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LISTENING TO THE HIGH-TECH CITY AND ITS VEHICLES: AUDITORY PERCEPTION OF ELECTRIC VEHICLES EMBEDDED IN SHENZHEN'S URBAN SOUNDSCAPE

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ABSTRACT

Electric vehicles can be utterly silent; thus manufacturers have started to artificially add alert sounds to cars to lower the risk for pedestrians in the streets. Yet, urban sound environments are often loud, chaotic, and uncontrolled, with pedestrians subjected to a multitude of cognitive stimuli, so that these environments become a challenge. On the example of Shenzhen City – a modern yet loud "high-tech" city with a comparatively high ratio of electric cars – this research studies how pedestrians perceive electric vehicles sonically as objects that are embedded in the urban soundscape. Five different street types served for data collection. Utilizing the collected data, a lab study involving 20 participants simulated urban street scenes with video and audio, followed by a questionnaire on audibility, comfort, attention, sense of control, and sense of safety. Findings indicate that the underground parking lot, with its specific soundscape, has the highest perceived audibility and attention. The food street provides more comfort, control and safety. Overall, for these three perception types, daytime is higher ranked than nighttime, while audibility and attention are less affected by the time of day. This study sheds light on urban soundscape characteristics and contributes future research directions including context-specific, dynamic sound design for enhancing electric vehicle alert sounds and pedestrian-vehicle interaction in dense urban environments.

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1. INTRODUCTION

In urban spaces, traffic noise is among the most prominent sources of sound [1]. Equally, in China, the Government's 2024 noise report lists traffic noise as one of the four major sources of noise [2, 3]. Cities worldwide have started to focus on sustainability by favoring electric vehicles. The same holds for Shenzhen, the city with the highest ratio of electric vehicles in China as of 2024 [2]. As cities move from gasoline to an increased number of electric vehicles, their soundscapes increasingly change. Combustion engine noise is less prevalent, and instead, pedestrians hear electric vehicles.

Shenzhen is a high-tech city in South China, known for its tech sector, for its rapid development, and for its role as a pioneering model city for China. Electric vehicles become an important component in the city's soundscape. Urban soundscapes are complex assemblages of perceived sounds of many sources that blend for the listening subject, and they have been studied widely [4–6]. The sound of electric vehicles has been equally studied [7, 8]. Traffic noise is also widely studied [9–12].

Our research specifically focuses on the intersection of electric vehicle sound and dense urban soundscapes, and more specifically, how pedestrians act with cars as sonic objects. Urban soundscapes have been called "lo-fi soundscapes" and they have been analyzed as complex for pedestrians as they, given the manifold number and nature of sounds around them, "lose perspective" and are subjected to "cross-talk" between their senses that are overpopulated, among others, with sounds [13]. Most objects generate sound as a consequence of users interacting with them. These auditory cues, combined with contextual information about their sources, allow pedestrians to deduce the nature of the interaction taking place [14]. Because electric vehicles produce less noise than traditional combustion engines, pedestrians are at a higher safety risk as they might not hear approaching vehicles [15]. In consequence, many countries have issued policies that require car manufacturers to build so-called alert sounds into their vehicles, which are played back when vehicles travel at a low speed, so as to warn pedestrians in their surroundings and increase their safety [16, 17]. Among them, China set the recommended standard GB/T 37153-2018 "Acoustic vehicle warning system of electric vehicles running at low speed", implemented in 2019, and which requires vehicles to play a warning sound when their speed is below 20km/h [18]. As a result, manufacturers have added warning sounds to help pedestrians more easily notice approaching vehicles. In densely populated urban spaces, vehicles often run at low speed. This means that the artificial warning sound playback, often referred to as AVAS (acoustical vehicle alert sound), increasingly becomes a part of the city's soundscape. Note that in this paper, we call these sounds simply "alert sounds."

In this paper, we aim at understanding the perspective of pedestrians who move in a huge "high-tech" city with a large ratio of electric vehicles. On the example of Shenzhen, we investigate how pedestrians perceive electric vehicles as sonic objects that are embedded in the complex, often loud and "lo-fi" soundscape of the city. With a mixed-method approach combining field observations, a lab experiment with a questionnaire, and statistical analysis, we pursue three primary research questions: (1) how do pedestrians perceive and respond to electric vehicles' alert sound designs in dense urban environments; (2) how does their perception of electric vehicles differ across several qualitatively different locations in the city; and (3) what is the correlation between the time of the day and the location within the city in terms of how pedestrians perceive electric vehicles? We collected data in Shenzhen to represent a modern, large, densely populated high-tech city with a large ratio of electric vehicles. The results of our research provide empirical data from a pedestrian's point of view that might point to future directions in improving both the sound design for urban environments with many electric vehicles, as well as in improving the sound design of vehicle's alert sounds specifically for applications in dense urban environments.

2. METHODOLOGY AND RESEARCH DESIGN

To investigate how pedestrians in several different environments within Shenzhen perceive alert sounds of electric cars as embedded objects in the larger soundscape, we used a mixed-method approach. This approach particularly helps us to identify patterns in their perception. This study employs qualitative and quantitative methods to comprehensively examine pedestrian perception of the sound emitted by electric cars – including their alert sound, yet which cannot exclusively be separated from other noise by electric vehicles running at low speed, such as and noise from tire and wind friction. Five different locations were chosen based on them being characteristic for Shenzhen, but also, based on them being categorically different from one another, so as to better represent the city (see Fig. 1). They include (1) a neighborhood street, (2) a "food street" with lots of small shops, (3) an underground parking lot of a well-frequented shopping mall, (4) a commercial plaza, and (5) a street within an modern office complex. Each location was recorded at three times of the day: morning (9am to 11am), afternoon (3pm to 5pm), and evening (8pm to 10pm) - to analyze variations in alert sound audibility under different ambient noise conditions. For the data collection, we used a single electric vehicle, driven by ourselves at a consistent speed of 25km/h. This allows for a controlled data set while alert sounds are emitted. The project consists of two primary phases: (1) fieldwork for data collection (including audio and video recording) in the five urban environments and (2) a structured user study in the laboratory. Fieldwork recordings provide real-world acoustic and visual data, while the user study evaluates how users perceive urban sound in a controlled testing environment.

2.1 On-Site Audio Recording

For audio recording, the RØDE NT-SF1 Ambisonic Microphone was mounted at 1.6 meters height on the sidewalk and connected to the PreMix-6 II audio recorder, ensuring consistent spatial audio recordings at a consistent gain setting. The ZOOM H6 recorder was positioned at the same height to capture stereo sound, while the Decibel Meter was held in the hand by an observer on the sidewalk to measure noise levels at an average pedestrian's ear level. The recording position diagram is shown in Fig. 2.

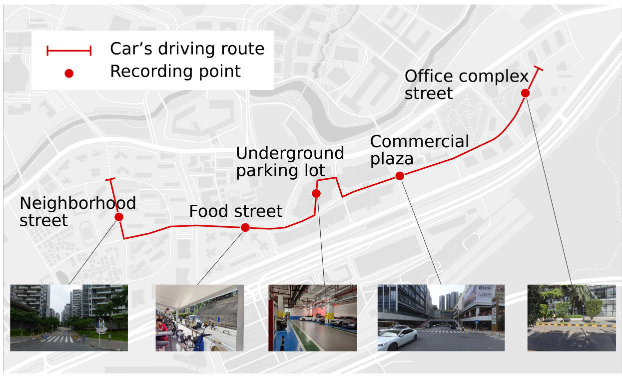

Figure 1. Fieldwork locations in Shenzhen.

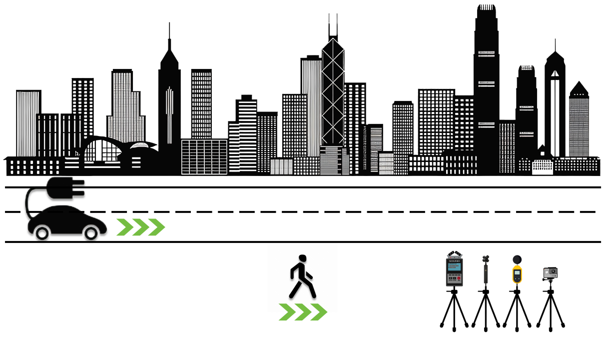

Figure 2. Audio and video recording setup.

We recorded audio always for 5 minutes as our test vehicle was passing by.

2.2 Video Recording

For video recording, a GoPro camera was held in the hand by an observer on the sidewalk to record street-level activity from a pedestrian's perspective. These video recordings were later synchronized with the audio recordings to provide a comprehensive dataset for the subsequent laboratory user study.

2.3 Post-Production of Recordings

Following data collection, the audio and video recordings underwent a post-production process aiming at enhancing their clarity and compatibility with playback systems. Ambisonic audio conversion was conducted using REAPER and RØDE's SoundField VST-plugin. Ambix-format audio was imported into REAPER, then processed with RØDE's SoundField plugin. The input was set to the Ambisonic B-format (Ambix) with an Upright mic placement, and the output was converted to stereo audio. This process ensured that the spatial audio could be accurately reproduced through headphones. RØDE's SoundField plugin also enabled visual monitoring of sound directionality and SPL (sound pressure levels), facilitating adjustments to horizontal and vertical positioning, so as to match a pedestrian's perspective onto the passing car in the street.

2.4 User Study Design

To analyze pedestrian perception of electric vehicles' alert sounds, a user study based on audiovisual street recordings was conducted with 20 participants. Every participant went through a within-subject experiment, ensuring that each participant experiences all conditions at the same variable levels. Each participant completed four experimental sessions: (1) hearing test without background noise to assess each participant's auditory ability; (2) collecting basic information of each participant such as age, gender, if they have a driving license, if they have driving experience, and if they have experience in driving an electric vehicle; (3) experiencing audiovisual recordings from our own data collection of the five different street scenes to assess context-specific perception, including a questionnaire that was filled in simultaneously with answers on a scale of 1-5; and (4) a personal structured interview. This study design allows for systematic comparisons of alert sound detectability as well as other forms of pedestrian perception of the electric vehicles embedded in the city.

Before the experiment began, we displayed a sample of the pure alert sound to participants to make sure they are familiar with the sound that is emitted from electric vehicles at low speed. Then, participants were subjected to a hearing test to ensure normal auditory function. The study was designed using PsychoPy, a behavioral experiment software, and consisted of 10 video clips categorized into daytime or nighttime recordings and the five different locations in the city. After watching each video, participants responded to a questionnaire evaluating five factors on a 1 to 5 Likert scale:

1. Audibility - I could clearly hear the electric vehicle's alert sound
2. Comfort - hearing the electric vehicle's alert sound is comforting me / not irritating me

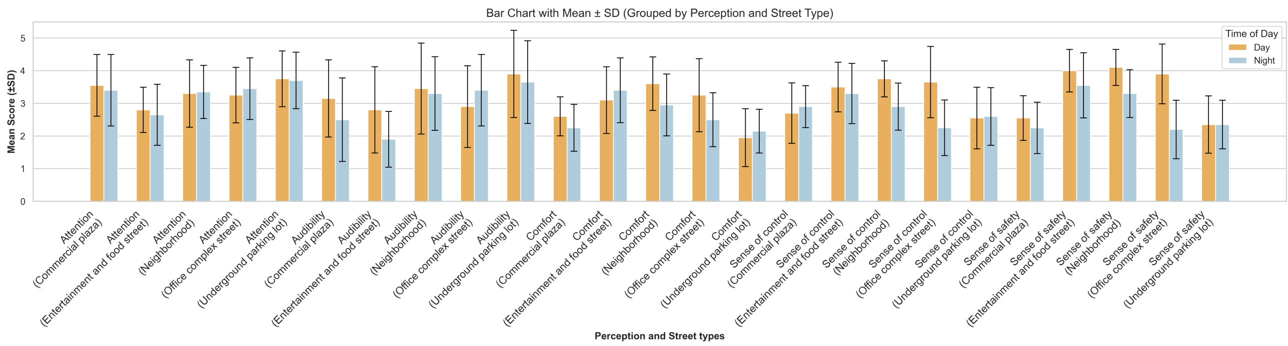

Figure 3. Results of perception types in different streets at day and night.

3. Attention - the electric vehicle's alert sound did not distract me while I was (virtually) walking
4. Sense of control - hearing the electric vehicle's alert sound made me feel I am in control of my surroundings while (virtually) walking
5. Sense of safety - the electric vehicle's alert sound made me feel safe

To make sure the data is valid, the questionnaire data is limited to the range that is within the haring test result's range of "normal hearing." A two-way ANOVA analysis was performed to assess the significance of the effect of time and road on perception. Following that, we used the Tukey HSD analysis to explore differences in perception among types of streets. All data management and analysis was performed using PyCharm software version 2024.3.1.1. The study has 20 valid questionnaire responses.

3. RESULTS

The mean and standard deviation of the five street types for each perception type are calculated and displayed in a bar chart separately for daytime and nighttime. The results of the preliminary analysis are illustrated in Fig. 3. Overall, there was positive and negative intersubject variability close to one point in perceived level. There was a high degree of variability between audibility and the sense of safety. Audibility and sense of security varied widely within groups of street types. The alert sound makes participants feel uncomfortable. The standard deviation demonstrates that participants have different extents of feelings, which requires further individual exploration and a larger quantity of data than our project can provide.

3.1 Extent of Impact in Function of Time and Location

Table 1 presents the significance results obtained from the two-way ANOVA analysis, and which is combined with figure 7 to show positive and negative trends. They explore the influence of daytime/nighttime and street types on participants' perceptual responses. In this paper, the result is considered as significant if the p value is smaller than 0.05.

3.2 Effects of Daytime/Nighttime

As illustrated in Fig. 4, time has a very significant effect on comfort, on the sense of control and the sense of safety. At daytime, participants feel higher level of these three kinds of perceptions. While for audibility and attention, the changes from daytime to nighttime are not significant.

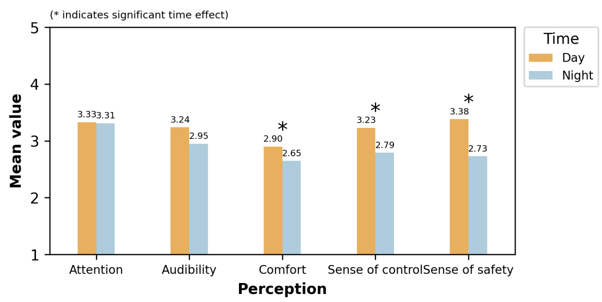

Figure 4. Perception changes in the time dimension.

3.3 Effects of Street Type

According to the results presented in Tab. 1, the street type has a significant influence on all five kinds of perceptions. Among them, In food street and neighborhood street, the levels of comfort, sense of control and sense of safety are positively high, with more than 3.2 point. However, in commercial plaza and underground parking lot, the levels of theses three street types are low. Conversely, attention shows higher points in these two street types.

Separately, the commercial plaza street has the highest level of attention but negatively low level of other kinds of perception. In the office complex street, these five kinds of perception show similar levels around score 3. For the neighborhood street, the levels are around 3.3, but participants have a higher sense of safety. In the underground parking lot, the level of attention and audibility is the highest while the participants feel the least comfort, the least sense of control and sense of safety.

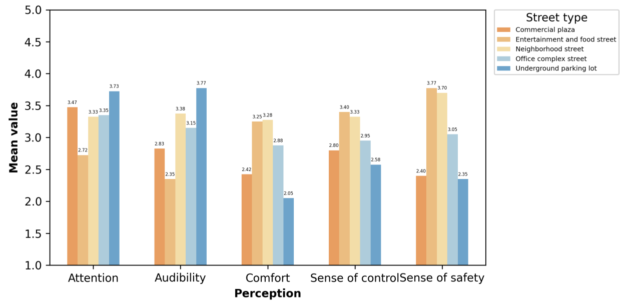

Figure 5. Perception changes in the street type dimension

3.4 Interaction Between Daytime and Street Time

The difference in how time affects perception of different street types is named an interaction. As the data shows in Tab. 1, at day and nighttime, the five street types have a significant influence on comfort, sense of control and sense of safety.

The chart in Fig. 6 demonstrates that all daytime scenes receive higher scores than the same scenes at night. Participants feel less comfortable at daytime than at night in the food street as well as in the underground parking lot. In the office complex street, the sense of control dramatically drops at night, and so does the sense of safety.

Table 1. Two-way ANOVA analysis (5 perception types)

Perception		sum_sq	df	F	PR(>F)
Audibility	C(Time)	4.205	1	2.827	0.094
	C(Street)	46.87	4	7.877	**p <.001**
	C(Time):C(Street)	11.47	4	1.928	0.107
	Residual	282.65	190		
Comfort	C(Time)	3.125	1	4.09	**0.045**
	C(Street)	45.35	4	14.84	**p <.001**
	C(Time):C(Street)	9.25	4	3.027	**0.019**
	Residual	145.15	190		
Attention	C(Time)	0.02	1	0.024	0.876
	C(Street)	21.72	4	6.576	**p <.001**
	C(Time):C(Street)	0.88	4	0.266	0.899
	Residual	156.9	190		
Control	C(Time)	9.68	1	13.64	**p <.001**
	C(Street)	19.53	4	6.882	**p <.001**
	C(Time):C(Street)	17.97	4	6.332	**p <.001**
	Residual	134.8	190		
Safety	C(Time)	21.125	1	33.52	**p <.001**
	C(Street)	74.42	4	29.52	**p <.001**
	C(Time):C(Street)	17.1	4	6.783	**p <.001**
	Residual	119.75	190		

4. DISCUSSION

4.1 Differences Between Street Types

Previous data shows that street types have a significant influence on all five kinds of perceptions. To explore the difference for the five streets types, this study uses the Tukey HSD method to run a post-hoc test. P values lower than 0.05 are regarded as significant difference.

4.1.1 Audibility

The underground parking lot is significantly different from the other street types and has the strongest audibility. The food street is significantly different from several other streets, which means its audibility value may be more disturbed. There were no significant differences between the neighborhood and the office complex streets, and the alert sounds had similar audibility in both environments as illustrated in Fig. 7.

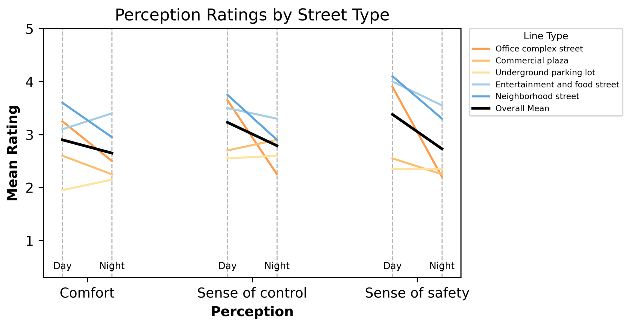

Figure 6. Interaction between time and street type on perception.

4.1.2 Comfort

Pedestrians' perceived comfort in regard to alert sound was the lowest in the underground parking lot. And pedestrians' perception of comfort is highly sensitive in this type of street environment. The commercial plaza street also differed significantly from multiple other street types with its distinctive style of comfort ratings. The neighborhood's and the food street's comfort ratings do not show obvious significance, which means that there are more similarities among these two types of soundscapes as shown in Fig. 7.

4.1.3 Attention

The food street is the scene that mostly differs from all other street types, suggesting that subjects' ratings of "attention" in regard to alert sounds are specific and unique, as is shown in Fig. 7. Several participants mentioned that the noisy background, the complicated flow of people, and the many visual disturbances distract their attention heavily.

4.1.4 Sense of Control

As shown in Fig. 7, there were significant differences in the perceived sense of control between the food street and the other street types, particularly the commercial plaza street, and the underground parking lot. Combining the mean values of the rating, the results indicate that these street types tend to elicit a feeling of control among pedestrians. At the same time, the office complex street was not significantly different from the other streets, which shows its potential of acting as an intermediate value or a reference type street.

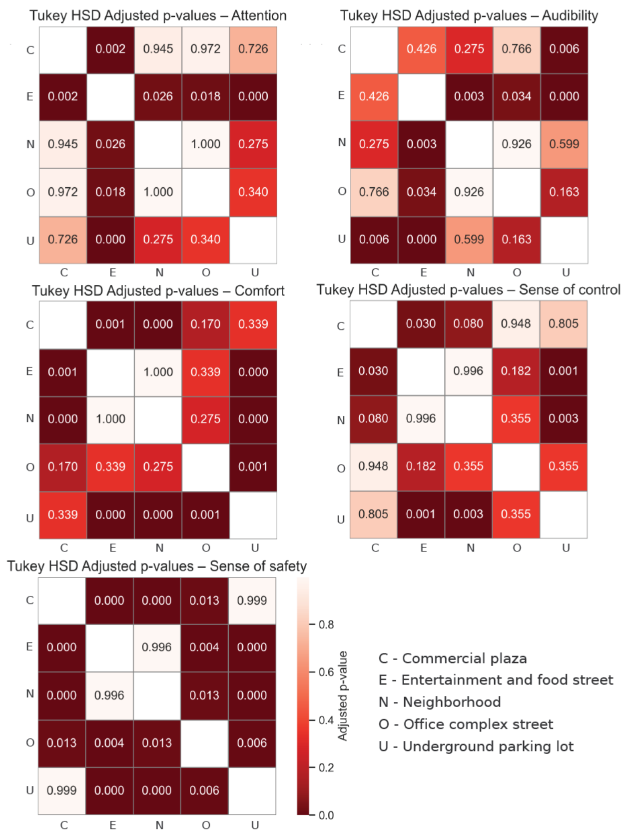

Figure 7. Differences between street types.

4.1.5 Sense of Safety

Fig. 7 indicates that the commercial plaza street and the underground parking lot have similar results in their perceived sense of safety, while the neighborhood and the food streets show similar levels of sense of safety. The result implies that the soundscape of these four street types have an analogous hearing perception related to safety. Except for the values mentioned, all street types show significant differences in terms of the perceived sense of safety.

5. CONCLUSIONS

On the example of Shenzhen, a "high-tech" city in South China, this research specifically focused on investigating how pedestrians perceive the electric vehicles' alert sounds as embedded in the urban environment. We studied their perception, via data collection at three different times of the day and night and on five different street types, and with a lab-run user study based on our own collected audiovisual footage from the streets, so as to understand how pedestrians react to the electric vehicles in these audiovisual scenes. The study evaluated five key sensory dimensions that relate to how pedestrains perceive electric vehicles: audibility, comfort, attention, sense of control, and sense of safety. The findings highlight distinct urban soundscape associated with each of the five street environments, and nuanced pedestrian perception with differences between daytime and nighttime in function of the five tested street types.

Our research shows that time has a very significant effect on comfort, sense of control and on the sense of safety, with daytime results being higher than nighttime results. The street type has a significant influence on all five kinds of perceptions. The underground parking lot consistently differed from other spaces across most dimensions, showing a significantly lower performance in comfort, sense of control, and sense of safety. It indicates its relative perceptual disadvantage. Similarly, the food street significantly outperformed other street types in comfort, attention, and sense of safety, highlighting its potential for fostering a positive urban experience for pedestrians in spite of electric vehicles present.

The findings suggest that equipping electric vehicles simply with unchanged sound signals that are emitted when the vehicle moves at speeds below 25 km/h might not be nuanced enough as a solution that can increase pedestrian safety. Instead, our results show that the perceived safety varies across locations and times, thus alert sounds might have to more dynamically adapt to time and the type of the environment that the vehicle is moving through. Our research points to the need for more targeted alert sound systems and dynamic sound design strategies for future vehicles particularly in complex urban space, and particularly for addressing under-performing soundscape environments such as underground parking lots, which are a crucial part of cities. Our work also points to the need of more nuanced discussions of urban soundscapes of which electric vehicles are increasingly part. Electric vehicles are sound objects that are perceived as embedded in urban soundscapes, and in turn, urban soundscapes need to more directly address the implications for inclusive, effective, and safe soundscapes.

The study's small number of participants in the laboratory experiment limits its applicability, however the results suggest strong potential for future research. Getting a larger sample size will improve the results. Potentially, audiovisual playback of street scene could be replaced by VR scenes that allow for more interaction.

6. ACKNOWLEDGMENTS

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