Photograph of the interior of the dwelling used for the neuroarchitecture experiment, NIU Campolivar (Fran Silvestre Arquitectos), Valencia. (Source: by the authors, 2024).

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An exploratory neuroarchitecture study: emotional responses to residential spaces using psychological and physiological indicators

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Abstract: This study explores the emotional impact of residential architecture through the combined use of psychological and physiological measures. A neuroarchitecture field experiment was conducted in a real, fully equipped dwelling with a sample of 30 participants. The participants walked through the various rooms in the dwelling under both daytime and nighttime conditions. Emotional responses were assessed using the PAD model (pleasure, arousal, dominance), and physiological signals, electroencephalogram (EEG), heart rate variability (HRV) and electrodermal activity (EDA). Statistically significant differences were found across rooms, time of day and gender. Collective areas—such as the living room and entrance forecourt—were associated with higher levels of pleasure and dominance and lower physiological activation, while individual spaces—such as bedrooms and bathrooms—elicited higher physiological activity and lower psychological emotional responses, particularly among female participants. An inverse relationship was found between pleasure/dominance and physiological activation, suggesting that physiological indicators could serve as non-intrusive proxies for subjective well-being. Nighttime exposure was also linked to increased arousal, likely due to circadian disruption caused by artificial lighting. These findings underscore the importance of integrating objective and subjective measures in architectural evaluations, as they offer actionable insights for the design of emotionally supportive residential environments. Limitations and directions for future research are discussed.

Keywords: neuroarchitecture; residential architecture; emotional response; psychological measures; physiological measures; user experience.

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1. Introduction

Neuroarchitecture is a discipline focused on the study of the relationship between the built environment and human experience at behavioral, cognitive and emotional levels, through physiological recording (Higuera-Trujillo et al., 2021). The discipline's development has followed a progressive trajectory, driven by the growing need to understand how built environments influence human perceptions, behaviors and emotional states. From the early formulations of Neutra (1954), who argued that architecture must address the neurological needs of its users, to the incorporation of advanced technologies, such as neuroimaging and virtual reality, the discipline has undergone significant evolution (Assem et al., 2023; Higuera-Trujillo et al., 2021; Wang et al., 2022).

Numerous studies have demonstrated that the built environment exerts a direct influence on brain activity, modulating cognitive functions such as creativity, attentional processes and stress regulation (Asim et al., 2023; Azzazy et al., 2021; Bruer, 1997; Malinin, 2014; Perry, 2002; St-Jean et al., 2022). Architectural variables such as spatial orientation, lighting conditions and acoustic quality are critical determinants of spatial perception and overall quality of life. At the physiological level, exposure to specific lighting parameters has been shown to impact on blood pressure, heart rate variability, cortical activation patterns, core body temperature and melatonin secretion (Bellia et al., 2011; Knez, 1995; Katsuura et al., 2005; Liu et al., 2024; Yan et al., 2012; Wilkins, 2016). Furthermore, variations in illuminance and correlated color temperature can significantly modulate cognitive performance and elicit differential physiological responses in users (Castilla et al., 2023; Castilla et al., 2024; Llinares et al., 2021a).

Other environmental variables have also been shown to exert significant effects on human health and performance. Prolonged exposure to excessive noise levels has been associated with elevated stress markers and impaired concentration, directly compromising both productivity and psychological well-being (Averill, 1973; Niza et al., 2024). The absence of natural elements in built environments has been linked to mental fatigue and diminished emotional well-being, highlighting the restorative role of biophilic design (Beemer et al., 2019; Glaser & Kiecolt-Glaser, 2005; Zhong et al., 2022). Color, as a design parameter, plays a critical role: variations in hue and saturation can modulate cognitive task performance, emotional states and autonomic physiological responses, particularly in educational settings (Al-Ayash et al., 2015; Llinares et al., 2021c). Architectural configurations themselves have been shown to influence neural activity, producing both beneficial and detrimental effects on the user experience, depending on their design characteristics (Eberhard, 2009). Open spaces, visual access to natural elements and the use of organic materials tend to facilitate relaxation, attentional restoration and creative thinking (Pinter-Wollman et al., 2018; Sharam et al., 2023; Taylor, 2021; Ulrich, 1984). In contrast, enclosed and stimulus-deprived environments may contribute to increased perceptions of isolation and heightened stress levels (Kiecolt-Glaser et al., 1998).

Advances in neuroscience have enabled the integration of novel methodologies into architectural research, notably neuroimaging techniques such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). These tools provide objective assessments of physiological responses to various built environments, facilitating the analysis of the neural correlates associated with spatial perception across diverse contexts, including art appreciation (Fairhall & Ishai, 2008; Van Leeuwen et al., 2022), residential settings (De Juan-Ripoll et al., 2024), healthcare facilities (Higuera-Trujillo et al., 2020), urban spaces (Llinares et al., 2020) and educational environments (Llinares et al., 2021b; Llorens-Gámez et al., 2022). These techniques have yielded robust empirical evidence about the capacity of architectural design to modulate neural activity and elicit positive experiential states in users (Cohen, 2017; Soares et al., 2016). Neuroscientific research further supports the notion that architectural environments can activate specific brain regions and influence gene expression pathways, thereby underscoring their critical role in human health and well-being (ANFA, 2005).

Systems for measuring user response

Users' responses to the built environment can be assessed through two main measurement systems: psychological approaches, based on self-reported experience, and physiological approaches, based on objective physiological indicators.

1.1. Psychological measurement of emotional responses

In the Evidence-Based Design field, as in the broader empirical literature (Andrade et al., 2017; Ulrich, 1984), self-report questionnaires have consistently served as the primary instrument for capturing user responses to architectural environments. Standardized tools based on self-report questionnaires have been developed to systematically, reliably and reproducibly assess subjective emotional responses to environmental stimuli. One of the most prominent among these is the PAD model (Pleasure–Arousal–Dominance), proposed by Mehrabian and Russell (1974), extensively used in the fields of environmental psychology and user-centered design, and increasingly being applied in architectural research (Divers, 2023; Mfon, 2023). The model is grounded on the premise that any stimulus—such as an architectural feature—elicits an emotional response, and that all emotional states can be decomposed into three fundamental dimensions: pleasure (hedonic valence or satisfaction), arousal (level of physiological activation) and dominance (perceived control over the environment). Through validated scales, the PAD model enables a structured and nuanced representation of the emotional experience associated with built environments, offering a more precise alternative to general or spontaneous evaluations.

However, self-report measures are inherently influenced by conscious cognitive processing, which may compromise the authenticity of the emotional responses reported by participants (Reinerman-Jones et al., 2010). A substantial body of research indicates that a significant proportion of emotional processing occurs unconsciously in response to environmental stimuli. Consequently, gaining a comprehensive understanding of how users perceive architectural spaces requires going beyond verbal reports, as these reports may not accurately capture their underlying mental and affective processes. According to widely cited estimates, approximately 95% of thoughts, emotions and learning processes occur at an unconscious level (Zaltman, 2003). In this context, several authors emphasize the importance of complementing subjective assessments with objective recordings of nervous system activity, and of physiological signals (Bagozzi et al., 1999; Oatley, 1992), on the basis that excluding the physiological component results in an incomplete characterization of the emotional experience (Lazarus, 1991).

1.2. Physiological measure of emotional response

As aforementioned, the psychological measurement of emotional responses can be influenced by the activation of conscious cognitive processes. Therefore, these instruments must be complemented with physiological recordings to obtain a more comprehensive picture of the emotional experience (Reinerman-Jones et al., 2013). In this regard, Izard (1992) argued that cognitive-emotional states are simultaneously characterized by both psychological and physiological components. This dual dimension is particularly important as measurements beyond conscious control provide a more objective assessment than self-report measures (Reinerman-Jones et al., 2010; Winkielman et al., 2001).

Multiple techniques are available for recording the activity of the central, autonomic and somatic nervous systems. Many rely on portable and minimally invasive devices that quantitatively measure central nervous system (Gramann, 2024; Teo et al., 2023) and sympathetic and parasympathetic system activity, which are responsible for states of arousal and relaxation, respectively (Dalmeida & Masala, 2021; Momynaliev & Ivanov, 2023).

Among the most commonly used techniques are: eye-tracking, a behavioral tool that aids in the analysis of visual attention paid by subjects to specific areas, which provides detailed metrics that can inform design decisions (Novák et al., 2024); electrocardiography (ECG), which records the heart rate variability (HRV) and has been used to assess affective responses to emotional stimuli (Hasnul et al., 2021) and in studies on arousal levels and stress detection (Li et al., 2023); electrodermal activity (EDA), which measures changes in skin conductance caused by sweating, and is linked to sympathetic nervous system activity (Boucsein, 2012; Critchley & Nagai, 2013; Henriques et al., 2013; Sachdeva et al., 2022); and electroencephalogram (EEG), considered one of the most sensitive techniques for detecting subtle changes in mental states such as attention, alertness and cognitive load (Liu et al., 2024; Perez et al., 2024).

Ultimately, a comprehensive assessment of users' emotional responses requires the integration of both measurement approaches: the subjective and the objective (based on physiological analysis techniques). The combined application of these methodologies to capture user experience and translate it into spatial design criteria represents a significant innovation in the scientific field.

In this context, the present study integrates psychological and physiological measurement systems to evaluate the emotional impact of a residential environment on its users. A case study was conducted in a newly built dwelling in Valencia (Spain). Both subjective, self-reported and physiological emotional responses were recorded and compared as the participants walked through the different rooms of the home. The analysis also considers potential variations based on time of day (daytime vs. nighttime conditions) and the gender of the participants. This approach provides a comprehensive understanding of how a residential space is perceived and experienced, offering valuable insights to identify design opportunities that can enhance user well-being. The results are presented graphically to facilitate interpretation and practical application. Overall, this research highlights the potential of applied neuroarchitecture in real-life contexts and promotes a user-centered approach to optimizing residential environments.

Figure 1 | Exterior view of the dwelling used in the experiment, showing its appearance under daytime (left) and nighttime (right) conditions. NIU Campolivar (Fran Silvestre Arquitectos), Valencia. (Source: by the authors, 2024).

2. Materials and methods

An in situ neuroarchitecture field study was performed. In this study, a sample of participants walked through a home, following a standardized protocol, while their psychological and physiological responses related to the emotional experience were recorded.

2.1. Participants

Some 30 people participated in the study. The age range was from 33 to 63 years (mean=50.68, std. deviation=8.35). The distribution by gender was balanced, with 45.5% men and 54.5% women. The participants were potential home buyers who met two main inclusion criteria: they were actively looking for a home; and had sufficient financial capacity to purchase a property with characteristics similar to the one shown. These criteria ensured that the experience was perceived as realistic and relevant, avoiding distortions in responses due to a mismatch between the home being evaluated and the participant's economic or motivational profile.

2.2. Space

A house in Valencia (Spain) was selected for the study (Figure 1). It was chosen because its full use was authorized for research purposes and because it is relatively representative of a single-family home.

A The property has a total floor area of approximately 150 m^2, organized into 10 spaces: rear terrace, front porch with pool, living room, entrance forecourt, kitchen, leisure room, single bedroom, two bathrooms (only one was analyzed) and a double bedroom. Figure 2 is a floor plan of the space. The dwelling was fully furnished and equipped, simulating real living conditions which allowed the participants to envision themselves inhabiting the space during the experience.

Figure 2 | Floor plan of the dwelling used for the experimental study.

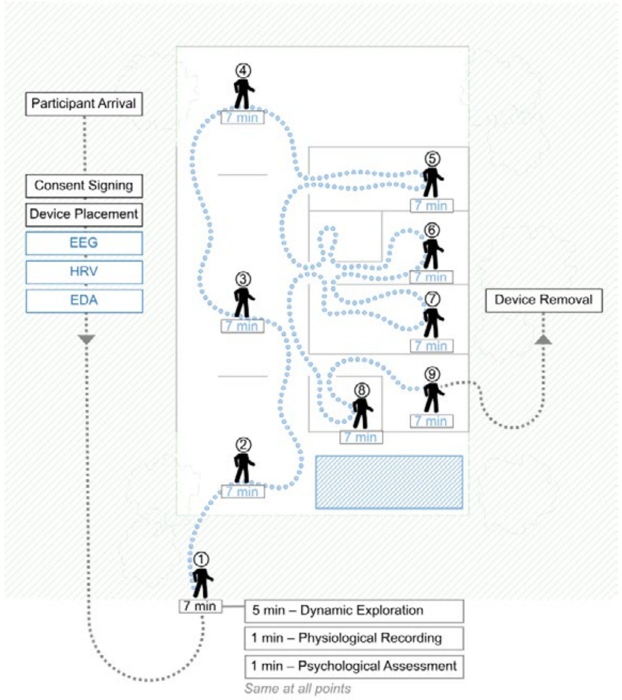

Figure 3 | Exploration itinerary and static observation points in the residential environment.

2.3. Procedure

A semi-free exploration procedure was designed. The participants walked through the same rooms in a predefined order (with the design allowing them to walk through the house in a sequential and intuitive manner), but were free to examine each room (see Figure 3). In each room they had: (a) 5 minutes of free dynamic exploration; and (b) 2 minutes of static exploration at a specific point (identical for all participants), where their physiological responses were recorded for 60 seconds and their psychological responses for the following 60 seconds. An interviewer accompanied the subjects at all times. This protocol combined the spontaneity of the experience with sufficient control to standardize conditions and facilitate data comparison. Figure 4 presents an image of a participant during the walkthrough.

2.4. Psychological records

The participants' psychological responses to the spaces were quantified using the PAD emotional model (Russell & Mehrabian, 1977). This model uses three basic dimensions: pleasure (in short: degree of enjoyment experienced), arousal (in short: level of emotional excitement) and dominance (in short: one's feeling of control over the environment). This conceptual framework, which originated in environmental psychology, has previously been used in studies on the built environment (Gifford et al., 2000). Each participant evaluated the dimensions of pleasure, arousal and dominance according to the items defined in the original article, recording their judgments after each phase of static exploration on a Likert scale from -5 (very low) to +5 (very high).

2.5. Physiological recordings

Physiological responses were recorded for each participant throughout the experiment, however, in this study only the periods corresponding to the static exploration points are examined. The iMotions Platform (v.10.1.0.15; www.imotions.com) was used on the research PC to manage the protocol and compile the corresponding data, including EEG (electroencephalogram), HRV (heart rate variability), and EDA (electrodermal response) recordings. Figure 5 shows a subject equipped with all the physiological recording devices.

EEG. The EEG records variations in electrical potential on the scalp caused by ionic currents caused by neuronal activity (Cohen, 2017). The b-Alert x10 device (www.advancedbrainmonitoring.com) was used, sampling at 256 Hz, with electrodes placed according to the 10-20 montage. EEGLAB (v.2024.1) was used for signal preprocessing and analysis (Delorme & Makeig, 2004). Preprocessing included: (1) baseline removal by mean subtraction; (2) bandpass filtering between 0.5 and 40 Hz (Gudmundsson et al., 2007); and (3) identification and discarding of corrupted channels, understood as those with kurtosis >5 SD or flat trace >10% of total duration (Delorme et al., 2001). Finally, the power spectral density was calculated using the Welch method, and the relative power metric in the beta band (13.00–30.00 Hz) of the frontal area was extracted. This metric has been associated with levels of mental activation, and its sustained increase can reflect acute stress (Engel & Fries, 2010; Yan et al., 2024).

HRV. The HRV records fluctuations in the duration of intervals between heartbeats. The b-Alert x10 device, again, was used. HRVAS, a freely distributed heart rate variability analysis software under the GNU GPL v3.0 license, was used for signal preprocessing and analysis (Ramshur, 2010). Preprocessing included: (1) automatic identification of R-peaks through the Pan-Tompkins algorithm (Pan & Tompkins, 1985); and (2) visual inspection to locate and correct artifacts. Finally, the interbeat intervals were analyzed in the time-frequency domain using the Welch method, defining the LF (0.05 - 0.15 Hz) and HF (0.15 - 0.40 Hz) bands and calculating the LF/HF ratio (Berntson et al., 1997). This metric quantifies the balance

Figure 4 | Subject performing the walkthrough during the experimental session. NIU Campolivar (Fran Silvestre Arquitectos), Valencia. (Source: by the authors, 2024).

Figure 5 | Subject equipped with EEG, HRV and EDA monitoring devices during the experiment. NIU Campolivar (Fran Silvestre Arquitectos), Valencia. (Source: by the authors, 2024).

between sympathetic activation, associated with the “fight or flight” response, and parasympathetic activity, linked to recovery processes (Malliani, 1999).

EDA. EDA records fluctuations in the electrodermal properties of the skin (Boucsein, 2012). The Shimmer 3GSR+ device (www.shimmersensing.com) was used, sampling at 128 Hz. Ledalab (v.3.4.9, www.ledalab.de) was used for signal preprocessing and analysis. Preprocessing included: (1) a low-pass Butterworth filter with a cutoff at 2.5 Hz (Valenza & Scilingo, 2014); (2) a reduction of the sampling frequency to 10 Hz (Lang et al., 2000); and (3) a visual inspection to locate and correct artifacts. Finally, the continuous decomposition analysis method was used to calculate the phasic metric (Benedek & Kaernbach, 2010), and the values obtained were normalized through the Venables and Christie procedure (1980). This metric reflects an increase in sympathetic activation and is related to level of arousal (Braithwaite et al., 2013).

2.6. Data analysis

The data collected—encompassing both psychological and physiological responses—were anonymized prior to conducting the statistical analyses required to address the research questions (Table 1). All analyses were performed using IBM SPSS Statistics software (version 27.0; www.ibm.com/products/spss-statistics).

3. Results

The following section reports the psychological and physiological responses recorded during the walkthrough of the 9 spaces of the dwelling. To facilitate interpretation of the results, the data are represented graphically (Figure 6). The circular diagrams show the mean values obtained for each of the variables analyzed, with the size of each circle indicating the magnitude of the corresponding mean. The figure also displays information on statistically significant differences in responses related to gender (male vs. female) and time of day (daytime vs. nighttime).

Table 1 | Statistical treatments.

Phase	Analysis and data used	Statistical treatment	Expected results
I. Analysis of psychological responses	Analysis of the variables obtained through the questionnaire: •Pleasure •Arousal •Dominance	Descriptive analysis (means and standard deviation).	Levels of perceived Pleasure, Arousal and Dominance by room in the dwelling.
		Friedman’s test (non-parametric repeated-measures ANOVA, χ^2 approximation) and pairwise post hoc comparisons using the Wilcoxon signed-rank test with Bonferroni correction.	Significant differences in the sensation of Pleasure, Arousal and Dominance between the rooms of the dwelling.
		U-Mann Whitney’s test (non-normally distributed data).	Significant differences in the sensation of Pleasure, Arousal and Dominance based on time of day (daytime vs. nighttime).
			Significant differences in the sensation of Pleasure, Arousal and Dominance based on gender (male vs. female).
II. Analysis of physiological responses	Analysis of the monitored variables: •EEG (Frontal Beta) •HRV (LF/HF) •EDA (Phasic)	Descriptive analysis (means and standard deviation).	Levels of physiological responses (EEG, HRV and EDA) by room in the dwelling.
		Friedman’s test (non-parametric repeated-measures ANOVA, χ^2 approximation) and pairwise post hoc comparisons using the Wilcoxon signed-rank test with Bonferroni correction.	Significant differences in physiological responses (EEG, HRV and EDA) between the rooms of the dwelling.
		U-Mann Whitney’s test (non-normally distributed data).	Significant differences in physiological responses (EEG, HRV and EDA) based on time of day (daytime vs. nighttime).
			Significant differences in physiological responses (EEG, HRV and EDA) based on gender (male vs. female).

Note: A significance level (p-value) below 0.05 was considered statistically significant in all tests. This threshold indicates that the likelihood of the observed differences occurring by chance is less than 5%. In addition to significance testing, effect size was calculated using r, which helps interpret the practical relevance of the results beyond statistical significance. According to Cohen’s guidelines: r ≈ 0.10: small effect; r ≈ 0.30: moderate effect and r ≥ 0.50: large effect. This allows a more nuanced understanding of the strength of the observed differences, particularly in non-parametric analyses such as the Mann–Whitney U test.

3.1. Phase I. Analysis of the psychological responses

Pleasure

The descriptive analysis (Table 2) indicated that the space with the highest average pleasantness score was the living room, followed by the rear terrace, the front porch with pool, the leisure room, the kitchen, the single bedroom, the entrance forecourt, the double bedroom and, finally, the bathroom (Figure 6a).

To assess whether the differences in pleasure perception between the spaces were statistically significant, Friedman's test was applied—a non-parametric repeated-measures test based on a χ^2 approximation. Pairwise post hoc comparisons were then conducted using the Wilcoxon signed-rank test with Bonferroni correction. The analysis revealed significant differences in the pleasure experienced in the different spaces (p < 0.001). Specifically, the bathroom elicited significantly less pleasure than the rear terrace (p<0.001, r=0.505), the front porch with pool (p<0 .001, r=.599) and the living room (p<0.001, r=0.622). The living room also returned significantly higher pleasure scores than did the entrance forecourt (p=0.030, r=0.411).

Regarding potential differences in pleasure perception between daytime and nighttime conditions, the Mann–Whitney U test revealed significantly more pleasant experiences during the day (p<0.001, r=0.199). As shown in Figure 6a, the rooms that elicited significantly higher levels of pleasure during the day compared to the night were the living room (p=0.013, r=0.306), the kitchen (p=0.002, r=0.389) and the leisure room (p<0.001, r=0.587).

Significant differences were also observed in pleasure perception based on gender (p<0.001, r=0.274). As shown in Figure 6a, women reported significantly higher pleasure levels than men in the rear terrace (p=0.004, r=0.353),

Table 2 | Descriptive analysis (means and standard deviations) of psychological and physiological responses.

	Psychological variables			Physiological variables		
	Pleasure	Arousal	Dominance	EEG Beta Frontal	HRV LF/HF	EDA Phasic
rear terrace						
mean	3.50	0.18	2.45	0.93	2.24	0.14
std deviation	1.42	3.21	1.79	1.31	1.70	0.10
front porch with pool						
mean	3.32	1.27	2.32	2.13	1.80	0.06
standard deviation	1.96	2.77	2.11	0.45	1.53	0.05
living room						
mean	3.68	0.68	2.86	1.38	2.41	0.07
std deviation	1.27	2.98	1.93	1.07	1.68	0.05
entrance forecourt						
mean	2.91	1.05	2.14	0.88	3.08	0.10
std deviation	1.90	3.08	1.86	2.23	2.48	0.01
kitchen						
mean	3.05	1.00	2.00	3.14	2.22	0.08
std deviation	1.89	3.01	2.17	1.82	1.53	0.06
leisure room						
mean	3.23	0.91	1.73	0.58	2.68	0.09
std deviation	1.66	2.63	2.24	0.89	1.68	0.09
single bedroom						
mean	3.00	0.36	1.86	4.63	3.63	0.12
std deviation	2.08	3.19	2.18	0.33	4.34	0.08
bathroom						
mean	2.32	0.64	1.45	3.42	3.66	0.08
std deviation	1.88	2.14	2.78	0.86	2.15	0.06
double bedroom						
mean	2.77	0.77	1.45	4.70	2.83	0.16
std deviation	2.29	3.24	2.68	2.48	2.00	0.13

Figure 6 | Graphical representation of the mean values of psychological responses (arousal, pleasure and dominance) during the visual exploration of the dwelling, in each of the evaluated rooms.
Note: The circular diagrams display the mean values obtained for each variable. The size and color of the circle represent the magnitude of the mean on a 0–4 scale (the original variable scale was adapted for visualization purposes): larger size and more intense blue hue correspond to higher mean values of the represented variable (see the visual scale indicated in the legend). A label of D/N and F/M on the graph indicates a statistically significant increase in emotional response (pleasure, arousal, dominance) during the day/night and female/male, respectively.

the front porch with pool ($p < 0.001$, r=0.472) the entrance forecourt (p=0.015, r=0.298), the single bedroom (p=0.003, r=0.360) and the bathroom ($p < 0.001$, r=0.472).

Arousal

The descriptive analysis (Table 2) revealed that the front porch with pool recorded the highest mean arousal score, followed by the entrance forecourt, the kitchen, the leisure room, the double bedroom, the living room, the bathroom, the single bedroom and, finally, the rear terrace (Figure 6b).

The repeated-measures comparison test showed that differences in arousal across spaces were statistically significant ($p < 0.001$). Post hoc Wilcoxon pairwise comparisons with Bonferroni correction indicated that the rear terrace elicited significantly lower arousal than both the double bedroom (p=0.018, r=0.429) and the front porch with pool (p=0.009, r=0.452).

Time of day also had a significant impact on perceived arousal. The Mann–Whitney U test showed that spaces viewed at night generated significantly higher arousal levels than those viewed during the day ($p < 0.001$, r=0.218). As shown in Figure 6b, this effect was especially notable in the front porch with pool (p=0.008, r=0.326), the living room (p=0.046, r=0.246), the entrance forecourt (p=0.035, r=0.259), the single bedroom (p=0.005, r=0.347), the bathroom ($p < 0.001$, r=0.564) and the double bedroom (p=0.047, r=0.306).

Regarding gender, the analysis revealed significantly higher arousal levels among female participants than among males (p=0.002, r=0.121), although no individual space showed statistically significant gender-related differences ($p > 0.05$).

Dominance

The descriptive statistics (Table 2) showed that the living room obtained the highest mean dominance score, followed by the rear terrace, the front porch with pool, the entrance forecourt and the kitchen. Lower average scores were found in the single bedroom, the leisure room and the double bedroom (Figure 6c).

Friedman's test confirmed statistically significant differences existed in dominance across the rooms ($p < 0.001$). Post hoc pairwise comparisons using the Wilcoxon test with Bonferroni adjustment revealed that the living room generated significantly higher feelings of dominance than the bathroom (*p*=0.002, r=0.493), the single bedroom (*p*=0.030, r=0.411), the leisure room (*p*=0.018, r=0.428) and the double bedroom ($p<0.001$, r=0.552). In addition, the double bedroom showed significantly lower dominance than the front porch with pool (*p*=0.030, r=0.411).

Dominance levels also varied according to time of day. The Mann–Whitney U test revealed significantly higher dominance scores for rooms viewed at night than for those viewed in daytime ($p<0.001$, r=0.153). As shown in Figure 6c, the rooms with significantly increased night-time dominance were the bathroom (*p*=0.033, r=0.263), the single bedroom (*p*=0.013, r=0.306) and the double bedroom (*p*=0.016, r=0.297).

Significant gender-based differences were also observed, with women reporting higher dominance levels overall ($p<0.001$, r=0.333). As shown in Figure 6c, this pattern was reflected in specific rooms where women experienced significantly more dominance, including the rear terrace ($p<0.001$, r=0.537), the front porch with pool (*p*=0.030, r=0.268), the living room (*p*=0.003, r=0.362), the entrance forecourt (*p*=0.014, r=0.304), the kitchen (*p*=0.038, r=0.256), the single bedroom ($p<0.001$, r=0.480), the bathroom (*p*=0.002, r=0.387) and the double bedroom (*p*=0.006, r=0.340).

3.2. Phase II. Analysis of physiological responses

Electroencephalogram: Frontal beta

The descriptive analysis (Table 2) showed that the double bedroom exhibited the highest average levels of frontal beta EEG activity, followed by the single bedroom, the bathroom, the kitchen, the front porch with pool, the living room, the rear terrace, the entrance forecourt and, last, the leisure room (Figure 7a).

Friedman's test confirmed that there were statistically significant differences in frontal beta activation across the different spaces (*p*=0.034). Pairwise comparisons using Wilcoxon tests with Bonferroni correction indicated that the rear terrace exhibited significantly higher frontal beta activity than did the entrance forecourt (*p*=0.015, r=0.492).

Time of day also had a significant influence on frontal beta activity levels. The Mann–Whitney U test revealed that spaces viewed during daytime generated higher activation in this band compared to those viewed at night (*p*=0.017, r=0.138). As shown in Figure 7a, this effect was particularly notable in the double bedroom (*p*=0.033, r=0.417).

Regarding gender, no significant differences in frontal beta activity were observed between female and male participants (*p*=0.734, r=0.018).

Heart Rate Variability: LF/HF

The descriptive statistics (Table 2) indicated that the bathroom obtained the highest mean score in LF/HR ratio ratings, followed in descending order by the single bedroom, the entrance forecourt, the double room, the leisure room, the living room, the rear terrace, the kitchen and, last, the front porch with pool (Figure 7b).

To determine whether the LF/HF ratio varied significantly across the different spaces, a Friedman's test was performed, followed by Wilcoxon signed-rank post hoc analyses with Bonferroni correction. The results showed a significant overall effect of the space on the LF/HF ratio ($p<0.001$). Notably, the bathroom elicited significantly different autonomic responses than did the rear terrace ($p<0.001$, r=0.742), front porch with pool ($p<0.001$, r=0.693) and living room ($p<0.001$, r=0.577). Similar significant differences were observed between the front porch with pool and the single bedroom ($p<0.001$, r=0.591), the front porch with pool and the double bedroom ($p<0.001$, r=0.579), and the kitchen and the bathroom (*p*=0.005, r=0.528), suggesting marked shifts in sympathovagal balance in these spaces.

Differences in LF/HF scores were also observed based on time of day. A Mann–Whitney U test indicated that nighttime evaluations were associated with significantly higher LF/HF scores than daytime evaluations ($p<0.001$, r=0.381). As shown in Figure 7b, this effect was particularly notable in the front porch with pool (*p*=0.002, r=0.567), the living room ($p<0.001$, r=0.667) and the bathroom (*p*=0.003, r=0.515).

Furthermore, the analysis revealed statistically significant differences between male and female participants, with women reporting higher LF/HF ratios overall (*p*=0.047, r=0.125). Post hoc analyses identified specific spaces where this effect was especially marked (Figure 7b), in the single room ($p<0.001$, r=0.580), the front porch with pool (*p*=0.004, r=0.472) and the bathroom (*p*=0.018, r=0.389).

Electrodermal Activity: Phasic

The descriptive statistics (Table 2) showed that the double bedroom elicited the highest mean phasic EDA activity, followed by the rear terrace, the single bedroom, the entrance forecourt and the leisure room. Lower average phasic responses were observed in the kitchen, the bathroom, the living room and the front porch with pool (Figure 7c).

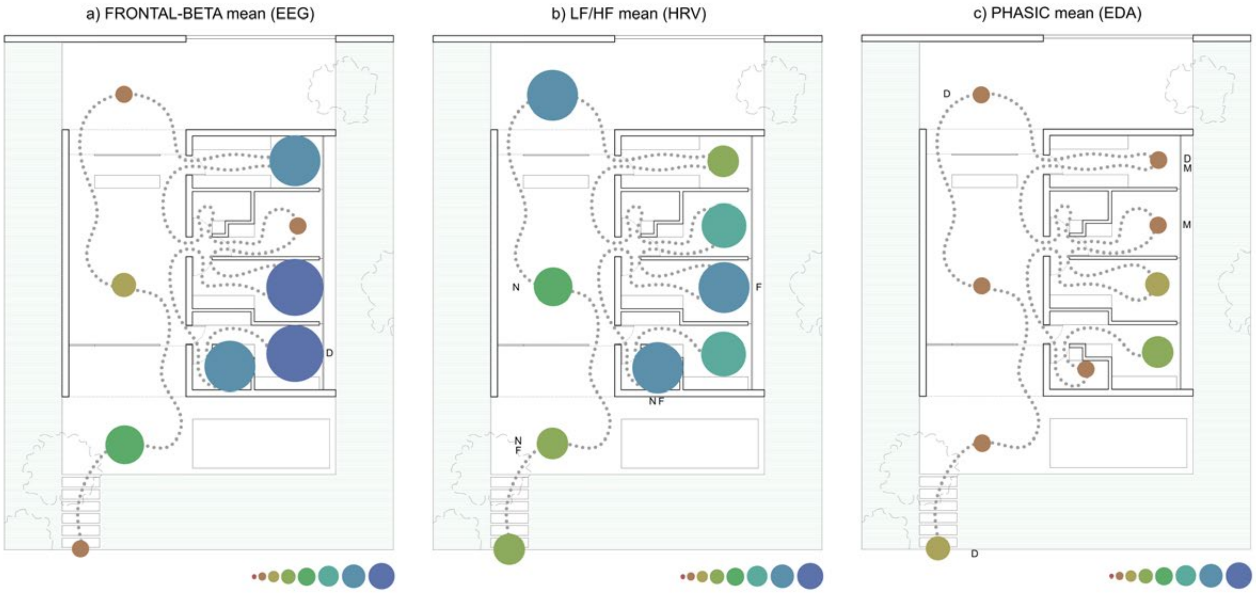

Figure 7 | Graphical representation of the mean values of physiological responses (Frontal-Beta, LF/HF and Phasic) during the visual exploration of the dwelling, in each of the evaluated rooms.

Note: The circular diagrams display the mean values obtained for each variable. The size and color of the circle represent the magnitude of the mean on a 0–4 scale (the original variable scale was adapted for visualization purposes): larger size and more intense blue hue correspond to higher mean values of the represented variable (see the visual scale indicated in the legend). A label of D/N and F/M on the graph indicates a statistically significant increase in emotional response (pleasure, arousal, dominance) during the day/night and female/male, respectively.

A Friedman's test revealed statistically significant differences in phasic EDA levels across the rooms (p=0.004). Post hoc pairwise comparisons using the Wilcoxon test with Bonferroni correction were conducted to explore differences in the phasic EDA mean values. Significant differences were observed between the rear terrace and front porch with pool (p=0.004, r=0.625), indicating markedly lower phasic EDA activity in front porch with pool. In addition, the front porch with pool showed significantly lower phasic activity than did the kitchen (p=0.011, r=0.606), the single bedroom (p=0.027, r=0.595) and the double bedroom (p=0.023, r=0.632). These findings suggest that specific environmental conditions elicited markedly different levels of sympathetic activation, as measured by phasic EDA responses

Time of day also influenced phasic EDA responses. A Mann–Whitney U test showed significantly higher phasic activity in rooms viewed at daytime than when viewed at night ($p<0.001$, r=0.222). As illustrated in Figure 7c, the rooms with significantly elevated daytime phasic EDA were the rear terrace (p=0.026, r=0.371), the entrance forecourt (p=0.005, r=0.595) and the kitchen ($p<0.001$, r=0.771).

Gender-based differences were also evident, with men showing overall higher phasic EDA levels than did women (p=0.020, r=0.152). As shown in Figure 7c, this trend was particularly marked in the kitchen (p=0.047, r=0.389) and the leisure room (p=0.023, r=0.467).

4. Discussion

This study is an innovative approach, based on the combined use of psychological and physiological indicators, to the emotional analysis of a residential space. The aim was to investigate how the various spaces in a real dwelling are perceived and experienced depending on time of day and user profile. The results provide valuable insights for architectural design focused on well-being.

The study raises important implications both at the methodological level and in terms of the findings obtained.

From a methodological standpoint, this study offers three key contributions that enhance its importance in the field of user-centered architectural design research. First, the evaluation was conducted in a real setting, a fully built and furnished dwelling, which allowed data collection to take place as participants physically moved through the different rooms. This approach introduces a dynamic dimension to emotional assessment, which is more closely aligned with the everyday experience of inhabiting a space. In contrast, most previous studies have relied on static stimuli such as images (Cuerdo-Vilches & Navas-Martín, 2021; Granié et al., 2014; Kim et al., 2019) and virtual representations (Scorpio et al., 2020; Sánchez-Sepúlveda et al., 2019), which, while useful, do not always capture the multisensory complexity of real spatial interaction. Second, the study combines subjective psychological measures (PAD model) with objective physiological recordings (EEG, HRV and EDA), enabling a methodological triangulation that is particularly valuable for analyzing emotional experiences. While users' self-reports about spaces can provide key insights into their conscious perceptions (Baird et al., 1978), numerous studies have pointed out that emotions also operate at automatic and unconscious levels, which, of course, are difficult to capture through self-report alone. In this context, the combination of both psychological and physiological metrics provides coherence and aligns with current research trends in emotional architecture, as demonstrated by recent studies applied to built environments (St-Jean et al., 2022) and systematic reviews that integrate subjective and physiological approaches (Wang et al., 2024). Finally, this methodology enables comparisons not only between different rooms, but also between users, permitting the identification of both common patterns and interindividual variability. This dual perspective—spatial and personal—is particularly important for the design of people-centered architecture.

The results of the study revealed consistently high levels of pleasure across all rooms of the dwelling. This overall positive response is likely influenced by the exceptional qualities of the house itself, which features a refined minimalist design and is immersed in a remarkable natural setting, surrounded by lush vegetation. Furthermore, statistically significant differences were observed in users' emotional responses based on room type, time of day (day vs. night), and gender (male vs. female). These differences were evident in both psychological measures (pleasure, arousal, and dominance) and physiological indicators (EEG, HRV, and EDA).

Overall, an inverse relationship was found between the sensation of pleasure/dominance and levels of physiological activation: rooms that elicited higher pleasure tended to generate lower physiological activation. This finding is particularly important as it suggests there is potential to estimate a person's subjective well-being through physiological indicators. One of the main advantages of this approach is that it allows the monitoring of users' emotional states in real time without interrupting their experience by applying questionnaires or other self-report methods.

It was observed that collective areas—such as the living room and entrance forecourt—produced higher levels of pleasure and dominance, along with lower levels of physiological activation (EEG, HRV and EDA), than did individual spaces such as bedrooms and bathrooms. This pattern was more pronounced in the psychological responses of female participants. One possible explanation lies in the architectural features of the dwelling—particularly floor-to-ceiling glazed facades—which may reduce the perception of privacy in private spaces, thereby negatively affecting the subjective experience (Dincer et al., 2024; Namazian & Mehdipour., 2013). Indeed, while participants responded very positively to the living spaces, some suggested that adding a bit more privacy in the bedrooms could further enhance the experience.

Another possible explanation is that individual spaces may be associated with more cognitively demanding tasks, such as studying or working, which may increase the cognitive load when imagining their use. This aligns with enactive and neurophysiological theories suggesting that architectural perception involves embodied simulations and cognitive affordances (Jelić et al., 2016; Vecchiato et al., 2015). In this sense, the fact that the dwelling was fully furnished and equipped, it is plausible that participants were able to project realistic usage scenarios in these spaces, making their evaluation more complex. It is also important to consider the physical size of the rooms: the living room, as a collective space, is significantly larger than the individual rooms, which may influence the emotional experience. Larger spaces are generally associated with feelings of openness and comfort, which may positively modulate the perception of pleasure and control (Shemesh et al., 2022; Valentine, 2024; Wang & Liu, 2023).

An additional example is the entrance area, which was rated very positively in terms of pleasure and dominance and was associated with low levels of physiological activation. This space was characterized by an abundance of vegetation which, unlike the primarily visual vegetation inside the dwelling, also offered olfactory stimulation, potentially intensifying the sensory experience (Higuera-Trujillo et al., 2020). In this regard, the scent of plants could enhance the feeling of well-being (Pálsdóttir et al., 2021), suggesting that the simultaneous presence of visual and olfactory stimuli from vegetation has the potential to amplify the positive effects on user perception (Zhang et al., 2017).

During nighttime assessments, a significant increase in perceived arousal was recorded. This result may be attributed to a mismatch between intense artificial lighting and human circadian rhythms, as human activity is biologically adapted to the daytime cycle (Fisk et al., 2018). Exposure to bright light at night may induce a state of alertness, which could explain the observed increase in perceived activation during these sessions.

This detailed analysis of the emotional response elicited by each room permits the identification of areas with potential for improvement. While the dwelling was generally rated as highly pleasant overall, and with a high sense of control, the results suggest that bedrooms possess a possible margin for enhancement. Based on these findings, it is possible to conduct a more in-depth analysis of specific design elements to identify specific strategies that can improve users' emotional experiences.

Finally, the study's limitations should be acknowledged. First, the research focused on one single dwelling. Although this permitted an in-depth spatial analysis and a precise evaluation of the tour, this focus limits the generalizability of the results to other residential contexts. Future studies could include different housing typologies to test the consistency of the observed patterns. Second, although the tour was fully controlled in terms of sequence and duration in each room, the experimental design did not compare different trajectories or the effect of a repetition of the tour, both of which could be important for assessing the stability or cumulative effect of the spatial experience. This might be addressed in future research. Finally, while the sample size was sufficient to detect significant differences between rooms, conditions (day/night) and gender, it did not allow for detailed subgroup analyses. Increasing the sample size would enable more precise examinations of individual variables such as age, occupational profile and/or prior familiarity with the environment.

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