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JASA ARTICLE

Effects of low-level electric vehicle noise on attention, electrodermal activity, workload, and annoyance

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ABSTRACT:
With the rise of electromobility, electric vehicles (EVs) and their acoustic vehicle alerting systems (AVAS) are becoming a part of urban acoustic environments. While AVAS signals are designed to enhance traffic safety, their environmental noise impact on non-involved listeners has yet to be systematically studied. This study investigates the effects of low-level indoor EV noise, including three common AVAS types, on attention, electrodermal activity (EDA), perceived workload, and noise annoyance. Sixty participants completed a combined Eriksen Flanker and spatial Stroop attention test under four sound conditions (silence, noise AVAS, multi-tone AVAS, and two-tone AVAS) while EDA was continuously recorded. All signals were presented at realistic indoor levels ($L_{A,eq} \leq 21.5$ dB), simulating closed-window exposure in modern buildings using a wave field synthesis-based auralization approach. While attention performance was unaffected, physiological and subjective responses varied significantly across conditions, with the two-tone AVAS resulting in the highest EDA, mental demand, and annoyance ratings. These findings suggest that highly tonal AVAS signals, despite potential benefits for detectability, may impose a greater perceptual and physiological burden on non-involved listeners such as residents. The results highlight the need for AVAS designs that strike a balance between safety and minimal disruption to the surrounding acoustic environment.
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I. INTRODUCTION

Transportation noise, and noise from road traffic in particular, poses a significant public health challenge worldwide. The latest European Environment Agency (2025) environmental noise report estimates that 24% of the total European population is exposed to long-term harmful transportation noise above the European Noise Directive threshold ($L_{den} \geq 55$ dB). Of these, approximately 112 million people are exposed to road traffic noise, mostly in densely populated urban areas. These exposure estimates, together with burden of disease studies (World Health Organization, 2011), highlight the public health relevance of road traffic noise worldwide, particularly in urban environments. In addition to long-term outcomes, acute exposure to road traffic noise can trigger immediate autonomic and cardiovascular responses, including increases in heart rate and blood pressure, reductions in heart rate variability, and heightened sympathetic arousal (Basner *et al.*, 2015). Experimental work also reports task-dependent decrements in attention and working-memory performance when task-irrelevant noise is present, which makes these physiological and cognitive measures useful end points for applied noise research (Marsh *et al.*, 2023).

With the ongoing transition to electromobility (International Energy Agency, 2025), the urban soundscape may change. At low speeds, electric vehicles (EVs) typically emit less noise than internal combustion engine vehicles (ICEVs) (Garay-Vega *et al.*, 2010; Pallas *et al.*, 2016), offering potential to reduce noise in urban slow-driving zones. However, this lower noise emission also reduces acoustic cues for pedestrians, cyclists, and other vulnerable road users, increasing collision risk. Accident data from several countries suggest a higher likelihood of collisions involving slow-moving EVs in urban areas (Edwards *et al.*, 2024; Hanna, 2009; Hou *et al.*, 2023; Morgan *et al.*, 2011; Wu *et al.*, 2011), and human subject studies confirm that, without visual cues or acoustic countermeasures, EVs are often detected later than ICEVs (Garay-Vega *et al.*, 2010; Goodes *et al.*, 2009; Kim *et al.*, 2012).

To address this safety issue, many countries require EVs to be fitted with an acoustic vehicle alerting system (AVAS) that emits artificial sounds to indicate vehicle position and behavior. In the United States, the Federal Motor Vehicle Safety Standard (FMVSS) No. 141 requires these warning sounds to comprise certain third-octave bands with minimum levels for specific speeds and maneuvers (National Highway Traffic Safety Administration, 2016a). The EU, China, Japan, and others follow UNECE Regulation No. 138 (UNECE, 2017), which similarly defines third-octave band requirements, minimum levels for different driving speeds, and a speed-dependent pitch shift, but also limits the maximum overall sound pressure level for AVAS-equipped vehicles to 75 dBA at 2 m distance. Both regulatory frameworks leave

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broad design freedom, resulting in diverse AVAS implementations, from engine-like to highly tonal or "futuristic" designs. This diversity raises the question of which types of AVAS sounds best balance traffic safety with impact on the quality of the acoustic environment, a trade-off that requires further research to inform future policy.

The aspect of AVAS traffic safety has been the subject of several studies, some of which were performed in the context of the development of FMVSS No. 141 (Hastings *et al.*, 2011; Hastings *et al.*, 2012; Hastings and McInnis, 2015). While most earlier research focused on the detectability of single EVs in a pass-by scenario (Mendonça *et al.*, 2013; Parizet *et al.*, 2014; Roan *et al.*, 2021), more recent studies investigated other relevant measures, such as time to collision estimation for accelerating EVs (Wessels *et al.*, 2022) or detectability in multi-vehicle scenarios (Walton *et al.*, 2025). In our recent study (Müller *et al.*, 2025b), we compared currently implemented AVAS signals in a laboratory experiment and found that some signals were significantly harder to localize in a static parking lot scenario, particularly when other vehicles used similar AVAS. Thus, even regulation-compliant signals can differ in detectability and localizability.

While traffic safety has been the primary focus of most AVAS research, the environmental and perceptual impacts of AVAS have received less attention. During FMVSS No. 141 development, the US National Highway Traffic Safety Administration (2016b) predicted that adding AVAS would change overall sound levels in urban contexts by less than 3 dB, a difference deemed imperceptible. However, such analyses overlook the fact that sounds with identical overall levels can differ significantly in human perception. For example, Altinsoy (2022) assessed subjective annoyance of recorded vehicle passages with different motorization and found that EV sounds were generally judged as less annoying than those of ICEVs. While AVAS-equipped EVs tended to be rated as more annoying than EVs without AVAS, annoyance varied strongly with design. Other work utilized psychoacoustical metrics to predict EV noise annoyance (Steinbach and Altinsoy, 2019) or to design AVAS for a balance of detectability and annoyance (Walton *et al.*, 2022). Additionally, psychoacoustic modeling with semantic attribute development was employed to optimize AVAS sounds from a consumer perspective (Kullukçu *et al.*, 2025). Despite evidence linking noise annoyance to reduced cognitive performance and increased physiological stress (Radun *et al.*, 2022; Song *et al.*, 2022), no studies have directly examined AVAS effects beyond annoyance.

To our knowledge, all existing AVAS studies have focused on outdoor situations, although most people spend the majority of their time indoors (Klepeis *et al.*, 2001; World Health Organization, 2014). A substantial share of urban traffic noise exposure thus occurs inside buildings, where sound transmission through facades and windows can noticeably change the sound character. For example, sharp components that are typically associated with high annoyance may be significantly reduced due to the nature of sound reduction. Conversely, low-frequency components that are less noticeable outdoors may dominate indoors, and it is not well documented under which conditions AVAS sounds from nearby streets are audible indoors in modern buildings, potentially affecting residents.

This study addresses the gap in understanding how AVAS sounds affect non-auditory responses in residential environments by investigating cognitive, physiological, and subjective measures in a realistic indoor laboratory setting. Building on Müller *et al.* (2025b), which assessed their localizability, we use the same three widely implemented AVAS types to enable a combined evaluation of traffic safety and indoor noise impacts.

II. METHODS

To evaluate the human response to low-level EV road traffic noise, a laboratory experiment was conducted using a loudspeaker-based reproduction in the Chalmers *Living Room Lab* as described in Sec. II A 1. The listening experiment consisted of an attention test (cf. Sec. II C 1) followed by a perceived workload and noise annoyance questionnaire (cf. Sec. II C 3), which was repeated for each participant for each of the four sound conditions (silence, noise AVAS, multi-tone AVAS, and two-tone AVAS, cf. Sec. II A 4). Throughout the experiment, the participants' electrodermal activity (EDA) was recorded as described in Sec. II C 2.

A. Acoustic setup and stimuli

1. Lab environment

The Chalmers *Living Room Lab* used for this study was specifically designed to create a realistic virtual acoustic environment for low-level indoor road-traffic noise experiments. The lab consists of two acoustically isolated rooms that are coupled via a gypsum double wall with an insulating window, as shown in Fig. 1. One of the rooms, the receiving room, is furnished to match the look and feel of a typical living room. The other room, the sending room, is equipped with a linear array of 24 Neumann KH80 DSP studio loudspeakers (Georg Neumann GmbH, Berlin, Germany) and fitted with heavy acoustic curtains and ceiling absorption to

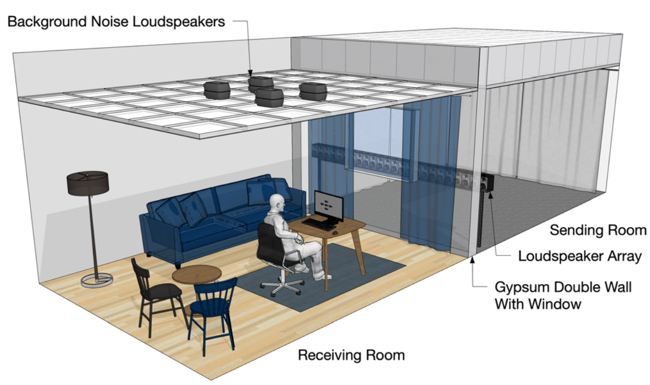

FIG. 1. *Living Room Lab* visualization including loudspeaker array in sending room, subject at participant position, and hidden background noise loudspeakers in the ceiling. The curtains in front of the window were closed during the experiment.

minimize unwanted reflections. The fundamental concept behind this setup is that a linear loudspeaker array in the sending room projects the incoming sound field of a free-field vehicle passage to the outside of the window using wave field synthesis (Ahrens, 2012; Verheijen, 1998). This sound then travels through the window, creating a realistic spatial distribution of the indoor sound field in the receiving room, including angle-of-incidence-dependent propagation mechanisms such as the coincidence effect (Vigran, 2008). This reproduction method is described in detail and perceptually validated in Müller *et al.* (2025a) and has been previously used for similar indoor road-traffic noise experiments (Müller *et al.*, 2021; Müller *et al.*, 2023). Since the window implemented in the living room lab has a quite high sound reduction index [weighted sound reduction index $R_W = 38$ dB, plot of sound reduction index R published in Müller *et al.* (2021)], a simple finite impulse response filter was applied to all loudspeaker signals to mimic the sound reduction of a more standard double pane unit with two 6 mm panes and an air filled cavity [using R values provided by ISO (2017)], resulting in an approximate $R_W = 31$ dB. For the experiment, study participants were seated at a small table with a 24-in. computer screen in the center of the room, facing the window, as illustrated in Fig. 1. The window itself was hidden behind acoustically transparent curtains, so the participants could not see any loudspeakers. Additionally, four Genelec 8020 loudspeakers (Genelec OY, Iisalmi, Finland) were hidden in the suspended ceiling of the receiving room to play back artificial background noise as described in Sec. II A 2.

2. Artificial background noise

Since the *Living Room Lab* environment is very silent with background noise levels below 12 dBA, artificial background noise was played back via four Genelec 8020 loudspeakers hidden in the suspended ceiling of the lab. This four-channel, uncorrelated broadband noise was generated using an analog noise generator and equalized by ear to resemble the characteristics of a quiet ventilation system, resulting in an A-weighted equivalent continuous sound pressure level of $L_{A,eq} = 19$ dB, measured at the participant position. Adding this artificial noise was motivated by the experience of previous experiments, where study participants reported perceiving the lab environment as unnaturally silent. The background noise was present before the participants entered the lab and maintained throughout the experiment, i.e., it was present for all stimuli and is included in the measurements presented in Figs. 4(b) and 4(c), as well as in the indoor levels reported in Sec. II A 4.

3. Pass-by auralization

The EV auralization toolbox, which we introduced and validated in Müller and Kropp (2024), was used to generate EV passages consisting of tire-road noise and three different types of AVAS signals, including a numerically calculated AVAS radiation directivity, a measured tire directivity, ground reflections, air absorption, and atmospheric turbulence causing mild amplitude fluctuations. The AVAS signals used in this study are re-synthesized based on measurements of existing EVs and representative for commonly used types of AVAS signals that comply with current UN and US regulations (National Highway Traffic Safety Administration, 2016a; UNECE, 2017): (1) a two-tone AVAS that consists of two amplitude modulated tones that change in pitch with vehicle velocity based on a Tesla Model Y 2019 (Tesla Inc., Austin, TX) driving backward, (2) a multi-tone AVAS that consists of a multitude of amplitude modulated tones with different velocity behaviour based on a Volkswagen ID.3 Pro Performance 2021 (Volkswagen AG, Wolfsburg, Germany) driving forward, and (3) noise AVAS, which consists of two bands of filtered noise (based on a Tesla Model Y 2019 driving forward).

The top row of Fig. 2 shows these isolated AVAS signals for an exemplary simulated outdoor passage, measured in front of the outdoor side of the window in the *Living Room Lab*. The center row shows the combination of AVAS and tire-road noise signals, where the exact same tire-road noise was used for all AVAS types. This tire-road noise was synthesized based on *in situ* recordings of radial non-studded winter tires, with an external rolling noise value of 72 dB, as per EU Regulation 2020/740 (European Parliament and Council of the European Union, 2020). These recording were performed on a Swedish road with dense asphalt concrete surface under dry and windless conditions by mounting an omnidirectional, free-field equalized microphone at 40 cm distance perpendicular to the tire. More details on the recording procedure and the resulting tire-road noise profiles are available in Müller and Kropp (2024).

The bottom row of Fig. 2 shows the resulting indoor signals after wave field synthesis and propagation through the window, recorded at the participant position in the receiving room. To make the characteristics of the different AVAS signals more distinguishable, the artificial background noise present during the experiment is excluded from these spectrograms.

4. Acoustic stimuli

Using the previously described auralization method and reproduction setup, 35 different passages with a mean velocity of 15 ± 3 km/h that were either constant speed, had a parabolic speed profile (implemented as second-order polynomials in time), or were randomly accelerating or decelerating in the range between 10 and 20 km/h were generated. Each passage was rendered for 20 s, simulating a two-lane street at 7.5 m distance to the facade. Figure 3 shows the velocity profiles for all 35 simulated passages. Combining these passages assuming an exponential traffic flow distribution with 350 passages per hour (Salter, 1989) resulted in a 6-min-long traffic signal. Using the same exact traffic distribution and tire-road noise signals, three different traffic stimuli were generated (hereafter referred to as "two-tone," "multi-tone," and "noise"), with the only difference between

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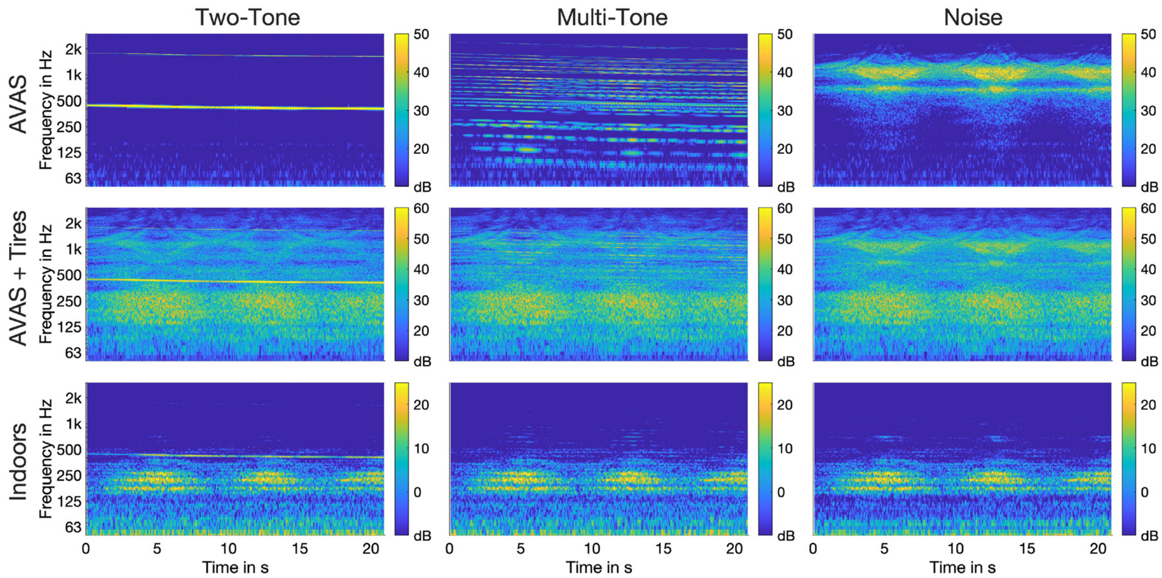

FIG. 2. Spectrograms of two-tone AVAS, multi-tone AVAS, and noise AVAS passage measured on outdoor side of window for isolated AVAS signal (top row), for AVAS and tire-road noise (center row), and for complete passage measured indoors at participant position, without artificial background noise (bottom row).

the three stimuli being the type of AVAS signal. In addition to the three pass-by stimuli, a silence condition was included in the experiment, comprising a low-level background noise described in Sec. II A 2.

As shown in Fig. 4(a), all three pass-by stimuli were normalized to result in the same outdoor A-weighted equivalent continuous sound pressure level of $L_{\mathrm{A,eq}} = 60$ dB with a maximum A-weighted sound pressure level of $L_{\mathrm{A,max}} = 66$ dB, averaged over two positions measured right in front of the window in the sending room. This level is consistent with *in situ* measurements for low-speed outdoor passages of the vehicles of interest at 7.5 m distance (Müller and Kropp, 2024). After propagation through the window and with the artificial background noise present, this resulted in indoor sound pressure levels of $L_{\mathrm{A,eq}} \leq 21.5$ dB and $L_{\mathrm{A,max}} \leq 29.8$ dB with a loudness below 0.3 SoneHMS

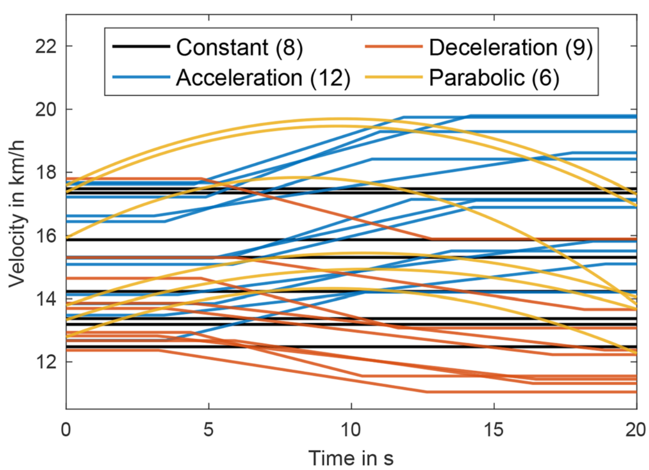

FIG. 3. Vehicle velocity as a function of time for all 35 simulated passages. Trajectories are grouped by profile type (constant, parabolic, linear acceleration, and linear deceleration).

(ECMA, 2022) as reported in detail in Table I. Calibrated binaural recordings of all stimuli are openly available at Müller *et al*. (2025c).

These single-number levels, together with the indoor level over time shown in Fig. 4(b) and the indoor spectra in Fig. 4(c), confirm that the differing spectral compositions of the AVAS signals produce slightly different indoor single-number levels, despite identical outdoor single-number levels. This demonstrates that, beyond the expected differences in human loudness perception between tonal and noise signals (Fastl and Zwicker, 2007), the type of AVAS signal can also affect indoor sound pressure levels. In this case, the sound energy for the two-tone AVAS is concentrated at two frequencies, which, when they happen to correspond to local dips in the double-pane window's transmission loss spectrum, may result in a higher indoor sound level than when the energy is more evenly distributed across frequencies with greater attenuation.

Summarized, the acoustic stimuli used in this study correspond to realistic indoor EV pass-by traffic noise for three different AVAS types with indoor sound pressure levels of up to $L_{\mathrm{A,eq}} = 21.5$ dB and $L_{\mathrm{A,max}} = 29.8$ dB, simulating a facade level of $L_{\mathrm{A,eq}} = 60$ dB. These noise levels fall well below the World Health Organization (1999) guidelines for community noise, which recommend that indoor equivalent sound pressure levels should not exceed 30 dBA to prevent sleep disturbance, and are also below the $L_{\mathrm{A,Max,Indoors}}$ thresholds for biological effects outlined in the World Health Organization (2009) night noise guidelines for Europe. While the levels for these short traffic signals are not directly translatable to the outdoor L_{den} and L_{night} values given in more recent recommendations, such as the World Health Organization (2018) environmental noise guidelines for the European Region, one can assume that the stimuli are within the range of expected levels during the day,

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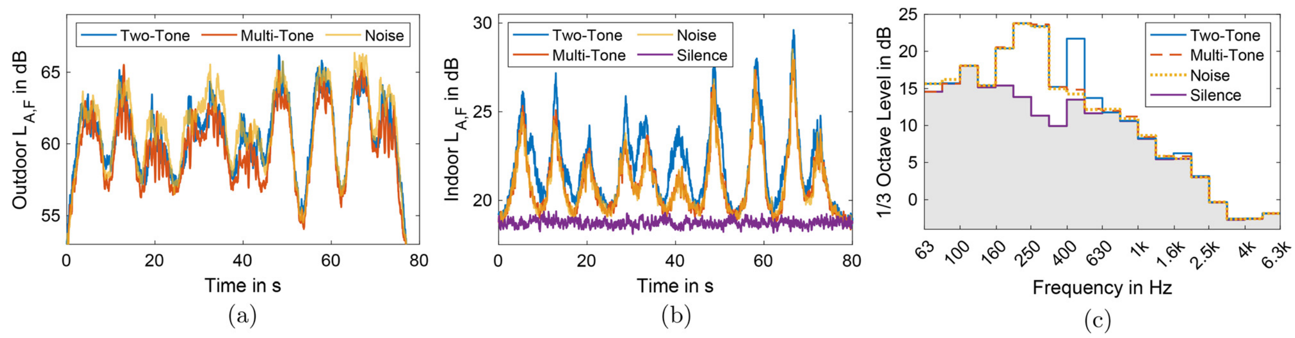

FIG. 4. Sound pressure level over time measured on outdoor side of window (a), at indoor participant position (b), and 1/3-octave spectra of stimuli at participant position (c).

which is, contrary to nighttime levels, the scenario most relevant for attention and perceived workload metrics evaluated in this study. Moreover, the levels used in this study are significantly lower than those commonly employed in research on the cognitive effects of noise (Marsh *et al.*, 2023; Schlittmeier and Marsh, 2021).

B. Participants

The experiment was performed by 63 participants, recruited from Chalmers University students and faculty members. Two of these 63 study participants were excluded from the following analysis due to technical errors during the experiment, and one participant was excluded due to a self-reported severe hearing impairment. The remaining 60 participants (30 female, 30 male) were between 21 and 61 years old, with a median age of 26 years, and had self-reported normal hearing. They gave their written consent for participation, as well as for the collection, processing, and publication of their data.

Twenty-one of the 60 participants stated that they had never performed such a listening experiment before, 12 seldom, 13 several times, and 14 many times. Before the experiment, the participants were also asked: "How often do you notice electric vehicles (cars/busses/trucks) and the special sounds they emit in your everyday life?" to which one subject responded "never," eight participants responded "rarely," 25 responded "occasionally," 18 responded "frequently," and eight participants responded "very frequently," indicating that most of the study participants had some prior experience of EV sounds.

TABLE I. A-weighted equivalent continuous sound pressure level, maximum A-weighted sound pressure level, and loudness according to ECMA (2022), measured at the participant position with artificial background noise present.

Stimulus	$L_{A,eq}$	$L_{A,max}$	Loudness N
Two-tone	21.51 dB	29.76 dB	0.29 SoneHMS
Multi-tone	20.72 dB	28.12 dB	0.25 SoneHMS
Noise	20.75 dB	28.57 dB	0.26 SoneHMS
Silence	18.72 dB	19.39 dB	0.20 SoneHMS

C. Experimental procedure

As illustrated in Fig. 5, each experiment round began with a 90-s break period, consisting of 45 s of silence followed by 45 s of the respective sound condition. The purpose of this break was that the initial silent period would allow participants to relax and reset, while the subsequent noise exposure period would help them focus on the sound environment, leading to more conscious noise annoyance ratings. During the break, a countdown on the computer screen showed the remaining time until the test started. This break was followed by a block of 180 attention test trials (cf. Sec. II C 1) under the respective sound condition, lasting approximately 5 min. After completing the attention task, participants answered a perceived workload questionnaire and rated their noise annoyance (cf. Sec. II C 3). This sequence of break, attention task, and questionnaire was repeated for each of the four sound conditions (silence, noise AVAS, two-tone AVAS, and multi-tone AVAS), and the participants' EDA was recorded during the entire experiment as described in Sec. II C 2. To control for potential order effects, all 24 possible condition orders were fully counterbalanced across the first 48 participants, and the remaining 12 participants were randomly assigned to one of the orders. Before starting the main experiment, participants completed a supervised training block of 18 attention trials with visual feedback for correct and incorrect responses. During this training phase, participants were also introduced to the workload and noise annoyance questionnaire format. The entire experiment was implemented using Psychtoolbox 3.0.21 (Kleiner *et al.*, 2007) in MATLAB R2024b (The Mathworks Inc., Natick, MA).

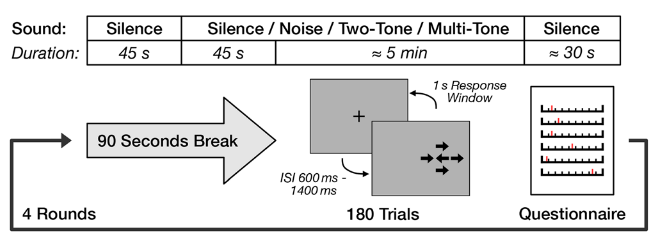

FIG. 5. Experiment procedure consisting of four repetitions of a block of 90-s break, 180 attention test trials, and a perceived workload and noise annoyance questionnaire.

1. Attention task

The main task in this experiment was a speeded arrow direction test, where participants indicated the direction of a central arrow while ignoring surrounding symbols and on-screen position. This paradigm probes selective attention and conflict control across sound conditions. The detailed implementation and the rationale for choosing it are described in the following.

In a previous study on the human response to time-structure differences in low-frequency traffic noise (Müller *et al.*, 2023), we assessed sustained attention using a continuous performance test (CPT) (Homack and Riccio, 2006; Strauss *et al.*, 2006). In this paradigm, participants were sequentially presented with single letters on a computer screen and instructed to respond to all letters except "X," which appeared in 10% of the trials. The CPT primarily probes sustained attention and response inhibition, two core subcomponents of executive functioning that rely on top-down attentional control, meaning participants actively maintain task rules and suppress automatic responses, rather than reacting reflexively to external cues, such as the traffic sounds presented. (Sarter *et al.*, 2001). In our earlier work, this task revealed a significant medium-sized performance difference between silence and one low-frequency noise condition at an indoor level of $L_{A,eq} = 40$ dB. However, each CPT block lasted approximately 14 min, and the repetitive and monotonous nature of the task caused substantial mental fatigue. This not only increased participant burden but also limited the number of sound conditions that could be feasibly included in a within-subject design. Moreover, the CPT does not capture other attentional control processes, such as conflict monitoring, selective attention, and spatial attention, that may be more sensitive to acute changes in auditory environments.

To address these limitations, we adopted a more time-efficient paradigm targeting a broader range of attentional control mechanisms. Specifically, we combined elements of the Eriksen flanker task (Eriksen and Eriksen, 1974) and the spatial Stroop task (Viviani *et al.*, 2024), both of which are widely used in cognitive neuroscience to assess executive control under conditions of stimulus conflict. The Eriksen Flanker Task measures selective attention and interference control by requiring participants to respond to a target stimulus flanked by distracting stimuli. Performance is typically reduced when the flankers are incongruent, meaning they differ from the target in a way that creates conflicting information, which must be suppressed. The spatial Stroop task, in contrast, measures spatial selective attention and stimulus–response compatibility by creating a conflict between a stimulus's identity (e.g., arrow direction) and its spatial location on the screen. When combined, these paradigms jointly probe executive attention, spatial processing, and conflict resolution. Similar combined approaches have been implemented in composite measures, such as the combined attention systems test and other modified versions of the attentional network test (ANT) that introduce spatial conflict manipulations (Almeida *et al.*, 2021; Fan *et al.*, 2002). While variations of the Stroop task have previously been used to investigate the effects of moderate and loud traffic noise on cognitive performance (Schlittmeier *et al.*, 2015), and the Flanker task and other modified ANTs have been applied to study the impact of background music on attention (Fernandez *et al.*, 2019; Orpella *et al.*, 2025), the combination of these tasks has, to our best knowledge, not yet been employed to examine human responses to traffic noise.

In our implementation, the target stimulus was a central arrow pointing left or right, flanked by four additional symbols in one of three configurations: congruent (same direction arrows), incongruent (opposite direction arrows), or neutral (non-directional dashes) (see Fig. 6). Two flankers appeared horizontally adjacent to the target, and two were placed vertically above and below it. Each arrow measured 0.83 cm in length with a 0.1 cm gap between adjacent arrows, corresponding to 0.8° and 0.1° of visual angle at a 60 cm viewing distance. These sizes and spacings follow established conventions from early Flanker task studies (Eriksen and Eriksen, 1974) and later implementations (Fan *et al.*, 2002). The full array was presented either centrally or spatially offset by 4° to the left or right, introducing a spatial conflict when the direction of the arrow and its location mismatched, which reflects the conflict manipulation characteristic of the spatial Stroop task.

Each trial began with a centrally placed fixation cross-shown for a variable inter-stimulus interval ranging from 600 to 1400 ms (mean: 1000 ms), followed by the visual stimulus. Participants had a 1-s response window to indicate the direction of the central arrow, after which the next trial began automatically, regardless of whether a response was made. Responses were made using two keys on opposite ends of the keyboard: one designated for "left" and the other for "right." Participants were instructed to answer as quickly as possible using their left index finger or thumb to press the key for "left" responses, and their right index finger or

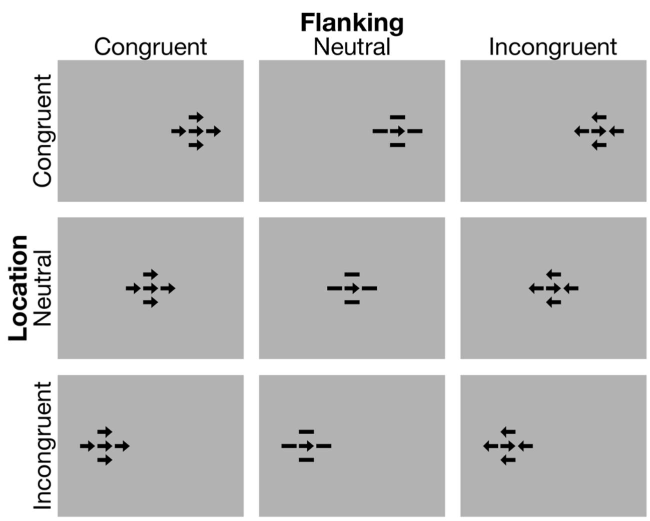

FIG. 6. Visual stimuli used for attention task. The corresponding set for the center arrow pointing left is not shown.

thumb for "right" responses, ensuring a spatially compatible motor mapping. The combination of two target directions, three flanker types, and three spatial locations yielded 18 stimulus types, each repeated ten times in randomized order per sound condition block (180 trials total, approximately 5 min). For analysis, both response accuracy and response time (RT) were recorded for each trial.

2. EDA

EDA reflects changes in the skin's electrical conductance, mainly caused by variations in sweat gland activity under the control of the sympathetic nervous system (Boucsein, 2012). Because sweat gland responses are closely linked to emotional and physiological arousal, EDA is widely used as an indicator of stress, alertness, and cognitive workload (Critchley, 2002). The tonic component of EDA, known as the skin conductance level (SCL), reflects the slowly varying baseline conductance over periods of tens of seconds to minutes, and is often interpreted as an index of general arousal. Superimposed on this are rapid, transient fluctuations called skin conductance responses (SCRs), which are typically associated with discrete stimuli or momentary increases in sympathetic activation. Increases in either SCL or SCR generally correspond to heightened sympathetic drive, making it a valuable noninvasive measure to assess the physiological response to environmental stimuli or internal states of stress and arousal.

In the present study, EDA was recorded continuously throughout the experiment using a g.GSRsensor2 (g.tec medical engineering GmbH, Schiedlberg, Austria) connected to a SQobold mobile data acquisition system (HEAD acoustics GmbH, Herzogenrath, Germany) with a sampling rate of 6 kHz. Reusable Ag/AgCl electrodes were placed on the palmar side of the distal phalanges of the middle and ring fingers of the left hand using Velcro straps (see Fig. 7). This allowed participants to use their left-hand index finger to press the "left" response button on the keyboard for the attention test while the electrode-bearing fingers remained stationary on the table surface. At setup, the velcro straps were tightened to a snug but comfortable fit, consistent with EDA guidelines (Boucsein, 2012), and participants were asked not to alter them during the task. The fit was verified as still snug at the end, which, considering the within-subject design of this study, limits any influence of strap tightness on condition comparisons.

For the subsequent analysis, only the approximately 5-min-long attention test window for each sound condition was extracted from the EDA recordings, as more complex baseline correction procedures (e.g., using the silent pre-attention test break as baseline) did not yield additional insights. The resulting EDA signals for each participant and sound condition were split into tonic and phasic components (Boucsein, 2012) using second-order Butterworth low-pass and high-pass filters with a cutoff frequency of 0.05 Hz. The tonic (low-pass) signal was averaged within each analysis segment to obtain the mean SCL for each participant and sound condition. The phasic (high-pass) signal was analyzed using the MATLAB findpeaks function with a minimum peak height and prominence of 0.05 μS and a minimum peak distance of 1 s. From this, the number of SCRs per minute and the summed SCR amplitude per minute were computed.

FIG. 7. Participant at experiment position in *Living Room Lab* with EDA electrodes attached to left hand distal phalanges of ring and middle finger, using left and right index fingers to press attention test response buttons on keyboard.

Because these metrics were calculated as averages over entire experiment blocks rather than based on precise SCR onset times, any transient fluctuations caused by minimal index-finger movements during the attention test were unlikely to influence the results. Moreover, such movements occurred equally across all sound conditions and hence would not affect the within-subject comparisons that are the primary interest in this study.

3. Workload and noise annoyance

After each of the four attention test blocks, participants completed a modified version of the NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988), one of the most widely used self-report questionnaires for assessing perceived workload (Hart, 2006) and frequently applied in noise-related research (Grenzebach and Romanus, 2022; Jafari *et al.*, 2019; Müller *et al.*, 2023; Smith-Jackson and Klein, 2009). The standard NASA-TLX consists of six items (mental demand, physical demand, temporal demand, performance, effort, and frustration), each rated on a continuous scale and typically combined into a weighted overall workload score. In this study, the physical demand item was expected to be negligible based on findings from previous work (Müller *et al.*, 2023) and was therefore replaced with a noise annoyance item, phrased as "How annoyed were you by the noise you heard during the experiment?"

The resulting six scales were: mental demand ("very low" to "very high"), temporal demand ("very low" to "very high"), performance ("perfect" to "failure"), effort ("very low" to "very high"), frustration ("very low" to "very high"), and noise annoyance ("not at all" to "very"). Participants rated each item using a continuous scale with 21 subdivisions, presented via a slider interface on the same computer screen used for the attention task. All responses were transformed to a 0–100 scale for analysis, and the weighting procedure used in the original NASA-TLX was omitted, a modification commonly referred to as Raw-TLX (Hart, 2006). Instead of computing a composite workload score, each scale was analyzed individually.

III. RESULTS

The following section presents the experiment results and analyzes the effects of the sound condition on attention (Sec. III A), EDA (Sec. III B), as well as perceived workload and noise annoyance (Sec. III C). For these analyses, a nonparametric approach was chosen using Friedman tests to assess main effects, followed by Wilcoxon signed-rank *post hoc* tests with Bonferroni correction. Friedman test statistics are reported as $\chi^2(df)$, where *df* denotes the degrees of freedom, and Wilcoxon signed-rank test results are reported as *Z*. Effect sizes for the Friedman test are expressed as Kendall's *W*, and for the Wilcoxon test as absolute *r* values, calculated as $Z/\sqrt{N}$. The within-subject 95% confidence intervals shown in Figs. 8–10 were computed using the Cousineau–Morey method (Cousineau, 2005; Morey, 2008).

Although linear mixed-effects models (LMEs) were explored and yielded overall similar results, the nonparametric approach was selected for its simplicity and robustness to violations of normality assumptions in some variables. Potential between-subject effects of gender were examined using LMEs but showed no statistical significance and are, for reasons of conciseness and as existing literature provides little reason to assume relevant gender effects, not reported further. All raw and pre-processed data, as well as the MATLAB routines used for the following statistical evaluation, are openly available at Müller *et al.* (2025c).

A. Attention

Figure 8 shows the individual subject results, arithmetic mean, and within-subject confidence intervals for the attention test mean RT [Fig. 8(a)], the within-subject standard deviation of the RT [Fig. 8(b)], and the total number of errors in the attention test [Fig. 8(c)]. Both the descriptive statistics and the Friedman test indicate that there was no significant effect of sound condition on either mean RT [$\chi^2(3) = 1.26, p = 0.739, W = 0.007$] or within-subject standard deviation of RT [$\chi^2(3) = 4.82, p = 0.185, W = 0.027$]. While the mean and within-subject 95% confidence intervals for the total number of errors show a trend of being slightly higher for the two-tone sound condition, a Friedman test could not confirm that this effect is statistically significant either [$\chi^2(3) = 4.82, p = 0.185, W = 0.027$]. Since no significant main effects were found, no further *post hoc* tests were conducted on the attention test results.

In addition to these results, other attention measures, such as the difference in RTs for congruent and incongruent visual stimuli or the number of errors separated by different flanking or spatial offset conditions, were also explored. However, none of these more advanced metrics yielded any additional significant insights, and to keep this paper concise, it was decided to report only the previously described overall values. In summary, these results suggest that low-level EV road traffic noise does not significantly impact attention, as assessed by a combined Eriksen flanker and spatial Stroop test.

B. EDA

Figure 9 shows the individual subject data, arithmetic mean, and within-subject confidence intervals for the SCL [Fig. 9(a)], the number of SCRs per minute [Fig. 9(b)], and the sum of SCR amplitudes per minute [Fig. 9(c)]. Friedman tests indicated a statistically significant main effect of the sound condition on all three measures, though with very small effect sizes [SCL: $\chi^2(3) = 7.90, p = 0.048, W = 0.044$; SCR rate: $\chi^2(3) = 12.14, p = 0.007, W = 0.067$; SCR sum: $\chi^2(3) = 15.48, p = 0.001, W = 0.086$].

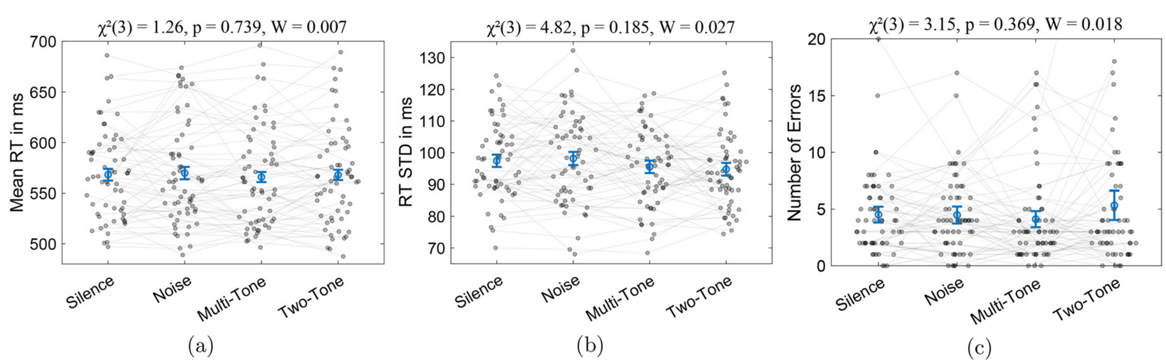

FIG. 8. Attention test results showing individual subject data (gray dots) and arithmetic mean with within-subject 95%-confidence intervals (blue error bars) for mean RT (a), within-subject standard deviation of RT (b), and total number of errors (c) for the four evaluated sound conditions. The subplot titles report Friedman test results for the main effect of sound condition.

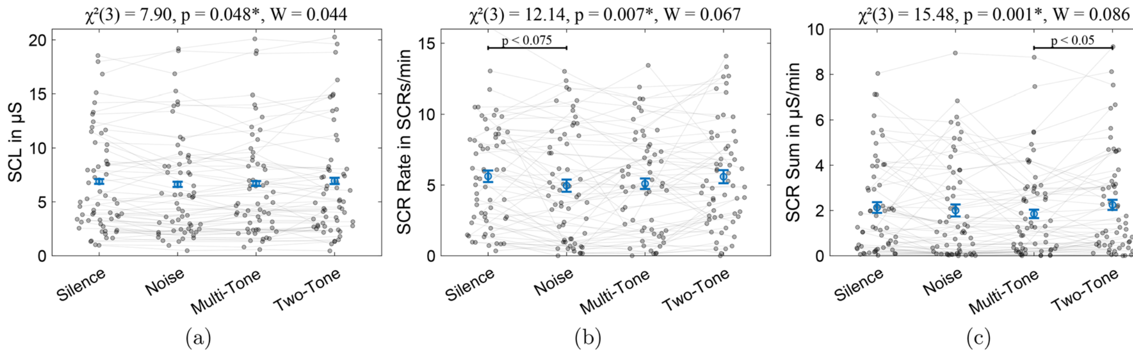

FIG. 9. EDA results showing individual subject data (gray dots) and arithmetic mean with within-subject 95% confidence intervals (blue error bars) for SCL (a), SCR rate (b), and sum of SCR amplitudes per minute (c) for the four evaluated sound conditions. The subplot titles report Friedman test results for the main effect of sound condition. The horizontal bars represent significant ($p < 0.05$) and near-significant ($p < 0.075$) Bonferroni corrected Wilcoxon signed-rank *post hoc* tests.

Even though these Friedman tests showed a small but statistically significant main effect of the sound condition on the SCL, none of the *post hoc* pairwise Wilcoxon signed-rank tests remained significant after Bonferroni correction (cf. Table II). This suggests that the observed effect of sound on SCL may reflect subtle, distributed differences rather than a strong contrast between specific pairs of conditions. For the SCR rate, none of the *post hoc* paired comparisons was significant at $\alpha = 0.05$. However, the comparison between silence and noise was near-significant with a medium effect size ($Z = 2.540$, $r = 0.328$, $\Delta = 0.664$ SCRs/min, $p_{\mathrm{Bon}} = 0.067$), suggesting that the analysis may have lacked sufficient power to detect significant differences after correcting for multiple comparisons across the four sound conditions. Finally, *post hoc* tests on the sum of SCR amplitudes revealed a significant difference between the multi-tone and the two-tone sound condition with a medium effect size ($Z = -2.944$, $r = 0.380$, $\Delta = -0.398\ \mu\mathrm{S/min}$, $p_{\mathrm{Bon}} = 0.019$).

In summary, these results show that even low-level road traffic noise can have an effect on EDA. Notably, the two-tone AVAS condition produced the highest total SCR amplitude per minute across all sound conditions, which, even though only statistically significant when compared to the multi-tone condition, suggests that the two-tone signal

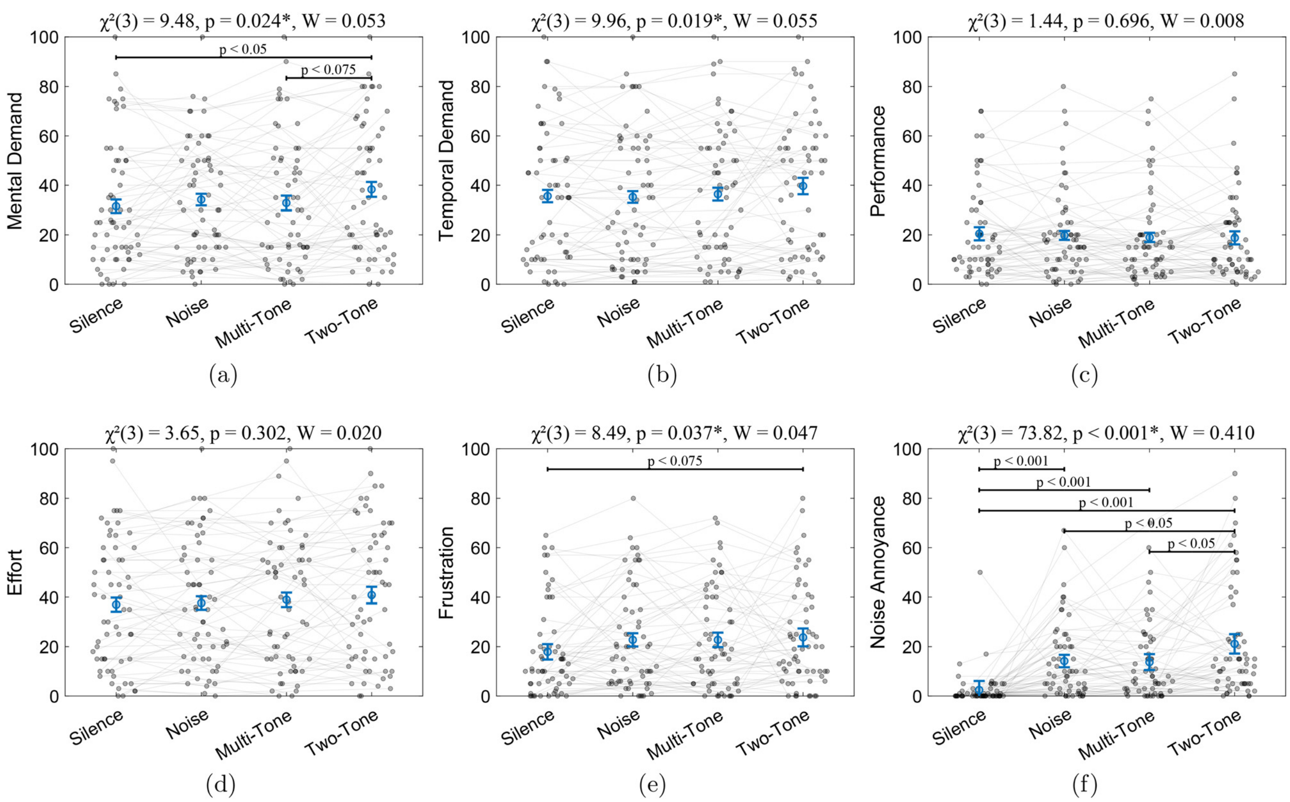

FIG. 10. Questionnaire results showing individual subject data (gray dots) and arithmetic mean with within-subject 95% confidence intervals (blue error bars) for mental demand (a), temporal demand (b), performance (c), effort (d), frustration (e), and noise annoyance (f). The subplot titles report Friedman test results, and horizontal bars represent significant ($p < 0.05$) and near-significant ($p < 0.075$) Bonferroni corrected Wilcoxon signed-rank *post hoc* tests.

TABLE II. EDA *post hoc* Wilcoxon signed-rank test results. Bold *p*-values indicate significance ($p < 0.05$).

		SCL				SCR rate				SCR amplitude sum			
Sound 1	Sound 2	Z	r	Δ (μS)	p_{Bon}	Z	r	Δ (SCRs/min)	p_{Bon}	Z	r	Δ (μS/min)	p_{Bon}
Silence	Noise	1.892	0.244	0.268	0.351	2.540	0.328	0.664	0.067	2.054	0.265	0.131	0.240
Silence	Multi-tone	1.421	0.183	0.190	0.932	1.811	0.234	0.525	0.421	1.656	0.214	0.281	0.586
Silence	Two-tone	0.250	0.032	−0.052	>0.999	0.206	0.027	0.027	>0.999	−0.368	0.048	−0.117	>0.999
Noise	Multi-tone	−1.119	0.144	−0.078	>0.999	−0.664	0.086	−0.139	>0.999	−0.257	0.033	0.150	>0.999
Noise	Two-tone	−1.870	0.241	−0.320	0.369	−1.962	0.253	−0.637	0.298	−1.834	0.237	−0.247	0.400
Multi-tone	Two-tone	−0.920	0.119	−0.242	>0.999	−2.136	0.276	−0.499	0.196	−2.944	0.380	−0.398	**0.019**

may evoke greater sympathetic arousal than other types of AVAS. Given the small absolute differences and the inherent variability of EDA measures, these effects should be interpreted as subtle indicators of altered arousal rather than robust or isolated physiological responses.

C. Workload and noise annoyance

Figure 10 shows the results obtained for the perceived workload and noise annoyance questionnaire. Based on the descriptive statistics, it is noticeable that the mean responses for the two-tone condition tend to be the highest for all measures except performance, and the mean values for silence show a trend of being the lowest for all questions except temporal demand and performance.

Friedman test confirmed a significant main effect of the sound condition on noise annoyance with a medium effect size [$\chi^2(3) = 73.82, p < 0.001, W = 0.410$] as well as a statistically significant but very small effect on perceived mental demand [$\chi^2(3) = 9.48, p = 0.024, W = 0.053$], temporal demand [$\chi^2(3) = 9.96, p = 0.019, W = 0.055$], and frustration [$\chi^2(3) = 8.49, p = 0.037, W = 0.047$]. No significant effect of sound condition on self-assessed performance [$\chi^2(3) = 1.44, p = 0.696, W = 0.008$] and effort [$\chi^2(3) = 3.65, p = 0.302, W = 0.020$] was found.

For those measures where the Friedman test showed a significant main effect, *post hoc* Bonferroni corrected Wilcoxon signed-rank tests were performed as reported in detail in Table III and indicated by the significances presented in Fig. 10.

For the noise annoyance, these *post hoc* tests revealed significant differences between silence and all three EV noise conditions ($p_{\text{Bon}} < 0.001$, $r > 0.7$), all with a large effect size. Additionally, a medium effect size significant difference was found between the noise annoyance for the two-tone AVAS and the noise AVAS ($Z = -2.903, r = 0.375, \Delta = -6.967, p_{\text{Bon}} = 0.022$) and between the two-tone and the multi-tone sound condition ($Z = -2.663, r = 0.344, \Delta = -7.400, p_{\text{Bon}} = 0.046$). This shows that not only were all three road traffic noise conditions rated as more annoying than the silence, but that the two-tone AVAS is judged as significantly more annoying than the other two AVAS signals.

This worse assessment of the two-tone AVAS can also be observed in the *post hoc* tests for perceived mental demand, where the only statistically significant difference was found between the two-tone condition and silence ($Z = -2.860, r = 0.369, \Delta = -6.800, p_{\text{Bon}} = 0.025$) and a near significant difference was found between two-tone and multi-tone AVAS ($Z = -2.619, r = 0.338, \Delta = -5.483, p_{\text{Bon}} = 0.053$), both with a medium effect size. While none of the *post hoc* tests for temporal demand showed any significant differences after Bonferroni correction, the *post hoc* tests for perceived frustration revealed a near-significant difference between the two-tone and silence conditions with a medium effect size ($Z = -2.557, r = 0.330, \Delta = -5.850, p_{\text{Bon}} = 0.063$).

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TABLE III. Perceived workload and noise annoyance *post hoc* Wilcoxon signed-rank test results. Only those measures that showed a significant main effect in the Friedman test are shown. Bold *p*-values indicate significant differences ($p < 0.05$).

		Mental demand				Temporal demand				Frustration				Noise annoyance			
Sound 1	Sound 2	Z	r	Δ	p_{Bon}	Z	r	Δ	p_{Bon}	Z	r	Δ	p_{Bon}	Z	r	Δ	p_{Bon}
Silence	Noise	−1.640	0.212	−2.683	0.606	0.329	0.042	0.350	> 0.999	−2.427	0.313	−4.850	0.091	−5.653	0.730	−11.733	**< 0.001**
Silence	Multi-tone	−1.023	0.132	−1.317	> 0.999	−0.711	0.092	−0.800	> 0.999	−2.366	0.305	−4.850	0.108	−5.598	0.723	−11.300	**< 0.001**
Silence	Two-tone	−2.860	0.369	−6.800	**0.025**	−2.146	0.277	−4.083	0.191	−2.557	0.330	−5.850	0.063	−6.037	0.779	−18.700	**< 0.001**
Noise	Multi-tone	0.575	0.074	1.367	> 0.999	−1.465	0.189	−1.150	0.858	−0.690	0.089	0.000	> 0.999	−0.075	0.010	0.433	> 0.999
Noise	Two-tone	−1.879	0.243	−4.117	0.362	−1.732	0.224	−4.433	0.499	−0.602	0.078	−1.000	> 0.999	−2.903	0.375	−6.967	**0.022**
Multi-tone	Two-tone	−2.619	0.338	−5.483	0.053	−1.259	0.163	−3.283	> 0.999	−0.439	0.057	−1.000	> 0.999	−2.663	0.344	−7.400	**0.046**

Summarized, the analysis of the subjective results shows that participants not only gave significantly different noise annoyance ratings for the various sound conditions, but that the sound also affected how demanding they perceived the attention test. Thereby, it is evident that the two-tone AVAS was not only judged as significantly more annoying than the other signals but also was the only sound that resulted in a significantly higher subjective mental demand and a near-significantly higher subjective frustration than the silence condition.

IV. DISCUSSION

A. Cognitive and physiological effects

As described in Sec. III A, the combined Eriksen Flanker and spatial Stroop test did not reveal any statistically significant effects of the sound condition on attention metrics. This is consistent with non-formal post-experiment interviews, where most study participants reported no influence of the traffic noise on their performance, and with the performance metric of the subjective workload questionnaire, which also showed no significant effect. In other words, participants maintained their level of attention across sound conditions, possibly at the cost of increased workload, as discussed in Sec. IV B. Given that our previous work found traffic noise at moderate levels to reduce sustained attention and inhibitory control (Müller *et al.*, 2023), the present outcome may point to several different interpretations. One possibility is that the 20 dB lower sound pressure levels compared to the earlier study may have been too weak to affect performance when only slightly exceeding the artificial background noise. Alternatively, the relatively monotonous character of the stimuli may have been less distracting than more pronounced or unexpected events. Yet, the observed physiological and subjective differences contradict a purely level- or character-based explanation. The absence of significant attention effects despite these differences may, therefore, indicate that the experiment design, and in particular the short block duration of the combined tests, was not sensitive enough to detect subtle changes in attention.

The physiological results, on the other hand, revealed more consistent patterns, with statistically significant main effects of sound condition on all three evaluated EDA metrics. Even though *post hoc* tests confirmed a direct difference only for one of the metrics and stimulus pairs (SCR sum for two-tone versus multi-tone stimuli), there was an overall trend of the two-tone signal evoking stronger sympathetic arousal than the other AVAS types. Given the small absolute differences and effect sizes, we remain cautious in interpreting this as strong evidence against a particular AVAS design. More importantly, the demonstration of significant EDA effects at such low indoor sound pressure levels is a novel finding, as most previous studies on physiological responses to noise used substantially higher exposures (Ellermeier *et al.*, 2020; Lee *et al.*, 2024; Masullo *et al.*, 2022; Mir *et al.*, 2023; Notbohm *et al.*, 2013;

Park *et al.*, 2018). Particularly noteworthy is that in the present study, the difference between stimulus and background continuous equivalent sound pressure level was less than 3 dB. In other contexts, extremely low background levels can make even faint stimuli clearly perceptible, despite their low absolute level. The relation between absolute sound pressure level, the stimulus-to-background difference, and the resulting cognitive or physiological response, therefore, remains to be investigated further. This issue may become increasingly relevant in environments where modern building constructions or quiet appliances reduce indoor background noise, making occasional low-level but clearly audible traffic events stand out more prominently.

Nevertheless, EDA measures are inherently variable, with individual differences and slow baseline drifts (Boucsein, 2012), so effect estimates should be interpreted with appropriate caution. While habituation of phasic skin conductance within a session is expected, the within-subject, fully counterbalanced design of this study, combined with the 90 s recovery and stabilization intervals between blocks, should distribute any monotonic habituation or slow drift across conditions rather than bias specific contrasts. Even so, future work could include trial index or time on task as covariates to further rule out carryover. Accordingly, the EDA findings in this study are best understood as group-level trends that complement subjective ratings, rather than as precise or individually diagnostic measures of noise impact.

B. Subjective effects

The subjective ratings from the workload and annoyance questionnaires show that AVAS signals can increase perceived effort and annoyance even at low indoor levels. Significant differences were found in mental demand, temporal demand, frustration, and especially noise annoyance. The two-tone AVAS signal consistently received the highest ratings across these dimensions, aligning with previous literature that links tonal and repetitive sounds to greater annoyance. These results suggest that participants invested more mental effort under certain AVAS conditions to maintain stable performance in the attention test.

Closer inspection of individual responses in Fig. 10 shows that some participants reacted in the opposite way to the overall group trend. This variability reflects the well-known individuality of noise annoyance, influenced by factors such as sensitivity to tonal sounds or personal coping strategies. The dissociation between subjective ratings and attention outcomes is also noteworthy. Participants reported higher workload and annoyance, and physiological measures confirmed stronger arousal, yet performance in the attention tasks remained unchanged. This suggests that subjective and physiological responses may capture aspects of noise impact that are not reflected in short-term cognitive performance metrics. Conversely, studies focusing only on annoyance cannot be assumed to reflect cognitive consequences, as the present data demonstrate. Finally, the relatively short exposure durations in this study likely underestimate longer-term effects. Annoyance and perceived workload may accumulate with extended or repeated exposures, which is particularly relevant in everyday environments.

C. Implications for AVAS design

Taken together with our previous findings on AVAS localizability (Müller *et al.*, 2025b), the current results indicate that AVAS signals composed of two pure amplitude-modulated tones perform poorly across multiple dimensions. Specifically, the two-tone AVAS was rated as most annoying, most mentally demanding, and evoked the highest physiological arousal, while also being substantially harder to localize. Although some studies suggest that highly tonal signals may enhance detectability (Hastings and McInnis, 2015), our data imply that such benefits may come at the cost of increased perceptual and physiological strain. These trade-offs underline the importance of considering human perception more explicitly in AVAS design, in addition to regulatory compliance and brand identity. Signals optimized solely for detectability or marketing purposes may fail when evaluated from a broader perceptual perspective, where annoyance, cognitive demand, and physiological arousal are also relevant outcomes. Moreover, the optimal signal design may depend strongly on context, as characteristics that support detectability in noisy outdoor traffic may at the same time create annoyance when perceived in quiet indoor environments. Future AVAS development should, therefore, aim for a more holistic approach that integrates perceptual evaluation early in the design process, exploring alternatives beyond simple tonal structures to achieve a better balance between detectability, localizability, and long-term acceptability.

D. Limitations and future work

This study evaluated only one representative signal per AVAS type, and it remains possible that alternative implementations could yield different results. Future research should explore a broader range of AVAS designs to assess the generalizability of our findings. Additionally, this study focused on closed-window scenarios with very low indoor noise levels. While this setup reflects typical modern building conditions, situations involving partially open windows or older facades may result in higher exposure and potentially stronger effects.

Additionally, the employed tire-road noise auralization method is based on a single, non-standardized *in situ* recording. Since tire-road noise is known to significantly vary with tire model, wear, temperature, and pavement type, our simulation may be limited in generalizability and not capture the range of spectral and temporal characteristics found in practice. Nevertheless, the primary objective of this study was to compare AVAS designs, and crossing multiple AVAS signals with multiple tire-road noise combinations would have multiplied conditions and complexity beyond what was feasible. Future work should incorporate well characterized tire noise simulations or standardized measurements across several tire models and pavements so that AVAS related effects can be assessed alongside the variability introduced by tire-road interactions.

Beyond attention, other cognitive domains such as working memory, decision-making, or problem-solving could be more sensitive to AVAS noise and warrant investigation. Moreover, our stimuli simulated a relatively constant traffic flow. More isolated and contextually salient events, such as a neighbor reversing into a driveway, may evoke different human responses and should be examined in future studies. The current sample size, while adequate for detecting moderate effects, may have limited power for subtler psychophysiological responses or interactions between conditions, suggesting that larger samples could strengthen conclusions. Additionally, future research should examine longer-term exposure to determine whether repeated or chronic exposure to EV sounds leads to habituation or cumulative stress.

Finally, the relationships between continuous equivalent sound pressure level, maximum sound pressure level, and background noise, as well as their effects on cognitive, subjective, and physiological responses, remain to be better understood. This is relevant not only for EVs but for environmental noise in general, where regulatory thresholds are often expressed only in overall weighted sound pressure levels that may not accurately capture human response variations across different acoustic environments.

V. CONCLUSION

This study investigated the effects of low-level EV road traffic noise, including three commonly implemented types of AVAS signals, on attention, EDA, perceived workload, and noise annoyance in an indoor living environment. While no significant impact on attention performance was observed, the physiological and subjective data revealed that even low-level EV traffic noise ($L_{\mathrm{A,eq}} \leq 21.5$ dB) can be associated with small but measurable differences in EDA and influence perceived mental demand, temporal demand, frustration, and annoyance, even though the observed effects were generally small to medium in size.

Among the tested AVAS types, the signal consisting only of two amplitude-modulated pure tones consistently produced the highest annoyance ratings, subjective workload, and electrodermal responses, with statistically significant differences observed in comparison to other AVAS types. These findings suggest that highly tonal AVAS signals, despite potential benefits for detectability, may impose a greater perceptual and physiological burden on non-involved individuals who are not the intended recipients of the warning, such as residents or other bystanders. When considered alongside previous results on AVAS localizability, the two-tone signal appears to perform poorly across multiple dimensions of human response.

These outcomes underscore the importance of striking a balance between traffic safety and environmental impact in AVAS design. Regulatory frameworks should consider not only detectability and compliance but also perceptual and physiological effects, especially in urban settings where exposure to road traffic noise in indoor living environments is common. Future research should explore a broader range of AVAS designs, higher exposure scenarios, and additional cognitive metrics to inform policy and design decisions further.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

The study was conducted in accordance with the Declaration of Helsinki and approved by the Swedish ethical review authority (Etikprövningsmyndigheten, 2024-04880, September 12, 2024). Informed consent was obtained from all study participants involved in the listening experiment.

DATA AVAILABILITY

All stimuli recordings and the data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.16901844 (Müller *et al.*, 2025c).

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