followed by the analysis of short-term fluctuations (determined in agreement with EN15757 but analysed also according to ASHRAE guidelines), has shown how much of a variety of outcomes can be expected. Moreover, it points at the importance of performing a proper data analysis, aiming at avoiding inappropriate interpretation and misleading the actual requirements of such places.

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