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WHEN SOUNDS BRING BACK MEMORIES: A PSYCHOPHYSIOLOGICAL APPROACH

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Abstract

Soundscapes influence emotional and cognitive states, yet their capacity to trigger autobiographical memory remains underexplored in psychoacoustics. This study is the second part of an audiovisual experiment investigating the relationships among soundscape perception, autobiographical memory retrieval, and soundscape arousal. Twenty-seven participants (university students and academic staff) were exposed to four of five scenes: 1. urban traffic, traffic masked 2. with water sounds, 3. with simple music, 4. with sleep music, and 5. with changes in loudness. Electrodermal activity and heart rate were recorded continuously. Following each scene, participants completed a structured memory elicitation protocol assessing whether the soundscape triggered autobiographical memory across eight associative dimensions: meaningful events, persons, places, activities, objects, time periods, thoughts, and emotions. A memory profile heatmap is proposed to visualise the proportion of participants who trigger each memory dimension in each scene, enabling direct comparison across conditions. Skin conductance response frequency and tonic electrodermal level slope are examined in relation to memory retrieval using linear mixed-effects models that account for the repeated-measures structure of the data. This multimodal framework bridges soundscape perception, autobiographical memory research, and objective physiological measurement, offering a novel perspective on how urban sound environments are experienced and remembered. Implications for soundscape design and evaluation are discussed.

Keywords: *Autobiographical memory, memory retrieval, urban soundscape, ERC, EDA.*

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1. Introduction

Soundscape research has increasingly examined the interplay between cognition, affect, and auditory perception, with several studies establishing robust links between how environments sound and how they are emotionally and cognitively experienced [1-4]. However, despite this growing body of work on soundscape-cognition-affect relationships, the role of memory and how established taxonomies of memory such as episodic, semantic, and autobiographical memory apply to sound and soundscape-induced recall remains comparatively underexplored.

The existing literature about memory retrieval in soundscape studies reports that around 40% of the investigated types of memory retrieval are related to autobiographical and collective memory [5].

Autobiographical memory (AM) is the memory system that stores and retrieves personal life experiences. It combines elements of episodic memory, which involves recollections of specific events, people, objects, and experiences tied to particular times and places, with semantic memory, which includes general knowledge, facts, and concepts about the world [6].

It emerges as one of the central mechanisms explaining why soundscapes matter to people beyond their acoustic properties. Sounds can "transport" listeners back to specific places, people, and periods of life, often described through the "Proustian" metaphor of involuntary memory [7-8]. The "Proustian" metaphor of involuntary memory refers to the unexpected and automatic recall of past experiences triggered by a sensory stimulus, such as a smell, taste, or sound [9].

Regarding the investigation of AM in soundscape studies, little methodological information is available on qualitative data collection for autobiographical memory assessment. Most of them concentrate on narratives [10] or the effects of walking to assess personal memories [7] of the past and connect them to the future [11].

In the 1980s, Barsalou [12] proposed a methodological protocol for assessing autobiographical memory

retrieval, consisting of interviews based on free and cued recall, and the central point is an event. Supportive questions can help in the retrieval of memories, e.g. people (family, friends, co-workers), places (cities, locations), actions (activities), objects (clothing, food, vehicles, etc.), time (weekday, holiday, weekend), and thoughts (justice, aesthetics, values). Since these meaningful events are usually connected to emotions, questions related to emotions are also helpful for understanding the nature of recall.

The verification of physiological effects during autobiographical memories was tested in studies not related to soundscape investigations [13, 14].

In Sheldon et al. [13], skin conductance (electro-dermal activity, EDA) and facial electromyography data were collected during autobiographical memory experiments using music as stimuli. Significant results were observed for the electromyography data. Another study on AM retrieval and arousal also measured electrodermal activity, heart rate (HR), and skin temperature. The stimuli were a narrative photo clip, and significant results were associated with EDA and HR [14].

In soundscape studies, the association between autobiographical memory and physiological data collection remains underexplored. Based on this overview, the aim of the study is to verify, through a multimodal framework, how soundscape perception varies across five audiovisual scenes, assess autobiographical memory retrieval for these scenes, and connect this with physiological data (e.g., electrodermal activity and heart rate) during the reproduction of the audiovisual scenes in a laboratory.

2. Methods

2.1 Audiovisual experiment

This study is the second part of a pilot study conducted to verify cognitive load, autobiographical memory retrieval, soundscape assessment, and physiological data collection. As shown in the experimental design, this work presents only the 2 min baseline (grey colour) and the 5 min soundscape assessment of emotions and memories (lavender colour), as shown in Fig. 1. Further information can be found in the work "Cognitive load under urban soundscapes: A physiological approach using digit span tasks"[15]. Data collection occurred in four sessions, and the audiovisual stimuli were presented in random order. The suggested order presented in Fig. 1 is illustrative. Five audiovisual stimuli were presented, resulting in uneven data collection across the scenes. The following scenes were presented: 'traffic', 'water', 'music simple', 'music sleep', and 'psychoacoustic' with loudness changes.

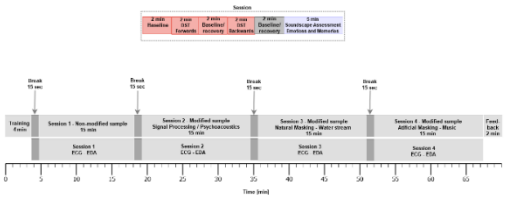

Figure 1. Experimental design.

For the task related to soundscape assessment of emotions and memories, the audiovisual scene was reproduced while closed- and open-ended questions appeared on a separate screen. Simultaneously, physiological data were collected. The following questions were used for this task:

A: Is your memory triggered by a specific sound or overall soundscape? (Sound / Soundscape) If Sound, please specify (leave blank if not applicable):

B: Describe your memory in as much detail as possible:

C: Is this a meaningful event? (Yes / No) If yes, specify; otherwise write none:

D: Is this connected to a person? (Yes / No) If yes, specify; otherwise write none:

E: Is this associated with a place? (Yes / No) If yes, specify; otherwise write none:

F: Is this linked to an activity? (Yes / No) If yes, specify; otherwise write none:

G: Is this associated with an object? (Yes / No) If yes, specify; otherwise write none:

H: Is this connected to a specific time? (Yes / No) If yes, specify; otherwise write none:

I: Is this associated with a thought? (Yes / No) If yes, specify; otherwise write none:

J: Is this connected to an emotion? (Yes / No) If yes, specify; otherwise write none:

To what extent is the present sound environment appropriate to the place? Please indicate in percentage (%)[16].

Does the soundscape evoke any emotions? If yes, which ones? [17]

For each scale below, to what extent do you agree or disagree? Attributes: pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, monotonous [16] and quiet, uncomfortable, comfortable, not annoying, noisy, exhausting, relaxing [17], (scales: strongly agree, agree, neither, disagree, strongly disagree).

To what extent do you presently hear the following types of sounds? (sounds: mechanical, human, natural) (scales: not at all, a little, moderately, a lot, dominates) [16].

Questions A-J follow the methodological approach suggested by Barsalou [12] for autobiographical memories.

2.2 Participants

The participants were 27 subjects, academic staff and students (20 m, 7 f), with M = 29.8 years, SD = 8.8 years. 59.6% of participants originated from Asia, 33.3% from Europe and 3.7% from South America. Of

the 27 participants, data from two participants were excluded due to technical and personal reasons.

2.3 Post-processing and statistical analysis

In the present study, only the questions about autobiographical memory will be analysed.
After data collection, the answers to questions A-J were dummy-coded, and curation based on the audio scene was conducted.
The distribution of responses for each audiovisual scene was visualised through the online tool SankeyMATIC, which generates Sankey diagrams for free autobiographical memory recall (question A) and cued recall (questions C-J).
To create a heatmap indicating the proportion of cues that contributed to autobiographical memory retrieval for urban soundscapes in each audiovisual scene, the open-source software RStudio was used through the package 'ggplot2' and the function 'geom_tile()'. Only responses which informed 'yes' for each factor were used for the generation of the heatmap.
The procedures for data collection, post-processing, and extraction of heart rate and electrodermal activity are described in the work presented in the first part of the experiment, "Cognitive load under urban soundscapes: A physiological approach using digit span tasks" [15].
The statistical analysis tested the delta (task – baseline) for each parameter. In this work, the same statistical procedure, Skillings-Mack tests corrected by Holm adjustment, was applied, as this nonparametric method accommodates missing or unbalanced data using the RStudio packages 'PMCMRplus' and 'dyplr'.

3. Results

3.1 Descriptive results

In the descriptive results, the absolute frequency of question A: Is your memory triggered by a specific sound or overall soundscape? (Fig.2) and the absolute frequencies of questions C-J about the factors that can trigger memory retrieval from the soundscape scenes (Fig. 3) are presented.

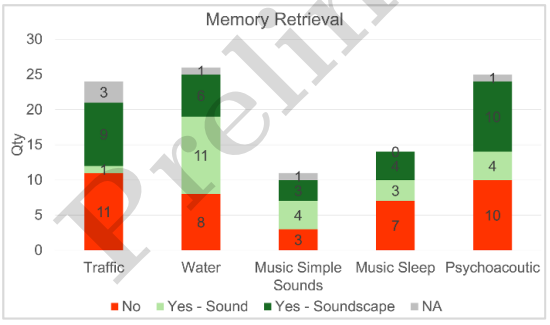

Figure 2. A: Answers for the question for each soundscape scene: Is your memory triggered by a specific sound or overall soundscape? (No /Yes -Sound / Yes -Soundscape / Not applicable- NA)

In Figure 2, it is observed that the traffic scene predominantly does not trigger memories (n = 11). The water scene triggered memories due to the water sound (n = 11), while in the Music Simple scene, the presented song most frequently triggered memories (n = 4). For the Music Sleep scene, no memory retrieval was the most common response (n = 7). Finally, for the psychoacoustic scene, a balance between memory retrieval from the overall soundscape (n = 10) and no memory retrieval (n = 10) was observed.
The results shown in Figure 3 highlight that place, activities, time period and emotions can trigger memory retrieval from urban soundscapes. The sound scenes that most frequently triggered memories were water for place (n = 17), time period (n = 16) and emotions (n = 15), while psychoacoustic changes in the soundscape scene were associated with triggered memories from activities (n = 15).

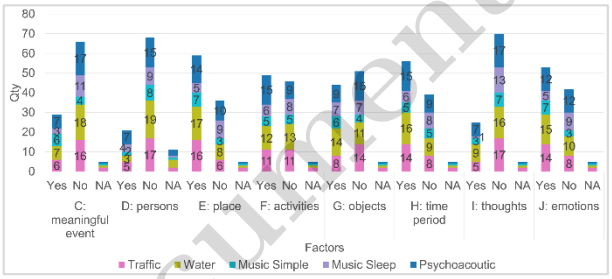

Figure 3. Factors that can trigger memory retrieval of urban soundscapes (meaningful event, persons, place, activities, objects, time period, thoughts, emotions).

3.2 Sankey diagram

The Sankey diagram shows the flow of answers for each factor influencing memory retrieval for each soundscape scene. The middle node represents responses to question A (Sound/Soundscape). The flows from the middle node to the right-side categories represent percentages derived from crosstabulation of question A and questions C–J, which allowed multiple answers per respondent; therefore, these percentages do not sum to 100% within each group.
Notably, although 39 participants reported in the free recall (question A, Figure 2) that the audiovisual scene did not trigger any memories, the cued recall (questions C–J) told a different story: across these eight factors, this same "No" group produced 73 affirmative answers, indicating that specific cues did in fact evoke memories that free recall alone failed to capture.
Overall, most memories were evoked in association with the soundscape response (n = 144 affirmative answers across factors), and the predominant factor triggering recall was place (n = 59), followed by time period (n = 56) and emotions (n = 53). Associations with 'persons' were the least frequently recalled factor (n = 21) (Figure 4).

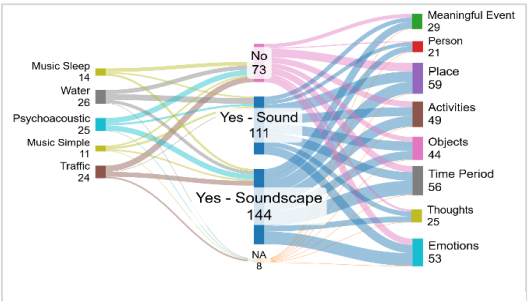

Figure 4. Sankey diagram shows the flow of responses for autobiographical memory retrieval and after reconsideration.

3.3 Heatmap

In the heatmap in Figure 5, only responses that reported 'yes' in the cued recall are shown, allowing the proportion of responses for each factor related to the presented scenes to be seen. For the 'Traffic' stimulus, the factors that helped recall autobiographical memories were places (0.73), time period, and emotions (0.64 each). Recall with 'Music Simple' was influenced by place and emotions (0.70 each) and by objects and meaningful events (0.60 each). Recalls from 'Music sleep' presented most often the influence of objects (0.50). The 'Psychoacoustic' stimulus presented recalls associated with time period and activities (0.62 each). Water sounds were most associated with recalls related to places (0.68) and time period (0.60).

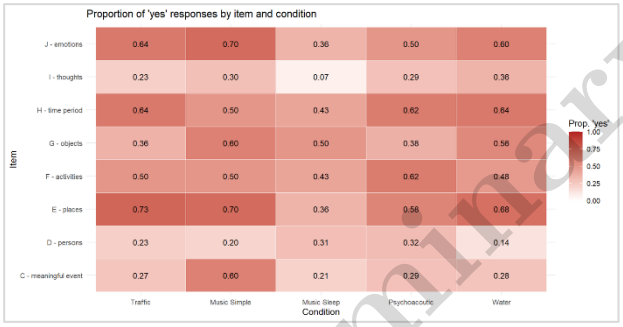

Figure 5. Heatmap of the 'yes' responses of questions C-J for factors influencing autobiographical memory retrieval for each soundscape scene.

3.5 Physiological results

To examine whether the autonomic response accompanying memory retrieval differed across the three soundscape conditions, Skillings-Mack tests were conducted on changes (Δ) in cardiac (HRV: SDNN, RMSSD) and electrodermal (SCR onset, risetime, peak amplitude, prominence, amplitude, frequency; SCL, SCL slope, SCL window) measures across Traffic, Water, and Psychoacoustic conditions, with Participant treated as a blocking factor (n = 15). This omnibus approach tests all three conditions simultaneously (df = 2), and is the statistically appropriate structure for this repeated-measures design, in place of separate pairwise comparisons. Given the 11 variables tested, p-values were adjusted using the Holm correction (Table 1).

Three variables showed uncorrected p-values below .05: SCR frequency ($\chi^2 = 8.49$, p = .014), SCL ($\chi^2 = 6.43$, p = .040), and SCL window ($\chi^2 = 6.19$, p = .045). However, none of these effects survived Holm correction (all p_Holm > .15), with SCR frequency showing the closest approach to corrected significance (p_Holm = .158). HRV measures showed weaker uncorrected effects by comparison (SDNN: $\chi^2 = 4.50$, p = .105; RMSSD: $\chi^2 = 3.22$, p = .200), and all remaining EDA variables (SCR onset, risetime, peak amplitude, prominence, amplitude; SCL slope) showed non-significant results both before and after correction (all uncorrected p > .18).

Table 1. Skillings-Mack Test Results Comparing Traffic, Water, and Psychoacoustic Conditions (n = 15)

Variable	χ^2	df	p	p (Holm)
Δ SDNN	4.5	2	0.105	0.843
Δ RMSSD	3.22	2	0.2	1
Δ SCR onset	1.43	2	0.489	1
Δ SCR risetime	1.82	2	0.403	1
Δ SCR peak amplitude	1.01	2	0.603	1
Δ SCR prominence	3.37	2	0.185	1
Δ SCR amplitude	0.24	2	0.886	1
Δ SCR frequency	8.49	2	0.014	0.158
Δ SCL	6.43	2	0.04	0.402
Δ SCL slope	0.2	2	0.903	1
Δ SCL window	6.19	2	0.045	0.407

4. Discussion

The present study examined whether different urban soundscape stimuli (traffic, water, music, and psychoacoustically manipulated sound) triggered autobiographical memory retrieval differently, and whether this retrieval was accompanied by distinguishable patterns of autonomic nervous system activity.

4.1 Divergence between free and cued recall

A central finding of the behavioural data is the substantial gap between free recall (question A) and cued recall (questions C–J). While 39 participants initially reported no memories triggered by the audiovisual scene under free recall, the same group generated 73 affirmative responses once prompted with specific cues (place, activity, time period, emotions, objects, persons, meaningful events). This dissociation suggests that autobiographical memories evoked by ambient soundscapes are often present in a latent or under-articulated form that free recall alone fails to surface, consistent with the broader memory literature showing that cued recall paradigms typically outperform free recall in eliciting event-specific details,

particularly for incidentally encoded or weakly consolidated associations [18]. This has a direct methodological implication: studies relying solely on spontaneous, unprompted memory reports may substantially underestimate the memory-evoking potential of environmental sound.

4.2 Sound-specific patterns of memory retrieval

The descriptive and Sankey results indicate that not all soundscapes cue memory through the same underlying mechanism. Water sounds were the strongest overall trigger, particularly for place, time period, and emotion, suggesting that natural, semantically rich sounds may evoke holistic, episodically structured memories anchored in spatial and temporal context. In contrast, the psychoacoustic condition, despite being an artificial manipulation, was most strongly associated with activity-based recall, implying that even non-naturalistic acoustic changes can engage procedural or action-related memory schemas, possibly through generalised arousal or novelty-driven attentional engagement rather than semantic association. The traffic scene, meanwhile, most frequently triggered no memory in free recall, yet the heatmap reveals that when it did cue a memory, it was strongly tied to place and time period (0.73 and 0.64 respectively), comparable in magnitude to water. This suggests that traffic sounds may have a higher threshold for triggering conscious memory retrieval, but once a memory is cued, it engages a similarly rich contextual representation as more evocative natural sounds.

4.3 Physiological findings in context.

The autonomic data helps contextualise these behavioural patterns, though the pattern that emerges differs from what might be expected based on the behavioural results alone. Across all three conditions, no variable reached statistical significance after correction for multiple comparisons. However, the pattern of uncorrected effects is informative: rather than HRV measures showing the strongest differentiation, as might be predicted from cardiac-arousal accounts of memory retrieval, the clearest, albeit non-significant after correction, signal emerged from electrodermal measures, specifically SCR frequency, SCL, and SCL window. SDNN and RMSSD showed comparatively weaker uncorrected effects ($p = .105$ and .200, respectively), suggesting that tonic and phasic electrodermal activity, rather than cardiac variability, may be the more sensitive markers of condition-dependent autonomic differentiation in this paradigm.

This finding is notable when juxtaposed with the behavioural data. Water sounds were by far the most effective trigger of explicit autobiographical memory, yet the physiological results do not indicate a correspondingly distinct autonomic profile unique to water relative to the other two conditions; rather, SCR frequency, SCL, and SCL window differentiated the three conditions as a set, without a clear indication from the omnibus test alone of which specific condition pair drives this pattern. This suggests that autonomic arousal, as indexed by HRV and EDA measures, may not be a necessary correlate of a soundscape's memory-triggering potential, or alternatively, that the physiological signature of memory retrieval in this paradigm is present but too subtle to detect reliably with the current sample size once corrected for multiple comparisons.

4.4 Limitations and future directions.

The absence of significant effects after correction for multiple comparisons, combined with the modest sample size, means the physiological findings reported here should be treated as exploratory.

A further methodological consideration concerns the electrodermal activity (EDA) sampling rate. In the present study, EDA was downsampled to 32 Hz, consistent with common recommendations for capturing skin conductance dynamics. However, given that the physiologically relevant frequency content of EDA signals (particularly slow-changing tonic measures such as SCL) typically falls below 5 Hz, future investigations could explore downsampling to a lower rate (e.g., 10 Hz) to assess whether reduced high-frequency noise improves signal-to-noise ratio and enhances the detectability of stimulus-related effects, particularly for tonic measures [19]. However, this trade-off should be evaluated separately for phasic measures dependent on precise event timing (e.g., SCR onset, risetime), where reduced temporal resolution could instead compromise measurement precision. Systematically comparing sampling rates within the same dataset would help clarify whether the trend-level effects observed here (e.g., for SCR prominence and frequency) are attenuated by measurement noise at higher sampling rates, or whether they remain stable across resampling choices.

5. Conclusions

This study examined whether urban soundscapes, 'traffic', 'water', 'music', and 'psychoacoustically manipulated sound' differentially trigger autobiographical memory retrieval and whether such retrieval is accompanied by distinguishable autonomic responses, revealing a clear dissociation between the two levels of analysis. Behaviourally, 'water' sounds emerged as the most reliable trigger of contextually rich memories, place, time, and emotion, while 'traffic' sounds showed a higher threshold for spontaneous retrieval despite evoking comparably rich memories once cued, and the marked gap between free and cued recall demonstrated that unprompted self-report substantially underestimates the memory-evoking potential of ambient sound. Physiologically, an omnibus Skillings-Mack test across three conditions (water, traffic, psychoacoustic) found that no variable reached statistical significance after correction for multiple comparisons, though electrodermal measures, SCR frequency, SCL, SCL window, showed the clearest uncorrected pattern of differentiation, ahead of cardiac HRV measures, suggesting that tonic and phasic electrodermal activity, rather than heart rate variability, may be the more sensitive autonomic

marker in this paradigm, and that a soundscape's memory-evoking potential is not straightforwardly mirrored in the magnitude of its peripheral physiological signature. Given the modest sample size, these physiological findings should be treated as preliminary, though the pattern observed for SCR frequency, SCL, and SCL window offers a promising target for future confirmatory work with larger, pre-registered samples, planned post hoc pairwise comparisons to localize condition-specific effects, trial-level linkage between specific memory cues and physiological signatures, and refined EDA sampling strategies, underscoring, overall, the value of combining cued behavioural recall with psychophysiological measures while cautioning against over-reliance on arousal alone as a marker of a soundscape's memory-evoking power.

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