

Linking EEG responses to ISO 12913 perceptual attributes within the Spanish SATP framework: an exploratory neurophysiological study[☆]

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ABSTRACT

The soundscape framework defined in ISO 12913 relies on survey-based assessments to characterise human perception through Perceptual Attributes (PA). While these attributes have been validated across multiple languages via the Soundscape Attribute Translation Project (SATP), these results were obtained through surveys, not through neurophysiological readings. This exploratory study addresses this potential neurophysiology of PA, specifically the relationship between Spanish SATP descriptors (language) and objective neurophysiological responses to sound recorded via electroencephalography (EEG).

Twelve participants were exposed to six contrasting audio excerpts from the SATP database, representing extreme positions within the pleasantness–eventfulness space. Subjective perception was recorded using the Spanish SATP protocol, while objective brain activity was measured through multi-channel EEG to compute Power Spectral Density (PSD) across the Delta, Theta, Alpha, and Beta bands. Given the multidimensional nature of the data, Self-Organising Maps (SOM) were employed to determine if these relationships could be organised into a neurophysiology of these Perceptual Attributes (PA) linking sound and language as perception. The results explore the relationship between soundscape as defined by ISO 12913 and the multidimensional modulation of brain rhythms, primarily in the Alpha and Delta bands.

Calm, non-anthropogenic sounds (e.g., birdsong) were associated with increased Alpha-band power, a marker for relaxation and comfort, whereas eventful or chaotic sounds elicited stronger Delta-band activity, consistent with pre-attentive tracking responses. SOM analysis revealed three well-defined clusters (Calm, Annoying, and Vibrant) that closely align with the PA constructs and mirror the spatial organisation of the ISO 12913 circumplex model.

This study shows that data obtained via EEG capture perceptual structures consistent with translated PA attributes. By framing these findings within the SATP framework, this methodology can provide a reproducible protocol for future cross-linguistic harmonisation and evidence-based urban acoustic design.

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1. Introduction

1.1. Subjective soundscape perception through surveys. The PA and the SATP experience

Research on urban soundscapes refers to how people perceive the acoustic environment in non-acoustic context [1]. The ‘soundscape’ term was introduced by Schaffer in 1977 [2], and it is linked to the development of ISO 12913 standards [1], which provide a framework for soundscape studies. A central instrument in this field is the Perceptual Attributes (PA) model outlined in ISO 12913-2 [3], which characterises emotional responses to urban acoustic environments across eight attributes [4].

Although PA is not easy to evaluate due to numerous influencing factors like subjectivity and affective dimensions [5], influence of the sociocultural context [6], difficulty in economic valuation [7] or sensory diversity and inclusion [8], soundscape research offers important insights for urban planning, supporting sustainable development and improving the response and engagement of public stakeholders to urban design [9]. This approach is gaining prominence over traditional noise studies, supported by evidence of the health benefits of certain urban sounds [10]. Beyond informing noise control and pollution prevention, soundscape research contributes significantly to quality of life, well-being, and health, highlighting the need for multilingual translations of the PA model for global use [11].

Assessing soundscape quality remains challenging, as it is impossible to intervene in the city without first conducting a rigorous diagnosis of the current situation. The difficulty is evidenced by proactive implementation challenges [12], methodological uncertainty [13] or the need for predictive modeling [14], requiring indicators and descriptors grounded in contextual human perception, as outlined ISO 12913-1 [1]. The relevance of this work is growing within public policy frameworks [15], with Part 4 of the standard representing the most significant contribution of the ISO 12913 series to policy development. This section aims to support practitioners in implementing soundscape interventions and in integrating soundscape criteria into noise action plans and related policies [16]. The ISO framework functions as a diagnostic tool for urban and landscape environments, relying primarily on survey-based methods.

The SATP started in 2019 as a network initiative led by the Acoustic Group at University College London (UCL). It later incorporated additional working groups from different nationalities, reaching 18 languages in 2022 [11]. The SATP initiative considered the 8 PA model dimensions proposed in Method A of ISO/TS 12913-2. A detailed account of the listening experiments conducted in Spain and the UK is available in [17,18].

This study is presented as a methodological contribution to the validation of translated PA constructs, investigating whether a neurophysiology of PA exists or not. The objective is to determine if these relationships can be organised to confirm the existence of a neurophysiology of PA that acts as an objective anchor for descriptors. By utilising the Spanish SATP protocol and validated descriptors such as agradable (‘pleasant’), caótico (‘chaotic’), or estimulante (‘vibrant’)

[18], this research seeks to verify whether translated terms maintain a consistent perceptual and biological structure, thereby facilitating construct equivalence within the international SATP framework. A description of the procedure and the proposed translation is available in [18] from which Table 1 is extracted.

1.2. EEG as a tool for measuring the objective perception of soundscapes

Electroencephalography (EEG) is an appropriate tool for objectively measuring the neurophysiological brain activity [19,20]. It is characterised by being non-invasive and having high temporal resolution [21], which allows precise tracking of when acoustic features are processed [22].

In the context of the SATP framework, neurophysiological measures based on EEG are utilised as objective indicators that are less susceptible to participant bias than subjective methods, such as translated questionnaires. EEG can yield valuable insights into both cognitive and emotional responses to sound, providing an essential physiological anchor to verify if standardised translations evoke the intended neural states. [23].

Brain-evoked neurophysiological activity is often analysed in terms of their power across Delta (0–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), and Beta (12–20 Hz) frequency bands [24], each associated with specific states of consciousness, cognitive functions and emotions [19]. By investigating the modulations of these bands in response to SATP stimuli, this study aims to explore a “neurophysiology of PA” that will enable the validation of the conceptual equivalence of PA attributes across different linguistic contexts.

For instance, annoying high-level sounds have been observed to disrupt brain activity by increasing Theta power while reducing Delta and Alpha powers. Prolonged exposure to elevated sound levels (55 to 100 dB) can further interfere with normal brain function. Conversely, natural sounds generally promoting relaxation tend to increase Alpha power, in contrast to disrupting noise [19].

2. Cognitive-emotional mechanisms associated with each frequency band

The Delta and Theta bands are associated with deep sleep, homeostatic processes, and neuronal repair during REM sleep, encompassing automatic or preconscious responses to auditory stimuli [19]. In the waking state, these bands may reflect sudden changes in acoustic perception via non-conscious mechanisms, indicate discomfort or noise, and participate in processing complex stimuli.

Delta activity generally decreases under excessive noise. For example, studies on traffic noise in university students show that loud sounds disrupt brain activity, manifesting as reduced Delta power [23]. While Alpha waves are more closely linked to activity processing, neural tracking of speech at the semantic level is dominated by Delta activity, suggesting that slow fluctuations in language processing occur within this band [25]. Although Delta can temporarily couple to the rhythm of an auditory stimulus, voluntary attention primarily engages Alpha and Theta waves [26]. Event-related potentials (ERPs) from changing sounds can influence Delta activity [27]. Greater Delta-band energy associated with more dynamic acoustic audio files may reflect an enhanced degree of cortical tracking of envelope fluctuations [28]. Whereas increased low-frequency power does not necessarily indicate a non-specific rise in neural activity, greater synchronization of neuronal activity with the slow temporal modulations of the stimulus. Such coupling between stimulus temporal dynamics and cortical responses has been widely documented in neural tracking studies of the acoustic envelope, particularly within low-frequency bands [29,30]. Similarly, exposure to sequences of varied stimuli elicits Delta responses via acoustic variation, giving rise to the Mismatch Negativity (MMN) evoked potential, whereby the brain detects deviations in sound without conscious attention. In relation to acoustic stimulation, the Theta band mainly

Table 1
SATP Spanish Stage-1 translation.

PA dimension	PA dimension ID	Spanish – Word 1 (preferred)	Spanish – Word 2
pleasant	p	agradable	placentero
chaotic	ch	caótico	confuse
vibrant	v	estimulante	vibrante
uneventful	u	sin actividad	estático
calm	ca	calmado	tranquilo
annoying	a	desagradable	molesto
eventful	e	con actividad	dinámico
monotonous	m	monótono	aburrido

Table 2
Relationship between auditory stimuli and EEG frequency band.

Brainwave	Stimulus Association	Effects produced by [dB & noise]
Delta (< 4 Hz)	Unconscious. Dominant during deep sleep; related to homeostatic and regenerative brain processes. Mismatch Negativity	Decreases with high noise levels (≥ 70 –80 dB), especially during sleep
Theta (4–8 Hz)	Intermediate. Present during REM sleep, deep relaxation, and meditation. In wakefulness, linked to cognitive load, sustained attention, and mental stress.	Increases with moderate to high noise (≥ 70 dB); reflects elevated attentional effort, stress, or cortical fatigue.
Alpha (8–12 Hz)	Relaxed conscious state. Associated with calm alertness and relaxed awareness. Decreases during active attention or cognitive engagement.	Decreases with noise exposure (≥ 60 –85 dB); indicates loss of relaxation, increased cortical activation, and stress response.
Beta (12–20 Hz)	Active consciousness. Associated with focused attention, active thinking, and cognitive alertness	Increases with moderate noise (< 80 dB) as a marker of cortical activation. Decreases under intense or prolonged noise (≥ 80 dB), reflecting cognitive overload or fatigue

reveals situations of fatigue, accumulated stress, nervousness or even states of anxiety [31]. It is primarily a semi-automatic stimulus, as it responds to emotional reactions that are neither conscious nor automatic.

Activity in the Alpha and Beta bands is linked to focused attention, memory, and cognitive processing, with increases in these bands corresponding to enhanced attention and memory performance.

The Alpha band is particularly associated with relaxation and restorative states in response to auditory stimuli, making it a key indicator of pleasure or displeasure. It predominates during conscious relaxation with eyes closed and is often measured during rest [32]. Pleasant sounds typically increase Alpha power, whereas annoying sounds reduce it [19]. Natural sounds generally promote relaxation, reflected in elevated Alpha activity, while noise tends to decrease this frequency band [23,24]. Sounds such as flowing water and birdsong are particularly effective in relieving mental stress and enhancing Alpha activity [24], making Alpha power a reliable indicator of comfort and psychophysiological health [33]. Conversely, exposure to annoying or loud sounds typically induces tension or stress, with various noise sources, such as traffic [23] or neighbours [34], significantly reducing Alpha power. Some studies suggest that psychoacoustic discomfort may paradoxically increase Alpha activity by inhibiting the primary stimulus [34]. Overall, Alpha activity reflects a restorative state, most pronounced with audio-only stimuli (eyes closed, no background noise). With audio-visual stimuli, Alpha can be suppressed due to increased demands on conscious attention, typically associated with Beta activity [35]. Theta and Beta activity are also affected by background noise in university environments, showing significant reductions that imply impaired attention [32]. Table 2 summarises the current understanding of brain responses to acoustic stimuli across main frequency bands: Delta [26], Theta [24,25,33,36], Alpha [19,24,26,33,37] and Beta [31,38].

2.1. Machine learning applied to analysis of objective (EEG) and subjective (ISO-12913) perception

The Self-Organising Map (SOM), or Kohonen Map, is an unsupervised competitive-learning algorithm developed by T. Kohonen [39,40], whose primary function is to Project high-dimensional data onto a two dimensional grid while preserving topological relationships [41,42]. Initially applied to automatic speech recognition, notably the “phonetic typewriter” [40,43], the SOM has also proven effective in time-related prediction tasks [44].

SOMs have been used to examine internal brain activity (EEG) and to

Table 3
Description of SATP stimuli and PA position.

Stimuli	Source (*)	quadrant /closest axis
1 (CG01)	Quiet music + laugh	1st / vibrant – monotonous
4 (CT301)	Petrol engine power saw	2nd / pleasant – annoying
17 (OS01d)	Percussion music + voices	1st / eventful – uneventful
19 (VP01b)	Distant birds + gulls	4th / calm – chaotic
21 (W06)	Distant water	4th / calm – chaotic
22 (W09)	Constant-frequency engine	3rd / pleasant – annoying

classify complex external acoustic stimuli [45,46]. Applications include the categorisation of humpback whale song units [43] and the recognition of information-bearing acoustic elements in animal alarm calls [47]. In underwater acoustics, the SOM is employed to map and identify sources of ambient noise [48], process multispectral acoustic-imaging (MSAI) data [49], and support acoustic fault detection in underwater vehicles [50].

The extensive volume of EEG data, together with survey data collected in accordance with the Spanish SATP protocol, provides a unique opportunity to use SOMs to jointly analyse and compare these large datasets. This approach is employed here to bridge the gap between subjective linguistic descriptors and objective neural activity, aiming to confirm the existence of a neurophysiological metalanguage. Specifically, the SOM is utilised to investigate the multidimensional relationship between the eight PA attributes of ISO 12913 and the brain's activity, validating whether the spatial organisation of neural rhythms mirrors the theoretical circumplex model. By identifying coherent perceptual–neural profiles, this study contributes a reproducible methodology for the international SATP project to verify construct consistency across diverse languages.

Specifically, this study focuses on two key research questions, organized into a discursive sequence: (1) *Is there a sound-related neurophysiology of PA that allows to establish a relationship between the PA and EEG readings?*, or the same question in other categories: *Is there any relationship between the PA attributes defined by the ISO 12913 standard and the brain's electroencephalographic activity?* And, if such a relationship exists (2), *Which attributes are involved?*

3. Methodology

3.1. Ethics & participants

The study was conducted at the University of Granada (UGR, Granada, Spain) following methodologies in accordance with the Ethical Principles of the World Medical Association (Declaration of Helsinki) for medical research involving human subjects. The study protocols were approved by the Human Research Ethics Committee of the University of Granada (Ref. 4510/CEIH/2024), ensuring compliance with the ethical principles of scientific research. Informed consent was obtained from all subjects of the study.

The study involved 12 participants (6 females and 6 males, 24–62 years old, mean $\pm$ SD = 44.8 $\pm$ 12.4 years old), who met the three inclusion criteria: (1) age > 18 years, (2) native Spanish speakers, and (3) absence of reported hearing or cognitive difficulties. Participants were recruited among students and staff at the UGR. Participants had diverse academic backgrounds spanning technical and social disciplines, and none had advanced musical training or professional musical experience, which could have modulated the neurophysiological response to the acoustic stimuli [51–53]. The sample size ($n = 12$) was selected in line with previous EEG studies on auditory-induced oscillations [54–57], given the absence of prior data for formal power estimation in this context.

Table 4
2023 Perceptual Attributes (PA) scores & R^2 (SSM).

Stimuli	p	v	e	ch	a	m	u	ca	P_{ISO}	E_{ISO}	R^2
1 (CG01)	4.00	4.00	4.00	1.00	1.00	1.00	1.00	2.00	0.561	0.427	0.913
4 (CT301)	1.00	1.00	5.00	4.00	5.00	3.00	1.00	1.00	-0.780	0.414	0.925
17 (OS01d)	3.00	4.00	5.00	3.00	1.00	1.00	1.00	1.00	0.177	0.707	0.941
19 (VP01b)	4.00	2.00	1.00	1.00	1.00	4.00	5.00	5.00	0.457	-0.707	0.973
21 (W06)	3.00	2.00	1.00	1.00	1.00	3.00	4.00	3.00	0.104	-0.384	0.908
22 (W09)	1.00	1.00	4.00	4.00	5.00	4.00	1.00	1.00	-0.707	0.237	0.896

3.2. Auditions procedure

From the SATP Project and based on the collected data [17,18] six of the 27 audio clips were selected by three criteria: qualitative difference (Table 3), quantitative difference and eccentricity in response (Table 4). The chosen clips represented markedly distinct auditory experience, ranging from relaxing sounds in quadrant one (audio files 1 and 17) to more unsettling sounds, such as a saw (audio file 4) or a low-frequency motor (audio file 22), as well as other sounds located in the fourth quadrant of the PA.

These six audio recordings are qualitatively highly distinct and were also rated very differently in the survey-based quantitative assessments, which supports their selection (Table 4). The third criterion for selecting audio clips for EEG analysis was the eccentricity of responses within the PA. Despite differences in sound, these clips produced responses closely following a cosine pattern in the Structural Summary Method (SSM), with R^2 values near 1, indicating extreme and consistent positioning along opposing dimensions across all participants (Table 4). Combined with their qualitative and quantitative differences, this justified their selection for EEG analysis.

Six auditory stimuli were selected from the 27 SATP audio excerpts to cover a broad range of soundscape scenarios within the pleasantness–eventfulness map defined in ISO 12913. The chosen excerpts were CG01, VP01b, W09, CT301, W06 and OS01d.

3.3. Objective soundscape perception through EEG

3.3.1. Stimulus

Each audio file selected, lasted 30 s and was presented sequentially with a randomly varying silent interval of 2.5–3.5 s between them. To obtain high-quality neurophysiological measurements, 10 repetitions of each excerpt were recorded, allowing the estimation of neural responses based on 300-second EEG segments per excerpt.

The audio was delivered through HD650 circumaural headphones (Sennheiser Electronic SE & Co., Wedemark, Germany) driven by a DX3 PRO + sound card (TOPPING Technology Co. LTD., Guangzhou, China). Stimulus presentation was controlled via custom MATLAB scripts (The MathWorks Inc., Natick, MA). Participants were instructed to remain awake and attentive throughout the session.

Acoustic calibration followed the SATP calibration protocol. The SATP set includes a 1-kHz calibration tone recorded at -6 dBFS when reproduced through Sennheiser HD650 headphones, corresponding to 355 mV RMS at the analogue output of the sound card [58] to achieve 94 dB SPL. In the first step, a calibration factor was obtained by determining the gain required for the calibration tone to reach 355 mV RMS at the output of the sound card used in this study. In the second step, this calibration factor was applied to all SATP audio excerpts.

3.3.2. Electroencephalography recording

Neurophysiological responses to the auditory stimuli were recorded using the EPOC X EEG system (EMOTIV Inc., San Francisco, CA) at a 128-Hz sampling rate. The wireless headset includes 14 channels—F3, F4, AF3, AF4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1 and O2—arranged according to the 10/10 International System [59]. Manufacturer-recommended procedures were followed to ensure high-quality EEG,

including moistening the felt sensors with conductive liquid to improve electrode–skin contact and verifying that the signal quality exceeded 80% as indicated by the acquisition software.

EEG synchronisation with the auditory stimuli was achieved via the Lab Streaming Layer protocol [60]. This protocol enabled joint recording of EEG signals and time-stamped triggers sent from MATLAB via Bluetooth. Triggers were sent at the onset and offset of each audio excerpt.

Participants kept their eyes closed throughout the recording session to minimise blink and eye-movement artefacts [61]. Participants were explicitly instructed not to fall asleep, and that any effect of the eyes-closed condition is assumed to be consistent across all experimental conditions [62–64].

3.3.3. EEG data analysis

EEG data were analysed in MATLAB using functions from the ‘Signal Processing and Communications’ and ‘Statistics and Machine Learning’ toolboxes. For each participant, electrode and audio excerpt, the EEG segments corresponding to the 10 repetitions were concatenated. Given the relevance of Fz for EEG-based emotion recognition [65], this channel was estimated as the average of F3 and F4, resulting in 15 EEG channels for analysis.

EEG signals were filtered using a 2nd-order Butterworth band-pass filter between 0.5 and 30 Hz, applied forward and backward to achieve zero-phase filtering and avoid phase distortion.

Power spectral density (PSD) was estimated using an adapted Welch method with artefact rejection. The procedure followed these steps: (1) EEG signals were divided into 4-second segments with 75% overlap (3-second overlap), forming a matrix whose columns corresponded to temporal segments; (2) each segment was windowed with a Hamming window to reduce spectral leakage; (3) artefact rejection was performed by computing each segment’s RMS energy and discarding the 30% most energetic segments (this fixed rejection threshold was chosen as a conservative strategy to ensure comparable PSD estimates across participants, while primarily removing high-amplitude artefacts, albeit at the cost of discarding some low-noise segments in cleaner recordings); (4) a periodogram was computed for each remaining segment as the squared magnitude of its FFT, normalised by segment length; (5) periodograms were averaged to obtain a stable PSD estimate, then normalised by both Hamming-window energy and the sampling frequency, yielding PSD values in physical units of V^2/Hz .

In addition to these global PSD estimates, time-resolved spectral energy was computed to characterise neural responses across the 30-second duration of each audio excerpt. A short-time Fourier transform was applied using 2-second Hamming windows with 50% overlap, giving a 1-second temporal resolution. PSD values at each time point were obtained by squaring FFT magnitudes and normalising by the sampling frequency and window energy, resulting in time-varying PSD estimates in V^2/Hz that preserved both spectral detail and its temporal evolution.

From both the global and time-resolved PSDs, spectral energy was calculated by integrating across the *Delta* (0–4 Hz), *Theta* (4–8 Hz), *Alpha* (8–12 Hz) and *Beta* (12–20 Hz) bands.

Table 5

Comparison of Perceptual Attributes (PA) global scores 2023–2025.

Description			SATP [Spain] 2023		2025	
PA POSITION	Stimuli	sound,	P _{ISO}	E _{ISO}	P _{ISO}	E _{ISO}
VIBRANT	1 (CG01)	swing with music	0.561	0.427	0.750	0.311
	17 (OS01d)	percussion music	0.177	0.707	0.420	0.817
ANNOYING-CHAOTIC	4 (CT301)	chainsaw	−0.780	0.414	−0.817	0.420
	22 (W09)	constant frequency motor	−0.707	0.237	−0.780	0.030
CALM	19 (VP01b)	birds	0.457	−0.707	0.561	−0.750
	21 (W06)	distant water	0.104	−0.384	0.707	−0.396

3.4. Subjective soundscape perception. SATP methodology

Following the electroencephalography (EEG) session, participants completed a questionnaire assessing their perception of the six audio clips, using the same categories as those employed in the SATP project [11]. Subjective perception was assessed by having participants listen to each audio clip again while completing a survey addressing the eight attributes defined in the ISO 12913–2 standard [3]. For more information on this methodology, which has been extensively tested in 18 languages, see [11].

The Soundscape Attributes Translation Project (SATP) is fundamentally grounded in the ISO 12913 standards series, aiming to address the research gap in translating soundscape descriptors for global cross-cultural studies [11]. Adopting the framework of ISO 12913–1, the project treats soundscape as a perceptual construct—the acoustic environment as perceived by people in context—rather than a purely physical phenomenon [1,9]. For its data collection methodology, the SATP utilizes the protocols of Method A from ISO/TS 12913–2:2018, focusing on the eight affective attributes (pleasant, vibrant, eventful, chaotic, annoying, monotonous, uneventful, and calm) [11]. Furthermore, it validates these translations through the analysis frameworks of ISO/TS 12913–3:2025, projecting responses into the two-dimensional circumplex model of pleasantness and eventfulness [66]. A pivotal contribution of the SATP is its four-step validation procedure, which employs Browne’s circular stochastic process model and the Structural Summary Method (SSM) to confirm that translated descriptors maintain a quasi-circumplex structure. By proposing “adjusted angles” for each language, the project corrects for linguistic variations, ensuring that soundscape evaluations are comparable, reliable, and standardized for cross-cultural research globally [11].

3.5. Analysis and comparison of the soundscape perception, both subjective (ISO 12913) and objective (EEG) using Machine learning

To integrate variables from subjective perception, as defined by ISO 12913, with objective EEG measures, Machine Learning methodologies were employed, offering an exploratory, multivariate approach to identify latent patterns in high-dimensional, complex data. This approach is suitable for combining heterogeneous variables without established causal models, using unsupervised techniques, specifically Self-Organizing Maps (SOM), originally proposed by Kohonen to explore, reduce, and visualise multidimensional data while preserving topological relationships [39,40]. SOMs have been successfully applied in contexts with non-linear relationships, non-normal distributions, and complex structures, including social, economic, and spatial data, as well as human voice classification [67,68].

The primary objective was to investigate relationships between Perceptual Attributes (PA) attributes defined in ISO 12913 and EEG activity during exposure to sound stimuli, while identifying coherent perceptual–neural profiles integrating subjective and objective measures. This preserves the multidimensional nature of both the soundscape model and brain activity, avoiding reduction to simple bivariate relationships [69,70].

The SOM model included 70 active variables: the eight PA attributes,

the two synthetic dimensions of the circumplex soundscape model—Pleasantness (P_{ISO}) and Eventfulness (E_{ISO})—and 60 EEG variables corresponding to Delta, Theta, Alpha, and Beta bands recorded at 14 sensors (F3, F4, AF3, AF4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2), with Fz estimated as the mean of F3 and F4 [71]. These variables capture neurophysiological patterns related to activation, attention, emotional valence, and cognitive load [72]. An additional 129 supplementary variables were included with Priority = 0, meaning they did not influence SOM training but allowed a posteriori analysis of contextual factors, such as audio file, participant, repetition, and time, facilitating semantic interpretation without bias [73,74]. EEG variables were logarithmically transformed to address asymmetry and long-tailed distributions, reduce the influence of extreme values, and improve numerical and topological stability, a standard practice in multivariate EEG analysis [75].

The SOM was implemented as a tool for knowledge discovery and profile identification, using Viscosity SOMine 7.2 (Build 6719) on 20,880 records and 199 attributes. The principal plane was 100 × 97 units, with a final topology of 940 nodes in 33 rows × 29 columns, trained over 27 cycles with a tension of 0.5. Final errors were a normalised distortion of 8.368 and a quantisation error of 6.978.

Profile numbers were determined using hierarchical cluster analysis on SOM prototypes, applying multiple statistical criteria and validation indices to ensure robust configurations [76]. Profiles were characterised using descriptive statistics and effect sizes (Cohen’s *d*) to quantify variable contributions beyond statistical significance, as recommended by Cohen (1988) [77] and the American Statistical Association. This procedure has been applied in prior SOM studies in perceptual and urban contexts [74], enabling identification of the most relevant PA attributes and EEG bands for each profile.

4. Results and discussion

4.1. Validation of SATP Spanish descriptors: comparative analysis 2023–2025

Once the surveys for this study were analysed, the results obtained (Table 5) are consistent with previous literature obtained in the SATP project in Spain [17,18].

For Spanish, two member countries were considered: one Spanish-speaking and one European-speaking; Spain and Chile. Table 5 presents the reference values for Spanish in Spain [18] alongside the values for the six stimuli obtained from ISO 12913 surveys of the twelve participants in this study.

The vibrant axis comprises the most dynamic sound environments, namely CG01 and OS01d, both of which contain music. Both recordings exhibit statistically significant differences in P_{ISO} between 2023 and 2025 (Table 5). The annoying–chaotic position comprises the two sound environments perceived as the most unpleasant: the CT301 chainsaw and the W09 constant-frequency motor. Within this quadrant, the CT301 recording shows no statistically significant differences 2023–2025, whereas W09 exhibits a significant change in E_{ISO}, with the constant-frequency motor being perceived as less eventful in 2025. Finally, the two non-anthropogenic sound environments, the birdsong

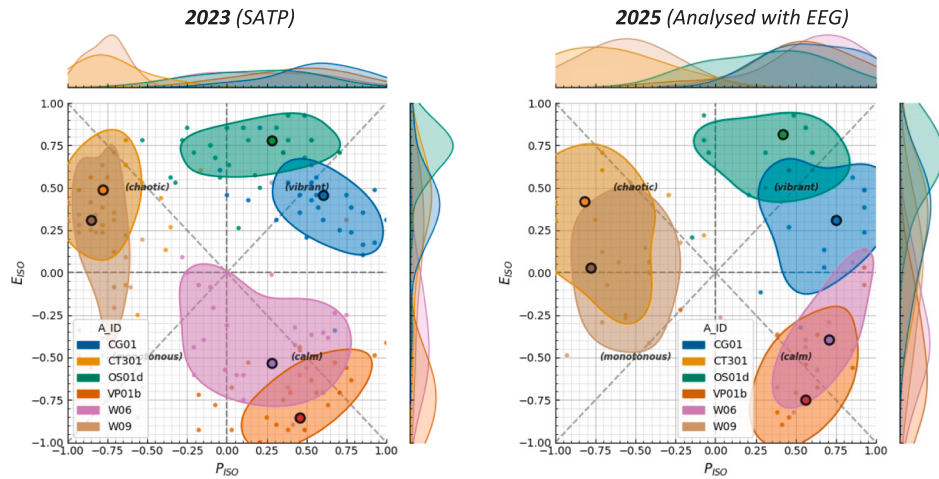


Fig. 1. Scatter plot of circumplex coordinates of PA model and median contour distributions comparison for SATP 2023 auditions (left) and EEG 2025 new auditions (right).

Table 6
2025 Perceptual Attributes (PA) scores & R^2 (SSM).

Stimuli	<i>p</i>	<i>v</i>	<i>e</i>	<i>ch</i>	<i>a</i>	<i>m</i>	<i>u</i>	<i>ca</i>	P_{ISO}	E_{ISO}	R^2
1 (CG01)	4.0	4.0	4.0	1.0	1.0	1.0	1.0	4.0	0.750	0.311	0.853
4 (CT301)	1.0	1.0	4.0	4.5	5.0	3.0	1.0	1.0	-0.817	0.420	0.906
17 (OS01d)	4.0	4.5	5.0	3.0	1.0	1.0	1.0	1.0	0.420	0.817	0.906
19 (VP01b)	5.0	2.0	1.0	1.0	1.0	4.0	4.0	5.0	0.561	-0.750	0.894
21 (W06)	5.0	3.0	2.0	1.0	1.0	3.0	3.0	5.0	0.707	-0.396	0.908
22 (W09)	1.0	1.0	3.0	3.0	5.0	4.0	2.0	1.0	-0.780	0.030	0.889

recording (VP01b) and the flowing water recording (W06), are located around the calm axis. Of these, only W06 exhibits a marked difference between 2023 and 2025, with the sound of flowing water being perceived as significantly more pleasant in 2025. Fig. 1 illustrates these differences in the PA model between the SATP project values published in 2023 [18] and the values obtained in this study (2025), which were analysed alongside electroencephalographic measurements.

It is noteworthy that the SATP Project [18] included 27 participants in Spain, whereas this study involved only 12. This difference in sample size may account for some of the observed discrepancies, with the SATP values likely being more representative. Nonetheless, the audio clips CT301, OS01d, and VP01b exhibit similar medians (Table 5). Minor differences are observed in CG01, while only W06 and W09 show substantially divergent values. It is also significant that the survey results indicate these stimuli remain extreme in their audio characteristics, even more so that in the SATP project, occupying peripheral positions within the PA diagram. These extreme and distinctive values for the six stimuli are clearly reflected in the survey outcomes of this study (Table 6), rendering the particularly suitable for electroencephalographic investigation.

Despite the substantial difference in sample size between the original SATP study ($N = 27$) and the current experimental cohort ($N = 12$), the global scores remain remarkably consistent. Specifically, the stimuli CT301 (chainsaw), OS01d (percussion), and VP01b (birdsong) exhibited nearly identical medians in both datasets (Table 5). This stability suggests that the Spanish SATP descriptors have established a robust conceptual structure that is resilient to variations in participant groups and experimental settings, providing a reliable subjective baseline for EEG-based validation.

The 2023–2025 comparison suggests that the validated Spanish descriptors remain stable, reliable, and meaningful tools for soundscape characterization. This provides the necessary empirical proof that the SATP protocol is ready for global application.

4.2. Mapping a neurophysiology of PA: soundscape and power spectrum density

The dataset comprises readings from 12 participants, recorded across 14 EEG electrodes, for 10 repetitions of each of the six audio files, sampled at 128 Hz over 30 s, and considering seven indices across multiple frequency bands.

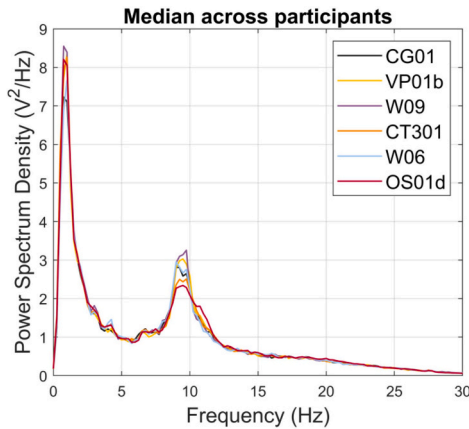
When comparing perceptual responses (ISO 12913) with average neural responses (SATP), establishing a direct and conclusive correlation is challenging due to substantial inter-individual variability in the spectral averages. Nevertheless, certain neural response patterns are consistently observed within participants. Previous studies have confirmed these natural perceptual differences, particularly noting Alpha-band peaks when participants are exposed to familiar auditory stimuli [34].

Each of the six audio recordings was presented ten times to validate the EEG data and minimise noise-related deviations. Within participants, repeated exposures elicited consistent perceptual responses, revealing stable individual patterns and indicating a participant specific internal coherence of perception. In contrast, the variability observed across participants reflects distinct perceptual profiles. Conversely, the variability of patterns between participants reflects distinct modes of perception. Overall, most participants exhibited prominent power density peaks in two frequency ranges: very low frequencies (near 1 below 4 Hz, corresponding to Delta waves) and the Alpha frequency range (approximately 8–12 Hz). Some participants also displayed spectral density peaks in the Theta range (4–8 Hz).

To provide a representative summary of the audio recordings while minimizing the influence of extreme values, median values were calculated across participants for each audio recording. This approach was particularly important because participant 6 exhibited substantially higher power spectral density values than the rest of the cohort. Although these measurements were internally consistent and no recording or processing errors were identified, the use of the mean

Table 7[V²] Full power spectrum density [V²/Hz] x [Hz]. Median per audio file.

	1 (CG01)	4 (CT301)	17 (OS01d)	19 (VP01b)	21 (W06)	22 (W09)
Delta	10.24	11.04	11.06	10.85	10.79	11.73
Theta	4.45	4.44	4.30	4.25	4.37	4.45
Alpha	7.99	8.38	7.71	8.60	8.50	8.33
Beta	4.33	4.42	4.43	4.25	4.36	4.19

**Fig. 2.** Power Spectrum Density [V²/Hz]. Median per audio file.

would have disproportionately weighted this participant and could have obscured the overall population trend. The median was therefore selected as a more robust measure of central tendency. The “[Supplementary Material](#)” reports the median values for each participant across the ten repetitions of each audio recording. Based on these data, [Table 7](#) summarises the minimum and maximum values, which are further illustrated in [Fig. 2](#).

4.3. Analysis of EEG power spectra per participant

The specific values of the power spectral density integrals of each participant are provided in the “[Supplementary Material](#)” (Table SM1), along with corresponding graphs of these spectra (Figures SM1–SM6).

Across the twelve participants, auditory stimuli elicited distinct patterns in Alpha and Delta-band power integrals, reflecting nuanced

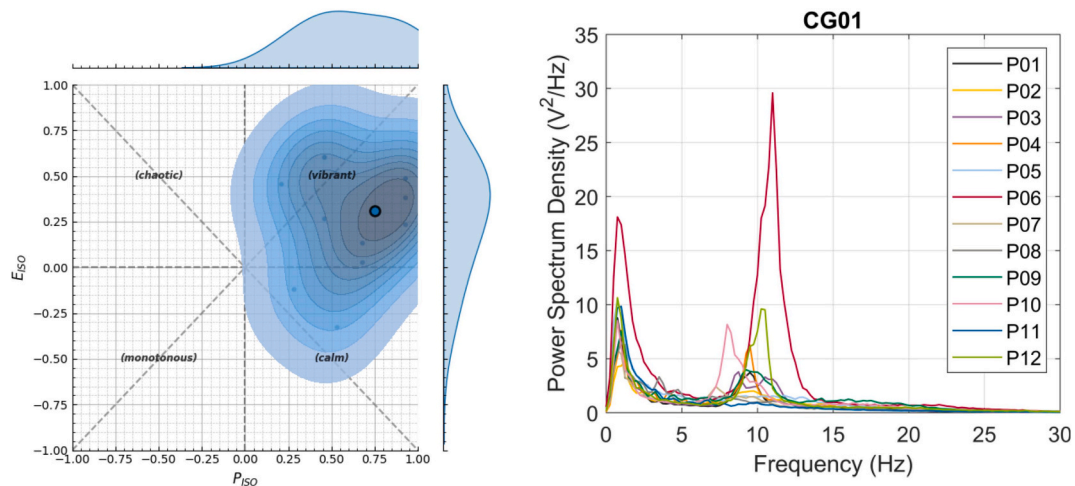
cortical responses. Participants 1 and 3 exhibit lower Alpha for OS01d (dynamic audio clip with percussive elements, vibrant-eventful) and higher Alpha for VP01b (calm-uneventful) or W09 (constant-frequency motor, annoying), suggesting a stress-reducing effect of calming sounds [\[34\]](#). Participant 2 shows heightened Alpha for W09 (constant-frequency motor, annoying) while Delta peaks for OS01d (dynamic audio clip with percussive elements, vibrant-eventful) and CG01 (swing with music, pleasant-vibrant), indicative of enhanced cortical tracking of slow temporal envelopes rather than generalised activity [\[28–30\]](#).

Participants 4 and 6 illustrate the influence of stimulus complexity. Participant 4 shows comparable Alpha for CT301 (chainsaw, annoying-chaotic) and OS01d (dynamic audio clip with percussive elements, vibrant-eventful) but lower Alpha for W09 (constant-frequency motor, annoying), with Delta highest for OS01d (11.24 V²). Participant 6 exhibits elevated Alpha across all stimuli (≥ 40 V²), peaking for W06 (distant water, calm-uneventful), and pronounced Delta for OS01d (33.48 V²), highlighting both stress-alleviating effects of natural sounds and enhanced neural synchronisation [\[28–30\]](#).

Participants 5, 7, and 8 share suppressed Alpha (4–6 V²) with flat profiles, yet Delta peaks differ: Participant 5 for W06 (distant water, calm-uneventful) alongside elevated Beta [\[78\]](#); Participant 7 for CT301 (chainsaw, annoying-chaotic), with Theta exceeding Alpha except for VP01b (birds, calm-uneventful), reflecting accumulated stress mitigated by natural sounds [\[24\]](#); Participant 8 for VP01b (birds, calm-uneventful) (13.06 V²), again highlighting calming non-anthropogenic stimuli [\[23,78\]](#).

Participants 9 and 10 show Alpha peaks for W09 (constant-frequency motor, annoying) and CT301 (chainsaw, annoying-chaotic) or CG01 (swing with music, pleasant-vibrant), with Delta similarly peaking for W09 (11.82–10.65 V²) and minimal response for W06 (distant water, calm-uneventful). Participant 11 displays minimal Alpha (2–3 V²) but maximal Delta (19–20 V²) for annoying sounds (CT301, W09), indicative of pre-attentive processing. Participant 12 demonstrates high Alpha for OS01d (dynamic audio clip with percussive elements, vibrant-eventful) and CG01 (swing with music, pleasant-vibrant) and consistently elevated Delta, peaking for W06 (distant water, calm-uneventful), confirming the stress-reducing effects of music and natural sounds [\[24\]](#).

In sum, dynamic and musical stimuli generally enhance Delta power, whereas natural or calming sounds elevate Alpha, with Theta often surpassing Alpha in participants showing stress markers. These inter-individual variations reveal the interplay between auditory characteristics, attentional engagement, stress modulation, and neural synchronisation.

**Fig. 3.** Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V²/Hz] per audio file CG01.

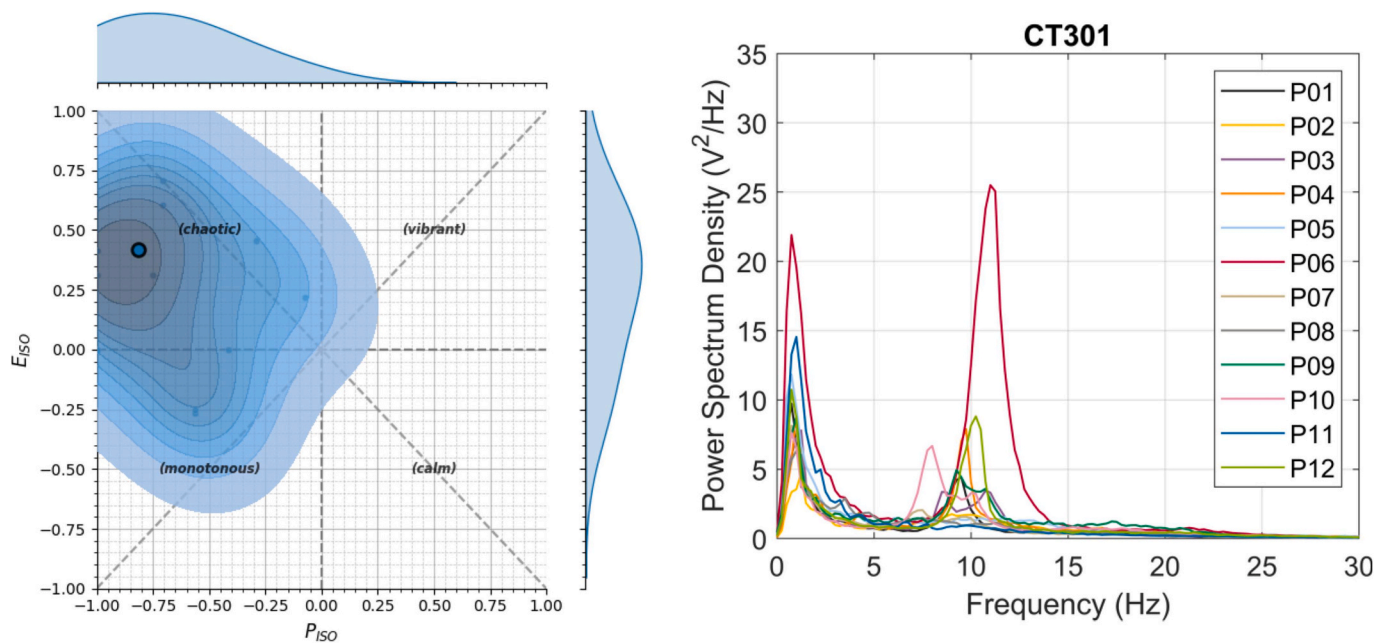


Fig. 4. Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V^2/Hz] per audio file CT301.

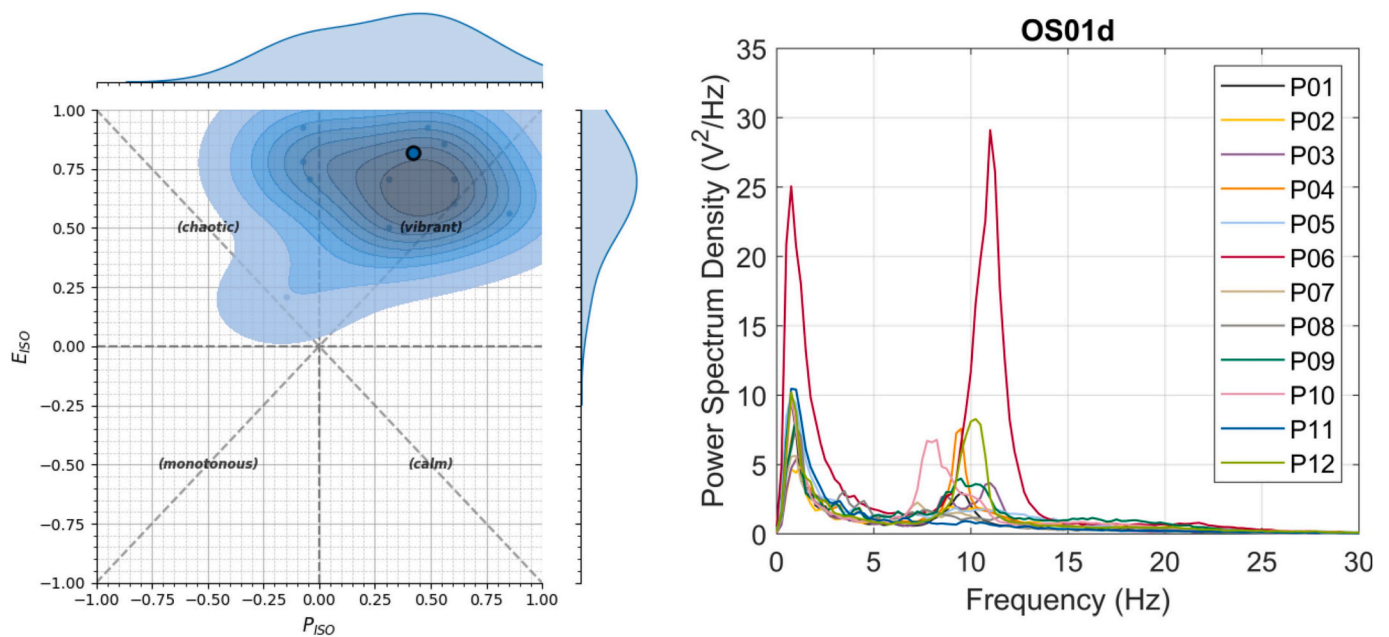


Fig. 5. Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V^2/Hz] per audio file OS01d.

5. Analysis of EEG power spectra in relation to ISO 12913 values for audio

Shifting the focus of the analysis and summarising the previous findings by participant, it is now possible to establish specific correlations between each of the six stimuli and all participants across the main frequency bands (Figs. 3–8).

Audio CG01 (swing with music, pleasant-vibrant) is associated with pronounced Alpha-band peaks, particularly in participants who respond positively to pleasant and dynamic sounds [19,24]. Strong conscious activation is evident in the Alpha potentials of P6 and P12 in response to this pleasant and comforting stimulus [20,79]. For P4, Delta-band activity is relatively low, suggesting that the sound does not have sufficient activity [28,29]. In P12, Delta activity is moderate but not pronounced,

indicating an unconscious perception that may reflect subtle mood changes or imaginative processes [79] (Fig. 3).

Audio CT301 (chainsaw, annoyed-chaotic) elicits high Delta-band peaks, reflecting unconscious reactivity in relation to activity and stronger neural synchronisation with the temporal dynamics of the stimulus [28–30]. It is among the most disruptive stimuli, with pronounced Delta activity in P3 and P7, and in some cases exceeding Alpha power, as observed in P11. Certain participants (P4 y P9) also display elevated Alpha-band activity, indicating conscious processing of the annoyed stimulus. In the remaining participants, Alpha power is relatively low compared with other stimuli, suggesting, as reported in studies on traffic noise [23], a suppression of Alpha activity in response to disruptive auditory input (Fig. 4).

Audio OS01d (percussive music, eventful-vibrant) generally elicits

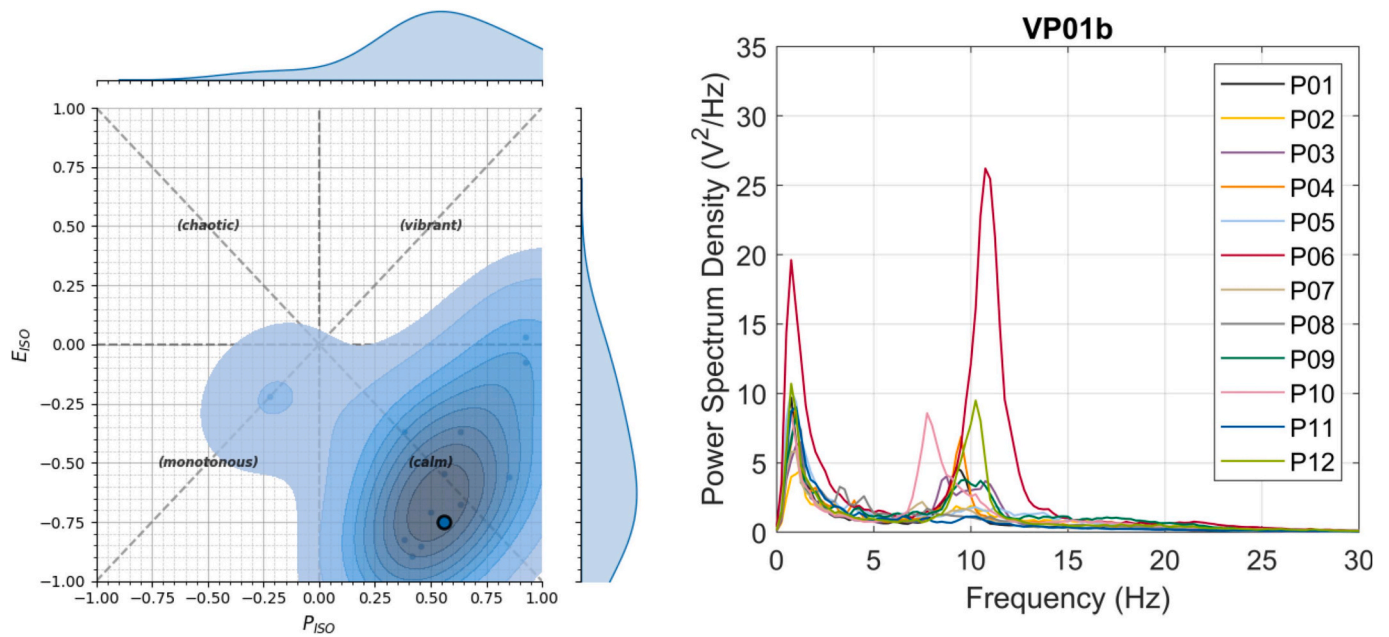


Fig. 6. Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V^2/Hz] per audio file VP01b.

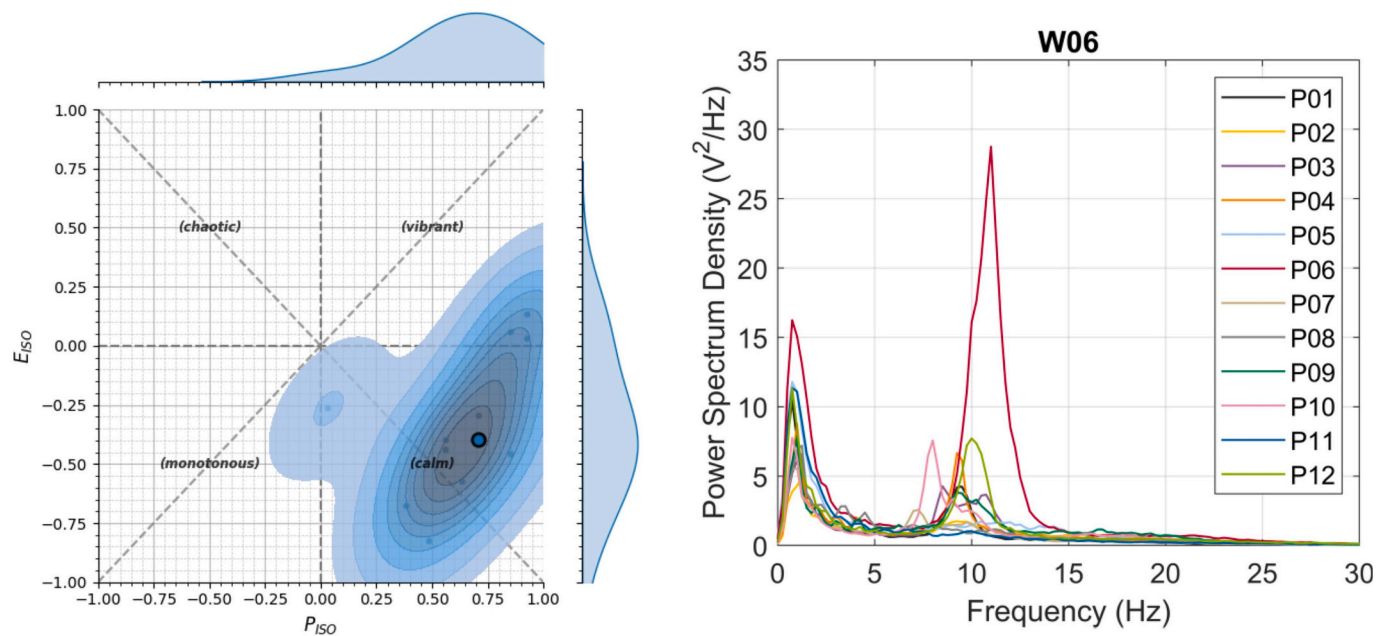


Fig. 7. Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V^2/Hz] per audio file W06.

lower Alpha-band power in several participants (P1 and P3), with the exception of P6, suggesting reduced conscious attention. This contrasts with the swing music in CG01, which is more relaxing and produces higher Alpha power [19]. Elevated Delta activity in P2 and P6 reflect either the unconscious perception of activity [28–30] or the engagement of imaginative processes and shifts in thought [79] (Fig. 5).

Audio VP01b (birds, calm-uneventful) does not cause peaks in the delta band, indicating a lack of activity, especially when compared to more dynamic (OS01d) and disturbing (W09) sounds. Some participants (P1, P12) also display Alpha-band peaks, reflecting conscious processing of the calm stimulus. Previous studies suggest that birdsong is the most relaxing auditory stimulus, surpassing other non-anthropogenic sounds such as water, as well as anthropogenic sounds like music [24], and can act as an anti-stress agent by enhancing Alpha activity [20,80]. Of

particular interest are the Theta-Alpha border peaks observed in P10, which despite the calm nature of the audio, indicate accumulated stress and may also relate to mood fluctuations [20] (Fig. 6).

Audio W06 (distant water, calm-uneventful) exhibits a similar response profile to VP01b. It generates strong Delta-band activity in multiple participants (P1, P5, P8 and P12), reflecting pronounced MMN evoked potentials due to contrast with other stimuli. An exception is P9, who displays considerably lower Delta activity. In the Alpha band, P6 again shows notably high potentials, consistent with studies indicating that the sound of water acts as a relaxing auditory stimulus [33,80] (Fig. 7).

Audio W09 (constant-frequency motor, distinctly annoyed) elicits strong responses in both the Alpha and Delta bands. Alpha power is considerably elevated in several participants (P1, P2, P3, and P9),

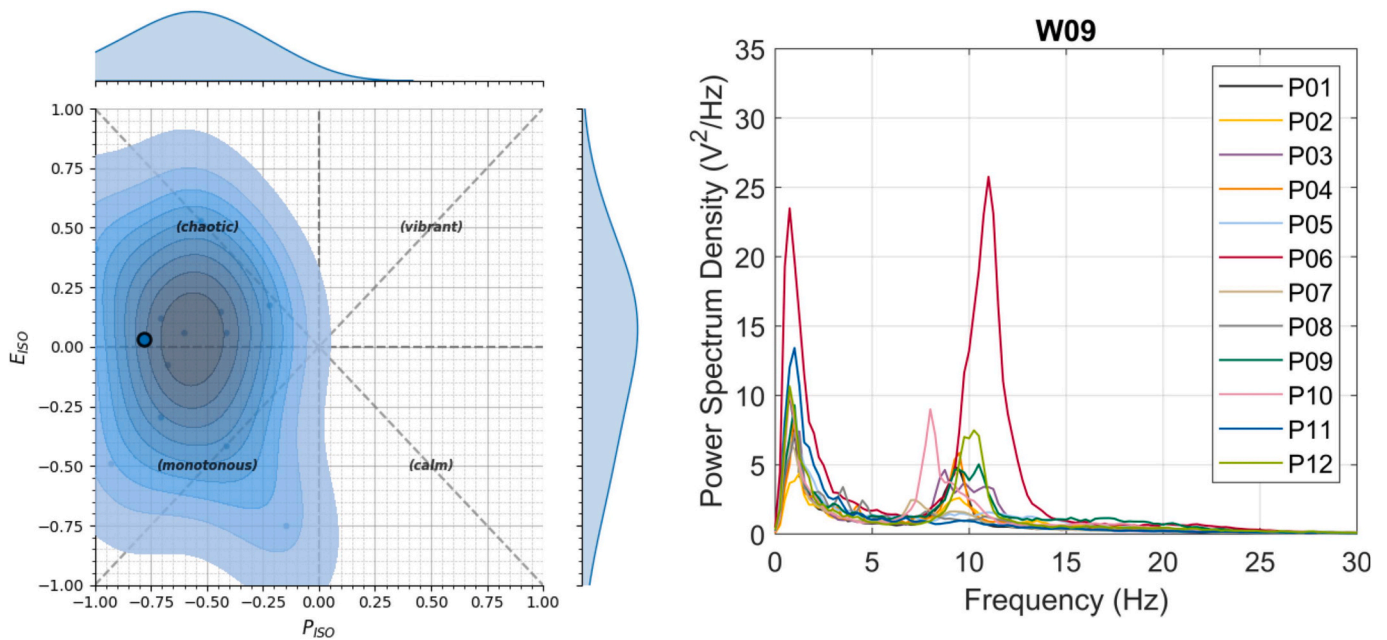


Fig. 8. Perceptual Attributes (PA) P_{ISO} & E_{ISO} and Power Spectrum Density [V^2/Hz] per audio file W09.

whereas it is markedly lower in others (P4, P12). This suggests that, despite being generally rated as annoying and in surveys, the sound may induce a state of mental relaxation in some participants (P1, P2, P3, P9), while in others it elicits distraction or boredom (P4, P12), akin to the effect of listening to constant-speed wind noise [24]. In the Delta band, P3 and P9 show high values, with the median power integral across all participants being the highest. It is noteworthy that this is not an active sound; its primary characteristic is that it is distinctly annoying. This may indicate a Mismatch Negativity (MMN) type evoked potential arising from auditory contrast. When presented within a random sequence of ten listens, the clearly annoying stimulus among the six serves as a contrasting auditory event (Fig. 8). In any case, this statement must be confirmed by other studies, as the MMN effect applies to sequences of less spaced auditory stimuli.

The constant-frequency motor (W09) elicits a paradoxical neurophysiological response, producing Alpha-band relaxation in some participants despite being perceived as annoying. This suggests that continuous, low-frequency sounds may simultaneously induce relaxation or habituation while being consciously rejected. W09 exhibits a dual response profile: elevated Alpha activity, associated with relaxation and restorative effects [19], and dominant Delta activity, interpreted as a Mismatch Negativity (MMN) response to an unconsciously detected contrasting or annoying stimulus [81].

These findings, comparable to continuous mechanical noise sources, indicate that acoustic stability may reduce cognitive load in some individuals but disrupt others, reflecting variability in Alpha responses [82]. Moreover, heightened Delta activity suggests a contrast effect that amplifies perceived annoyance even at moderate sound levels [86]. Inter-individual differences further confirm that such stimuli may be either restorative or stressful depending on neural processing [34].

Overall, the use of Self-Organising Maps (SOMs) reveals that subjective acoustic descriptors correspond to complex neural patterns, supporting evidence-based urban sound design [20] and the development of healthier acoustic environments [83].

5.1. EEG as a tool for cross-linguistic construct equivalence

The added value of the electroencephalography (EEG) approach in the context of the Soundscape Attribute Translation Project (SATP) lies in its ability to provide an objective neurophysiological anchor for

subjective linguistic descriptors [31]. While the SATP has validated soundscape attributes across eighteen languages, these translations remain fundamentally subjective and prone to participant bias or cultural nuances in interpretation [84].

EEG supports the future assessment of conceptual equivalence by identifying a “neurophysiology of PA”, a set of biological response patterns that transcend specific languages. Concrete ways this approach supports cross-linguistic validation include:

- **Physiological Verification of Translated Terms:** By linking specific brain rhythms to translated attributes—such as the Alpha band (8–12 Hz) to “calmado” (calm) and the Delta band (< 4 Hz) to “desagradable” (annoying)—researchers can verify if the same neural signatures are evoked by equivalent terms in other languages [19,24,33,34]. If the term pleasant in English and “agradable” in Spanish both map to the same Alpha-dominant neural cluster, their construct equivalence is biologically confirmed [85].
- **Validation of the Axis-Rotation Hypothesis:** The SATP framework uses an axis-rotation hypothesis to account for how different languages perceive the relationship between attributes like “pleasantness” and “eventfulness” [86]. EEG data, processed through Self-Organising Maps (SOM), can validate these rotations by demonstrating whether the spatial organisation of neural responses mirrors the theoretical shifts proposed for a given language.
- **A Bias-Free Diagnostic:** Unlike surveys, which are filtered through conscious cognitive processes and cultural expectations, EEG captures pre-attentive and unconscious responses (such as Mismatch Negativity in the Delta band), providing a raw measure of how an environment is perceived regardless of the language used to describe it [19,25,27].

5.2. Exploring the neurophysiology of sound & language through Self-Organising maps (SOMs): SATP framework and EEG

Following the analysis of the extensive electroencephalography dataset (over 300,000 values) in relation to the PA survey data (720 values), three distinct clusters become evident. The resulting images illustrate correlations between the variables, highlighting emerging patterns across both neurophysiological responses and survey outcomes. Warm colours indicate the presence of response patterns, whereas cool

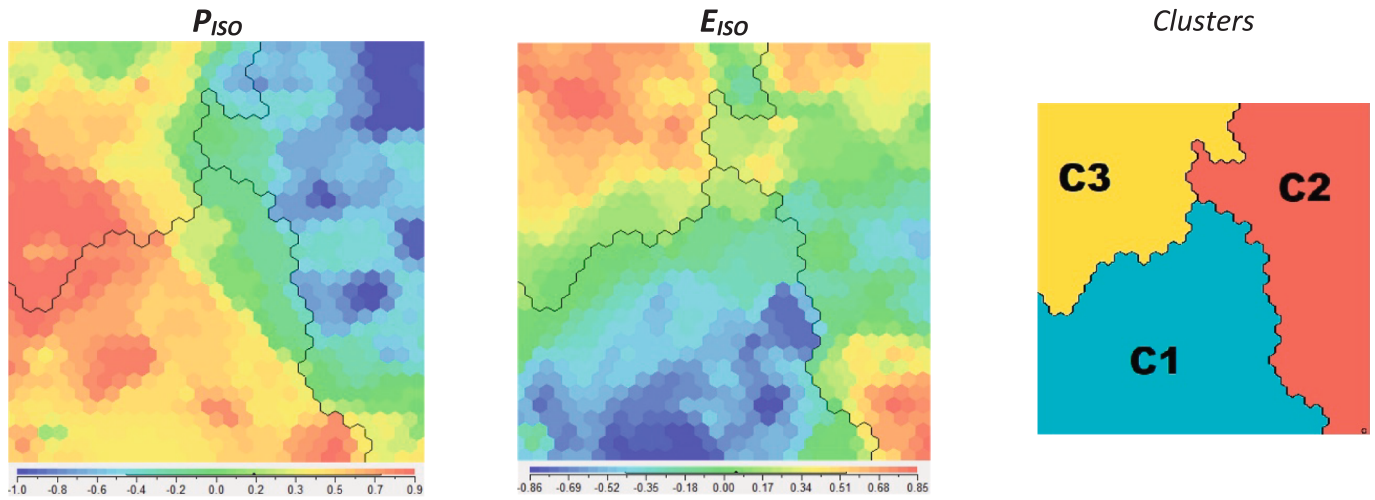


Fig. 9. SOM maps. P_{ISO} & E_{ISO} & electrophysiology using EEG.

Table 8

Cluster occupancy density according to the 8 PA attributes.

PA dimension	Population		Profile C1				Profile C2				Profile C3			
	20,880 records		7941 records (38.03%)				7300 records (34.96%)				5639 records (27.01%)			
	M	SD	M	SD	ES	ES	M	SD	ES	ES	M	SD	ES	ES
Pleasant	56.70	40.60	78.50	27.50	0.54	++	15.20	28.40	-1.02	--	79.70	23.80	0.57	++
Chaotic	36.60	36.60	9.00	13.10	-0.75	--	70.80	29.70	0.93	+++	31.20	30.90	-0.15	--
Vibrant	43.90	34.90	44.50	31.10	0.02	--	18.10	23.80	-0.74	--	76.30	22.50	0.93	+++
Uneventful	34.10	35.70	55.80	33.20	0.61	++	28.60	36.00	-0.15	--	10.70	15.70	-0.66	--
Calm	47.30	42.30	85.10	22.90	0.89	+++	9.60	22.00	-0.89	--	43.00	37.10	-0.10	--
Annoying	32.70	40.10	6.40	7.20	-0.66	--	76.90	34.00	1.10	+++	12.40	21.30	-0.51	--
Eventful	58.70	34.30	33.10	27.40	-0.75	--	67.60	32.90	0.26	+	83.30	16.30	0.72	++
Monotonous	47.30	34.70	61.20	25.20	0.40	+	54.70	37.90	0.21	+	18.20	22.60	-0.84	--
P (ISO)	0.15	0.62	0.50	0.31	0.57	++	-0.54	0.39	-1.10	--	0.53	0.40	0.62	++
E (ISO)	0.05	0.49	-0.40	0.32	-0.92	--	0.21	0.36	0.34	+	0.47	0.28	0.87	+++

Abbreviations: M: Mean; SD: Standard Deviation; ES: Size of Effect.

colours denote the absence of correlations. In an initial comparison with P_{ISO} and E_{ISO} , no specific localisation of the parameters is apparent; however, a clearly defined empty region is observed, corresponding to one of the clusters (Fig. 9).

P_{ISO} is primarily located in clusters C1 and C3, with minimal or negligible presence in C2. E_{ISO} displays a complementary pattern, occupying clusters C2 and C3 while showing no relevance in C1, suggesting a relationship of relative antonymy (Table 8). P_{ISO} is positioned at the antipodes of cluster C2, which corresponds to the annoyed dimension, centered between monotonous and chaotic stimuli (Fig. 9). Conversely, E_{ISO} is situated at the antipodes of cluster C1, corresponding to inactivity but shifted towards calm. While P_{ISO} aligns closely with the unpleasantness represented in cluster C2, E_{ISO} aligns with calmness, albeit partially reflecting inactivity. In this context, the calm attribute best characterizes cluster C2 (Fig. 13), and the SOM maps indicate that, according to EEG data, E_{ISO} exhibits a shift towards the chaotic-calm diagonal.

SATP Framework can be a Basis for a neurophysiology of PA (ISO 12913). The high correspondence between these survey results and the subsequent neurophysiological findings suggests the validity of the axis-rotation hypothesis proposed by the SATP [11]. The fact that these stable Spanish descriptors align with the Self-Organising Map (SOM) clusters (where “*calmado*” matches the high Alpha power of Cluster 1 and “*desagradable*” matches the Delta power of Cluster 2) proves that the a neurophysiology of PA, grounded in a consistent linguistic framework, is possible.

5.3. Analysis for each audio using SOMs

Analysed using SOM maps, the EEG-based perception of each of the six audio clips is clearly defined within the three clusters. This indicates that neurophysiological responses align closely with the median positions derived from the PA [66].

Audio CG01 (swing with music, pleasant-vibrant) is predominantly located in cluster 3 of the SOM map, with a portion extending into cluster 1. Audio OS01d (percussive music, eventful-vibrant) is more clearly concentrated in cluster 3, reflecting a higher response density. These observations indicate that neurophysiological responses associated with activity and movement, are primarily represented in cluster 3. Responses related to pleasantness are situated between the upper region of cluster 1 and cluster 3, positioning the center of cluster 3 closer to the vibrant axis (Fig. 10).

Audio CT301 (chainsaw, annoyed-chaotic) is predominantly situated within cluster 2 of the SOM map. This sound is associated with activity and exhibits qualitative discontinuities. In contrast, audio W09 (constant-frequency motor, distinctly annoyed) is primarily perceived as annoyed without any association to activity or event-related connotations. Despite its unpleasantness, W09 partially extends into cluster 1 in the EEG data, which is linked to calm sounds (Fig. 11).

Audio VP01b (birds, calm-uneventful) and audio W06 (distant water, calm-uneventful) are qualitatively distinct, yet both are strongly associated with calmness and non-anthropogenic sounds (sounds not generated by humans). Notably, the neurophysiological responses to both stimuli align clearly with cluster 1 (Fig. 12).

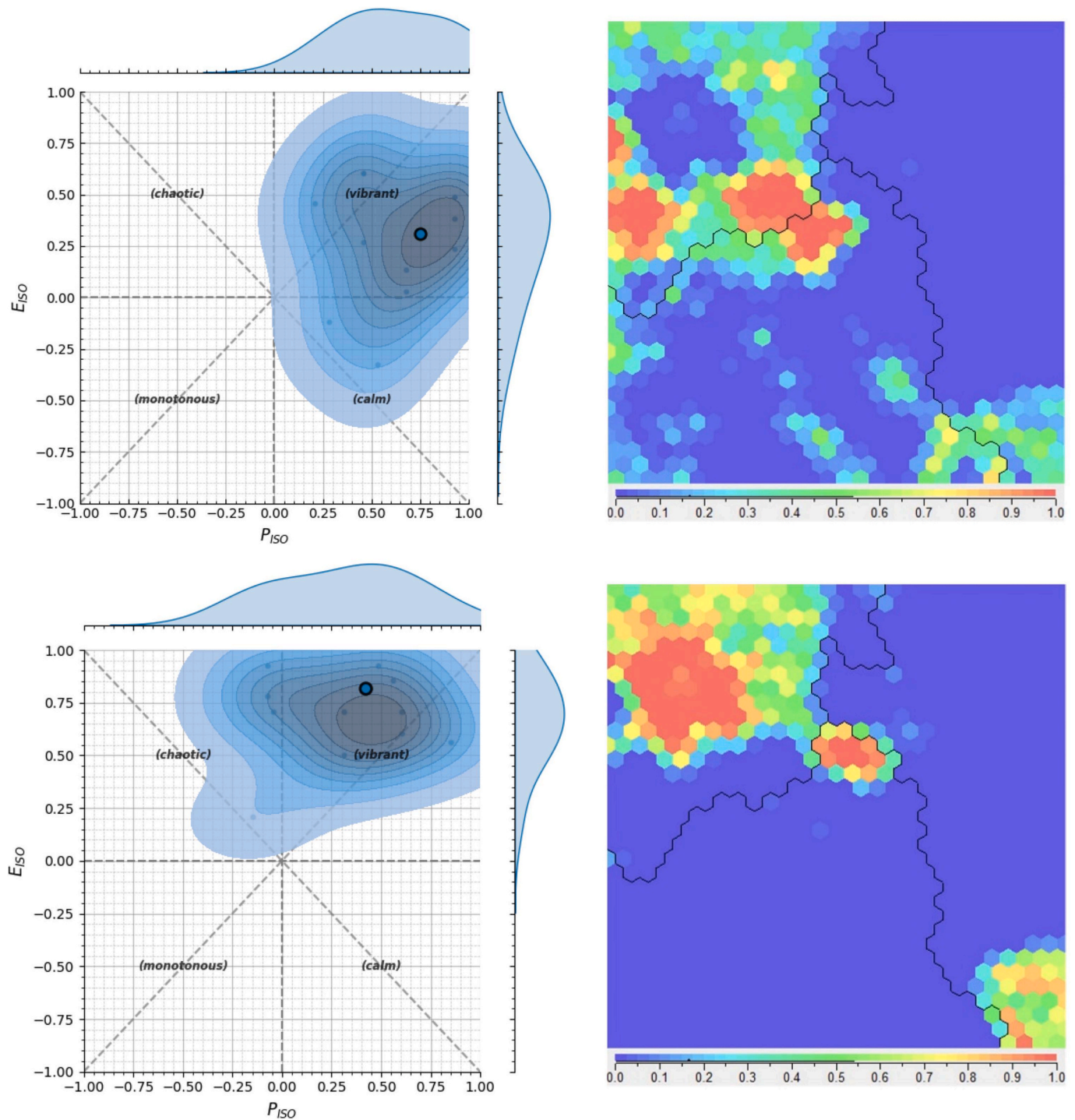


Fig. 10. [PA + EEG] into SOM map per audio file CG01 (up) & OS01d (down).

SOM maps enable the analysis of each of the eight PA attributes in relation to EEG data (Fig. 13). Of particular note is the maximum cluster fit observed for three attributes: calm to cluster 1, annoying to cluster 2, and vibrant to cluster 3. These attributes correspond closely with the PA model for each audio clip (Table 8). This alignment demonstrates that the EEG readings support the validity of the PA model established in ISO 12913 [87], as the machine-learning system identifies consistent response patterns between the survey data and the neurophysiological measurements.

5.4. Properties of psychoacoustic parameters in relation to EEG indicators and the results of SOM maps

The integration of psychoacoustic parameters (Fig. 14), electroencephalography (EEG) data, and Self-Organizing Maps (SOM) facilitates the identification of a neurophysiological basis for sound perception, in which objective acoustic stimuli are systematically linked to specific neural states and sound perception descriptors. This multidimensional analysis organizes soundscape perception into three primary clusters that align with the ISO 12913 circumplex model (Table 9).

The 'Calm' Cluster (C1): VP01b (Birdsong) and W06 (Distant

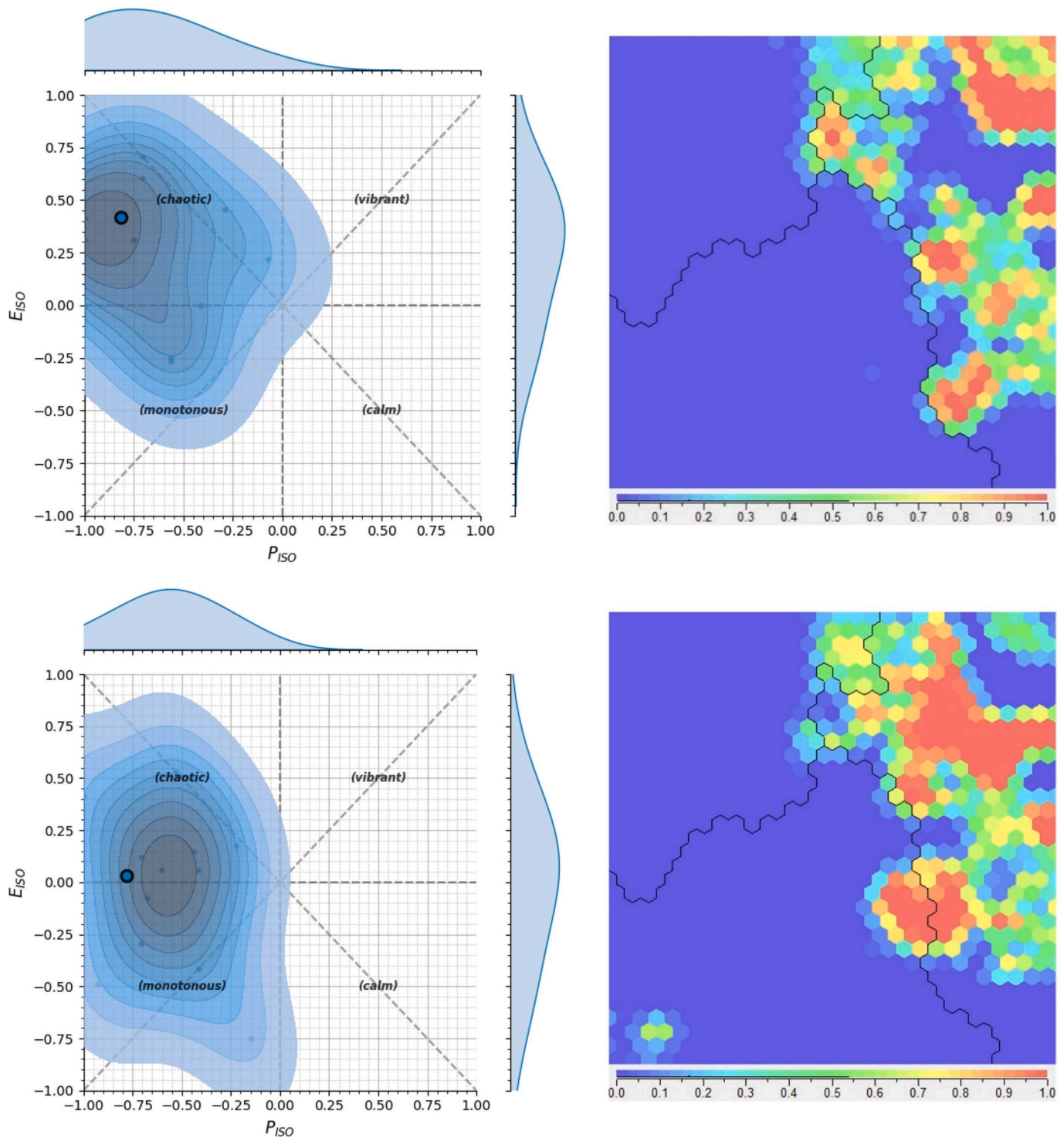


Fig. 11. [PA + EEG] into SOM map per audio file CT301 (up) & W09 (down).

Water). This cluster is defined by low-intensity stimuli associated with restorative states and psychological comfort.

- **Psychoacoustic Parameters:** These excerpts exhibit the lowest Levels (dBA) in the study (VP01b: 30 dBA; W06: 42 dBA). Their loudness is minimal, particularly for VP01b (1 sone). Furthermore, they demonstrate the lowest recorded values for sharpness (0.8–1.4 acum) and roughness (0.12 asper).
- **EEG Indicators:** These stimuli elicit prominent power density peaks in the Alpha band (8–12 Hz). Increased Alpha activity is a reliable

indicator for relaxation, reduced mental stress, and conscious states of calm alertness.

- **SOM Results:** Both stimuli are positioned within Cluster 1, which correlates with the “calm” and “uneventful” attributes.

The “Annoying” Cluster (C2): CT301 (Chain saw) and W09 (Constant Motor) This cluster represents aggressive or disruptive stimuli that trigger pre-attentive stress responses.

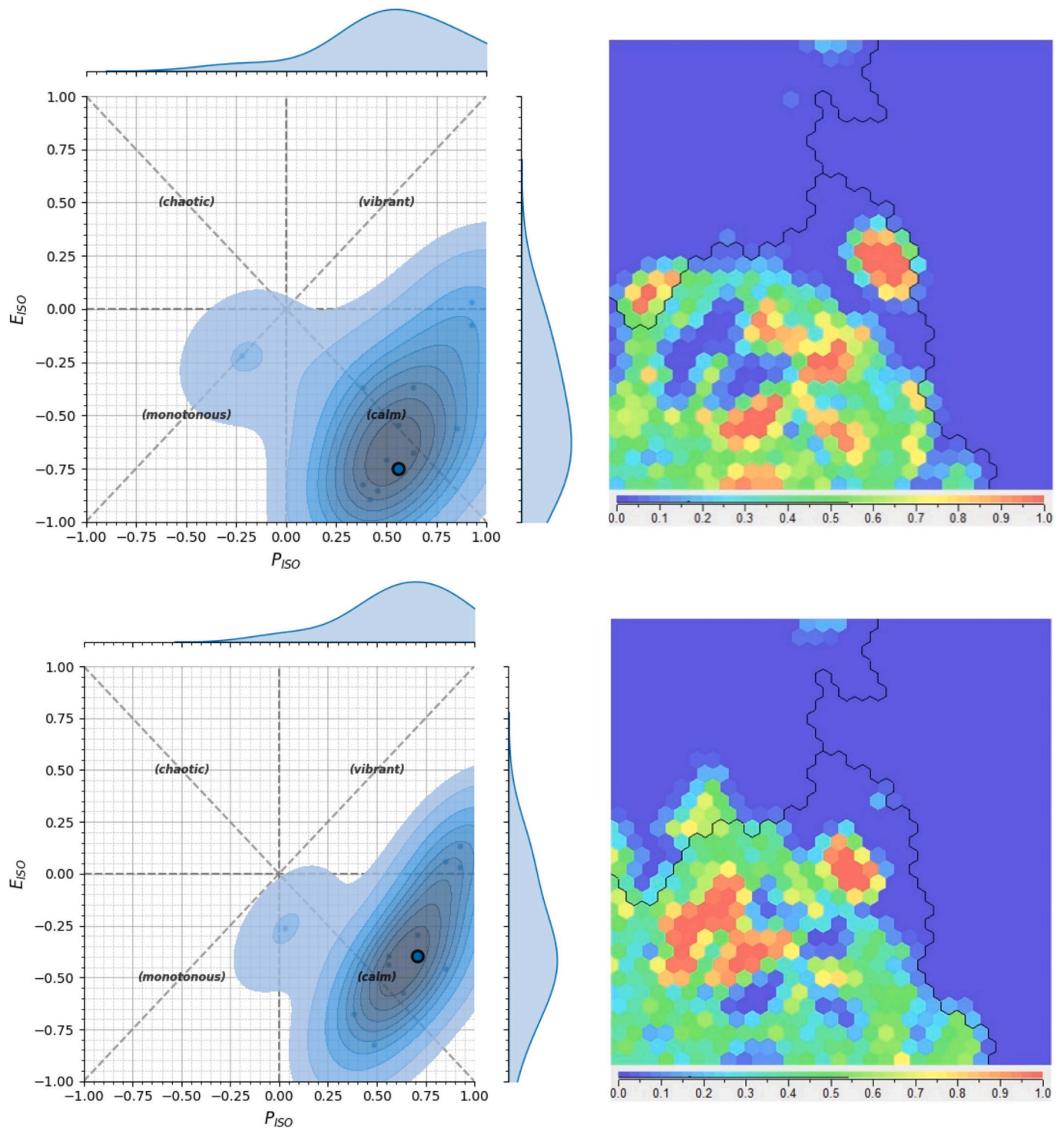


Fig. 12. [PA + EEG] into SOM map per audio file VP01b (up) & W06 (down).

- **Psychoacoustic Parameters:** CT301 records the highest Levels (75 dBA), Loudness (43 sone), Sharpness (1.8 acum) and Tonality (T5, 1.7 tuHMS) perceived as prominent. W09 is distinguished by having the highest Roughness (0.44 asper) across all stimuli.
- **EEG Indicators:** These sounds elicit significant activation in the Delta band (<4Hz), associated with unconscious reactivity and pre-attentive processing of disruptive input. In CT301, this is accompanied by a suppression of Alpha activity, a typical physiological response to noise-induced tension.

- **SOM Results:** These excerpts occupy Cluster 2, which is associated with the “annoying” and “chaotic” dimensions.

The 'Vibrant' Cluster (C3): CG01 (Swing Music) and OS01d (Percussion and Voices). This cluster comprises dynamic stimuli with complex temporal structures that engage cortical tracking mechanisms.

- **Psychoacoustic Parameters:** These files maintain moderate Levels (55–65 dBA) and Loudness (10–21 sone). Notably, OS01d exhibits

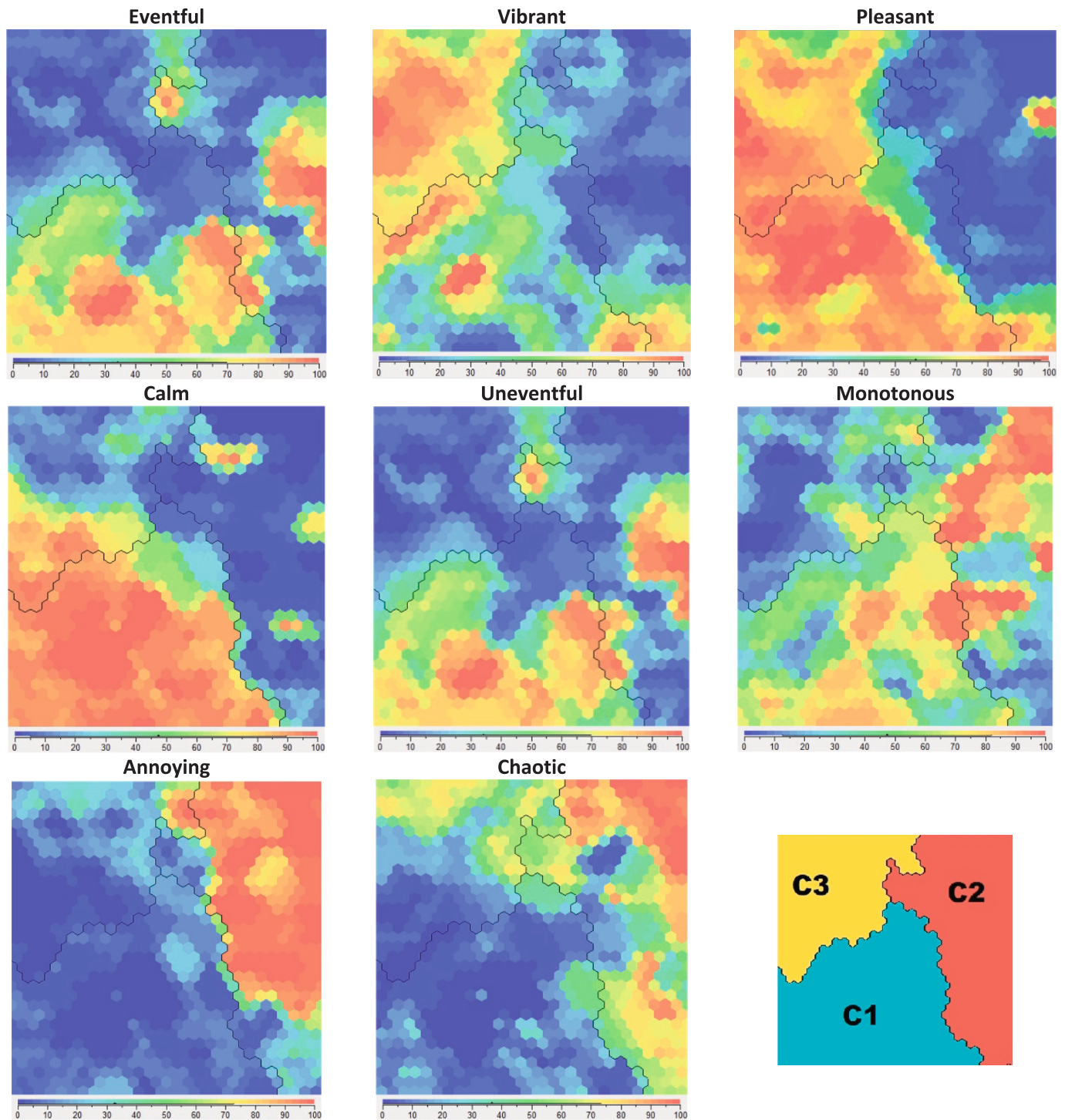


Fig. 13. SOM maps generated based on the interactions of the eight Perceptual Attributes (PA) and the per-second neurophysiological data recorded via EEG while listening to the audio clips.

the highest Fluctuation Strength (0.10–0.14 vacil) due to its rhythmic percussive nature.

- **EEG Indicators:** CG01 produces elevated Alpha peaks, reflecting positive activation and aesthetic pleasure. OS01d elicits high Delta-band energy, interpreted as cortical tracking (neural synchronisation) of the stimulus's slow temporal envelope and rhythmic fluctuations.
- **SOM Results:** These stimuli are located in Cluster 3, aligning with the “vibrant” and “eventful” affective qualities.

6. Conclusions

This study provides preliminary evidence of a systematic relationship between the Perceptual Attributes (PA) defined in ISO 12913 and patterns of neurophysiological brain activity. The findings suggest that PA may be associated with measurable electrophysiological responses, supporting the hypothesis of a neurophysiological basis for soundscape perception. Rather than reflecting a simple one-to-one correspondence, these associations appear to involve multidimensional modulation of existing brain rhythms, particularly within the Alpha and Delta



Fig. 14. Psychoacoustic parameters and levels per audio file.

Table 9

Qualitative summary of neuro-psychoacoustic associations.

Key Parameter	Physical Trend	Dominant EEG Response	SOM Cluster
Low Levels / Loudness	VP01b, W06	Alpha (Relaxation)	C1 (Calm)
High Levels / Roughness	CT301, W09	Delta (Stress/Reactivity)	C2 (Annoying)
High Fluctuation Strength	OS01d, CG01	Delta (Neural Tracking) / Alpha	C3 (Vibrant)

frequency bands.

Specifically, Alpha-band power (8–13 Hz) serves as a reliable marker for restorative and calm states, increasing significantly during exposure to non-anthropogenic sounds like birdsong (VP01b) and murmuring water (W06). Conversely, Delta-band activity (< 4 Hz) is associated with eventfulness and annoyance, reflecting pre-attentive responses to disruptive stimuli and the cortical tracking of complex temporal envelopes in dynamic sounds. Pleasantness [P_{ISO}] and Eventfulness [E_{ISO}] are associated with the amplitude of brain rhythms linked to cognitive

and emotional states, primarily within the Delta and Alpha frequency bands. High Eventfulness (E_{ISO}) values are associated with elevated power spectra in the Delta band (0–4 Hz). Conversely, due to auditory contrast, Delta-band activity is also high for audio clips perceived as dynamic or very different.

Through the use of Self-Organising Maps (SOM), the research identified three robust clusters (Calm, Annoying, and Vibrant) which spatially mirror the theoretical axes of the ISO 12913 circumplex model. There is a clear relationship between low-activity or calm non-anthropogenic sounds and cluster 1 of the SOM maps, indicating that these stimuli elicit highly consistent neurophysiological responses in opposition to the vibrant and annoying axes.

The calm sounds represented in Cluster 1 (birds, water) exhibited low values of Loudness, Sharpness, and Roughness, and were associated with high power in the Alpha band. Unpleasant sounds grouped within Cluster 2 (chainsaw, steady engine noise) showed high Roughness and Tonality values, together with elevated sound levels, and were correlated with Delta-band activation. Finally, the vibrant sounds included in Cluster 3 (music, percussion) were characterised by high Fluctuation values and increased Alpha-band activity. These findings validate the stability of the Spanish SATP framework, confirming that translated

descriptors maintain a consistent neurophysiological structure.

The present findings should, however, be interpreted in light of several important limitations. First, the study was conducted with a relatively small sample of twelve participants, and consequently the results should be regarded as exploratory rather than definitive. Whilst the consistency of the observed EEG patterns across participants is encouraging, the limited sample size constrains the statistical power of the analyses and the generalisability of the conclusions. Secondly, the study examined a carefully selected subset of six recordings from the SATP database, representing the principal regions of the ISO 12913 circumplex model. Whether the observed neurophysiological patterns remain stable across the full range of SATP sound environments and across larger, more diverse populations remains to be established.

Despite these limitations, the study demonstrates the feasibility of integrating EEG measurements with the ISO 12913 perceptual framework and provides a methodological foundation for future research. The protocol developed here can be readily extended within the SATP project to include larger participant cohorts, additional languages and cultures, and the complete SATP sound database. Such studies will enable a more comprehensive assessment of the neurophysiological consistency of translated perceptual attributes and determine whether the relationships identified in this exploratory investigation constitute global indicators of soundscape perception. In this respect, the present work should be viewed as an initial step towards the development of an evidence-based neurophysiological framework for the cross-linguistic validation of ISO 12913 perceptual attributes.

CRediT authorship contribution statement

Rafael García-Quesada: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Joaquín T. Valderama:** Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Jerónimo Vida Manzano:** Validation, Supervision, Project administration, Investigation. **Ángel F. Ramos-Ridao:** Validation, Supervision, Project administration. **José Antonio Almagro:** Formal analysis, Data curation. **Francisco J. Abarca Álvarez:** Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apacoust.2026.111508>.

Data availability

Processed data in “[Supplementary Material](#)” and Zenodo (SATP).

Raw EEG readings private for confidentiality

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