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An Environmentally Adaptive Warning Sound System For Electric Vehicles

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ABSTRACT

Electric vehicles are quiet at low speeds compared to their internal combustion engine counterparts, leading to regulations on the mandatory use of artificial warning sounds for their detection, as a safety measure for other road users. Arguments against the concept have been voiced focusing on the resulting environmental noise pollution, while at the same time some of the practical implementations have been shown to be somewhat ineffective when tested in an urban environment. To satisfy the need to both minimise noise pollution and ensure that the warning sound is sufficiently audible within any noise environment, an environmentally adaptive warning sound system is conceptualised and investigated. The system employs an adaptation algorithm that estimates the auditory masking thresholds due to a potentially changing sonic environment, and uses this information to adapt the warning sound not only in level, but also in spectral content. The system aims to render the vehicle detectable in both quiet and noisy environments without unnecessarily increasing its overall sound output level, therefore limiting noise pollution. The effectiveness of the adaptive equalisation algorithm is tested and evaluated under a variety of environmental noise scenarios.

Keywords: Warning, Environment, Adaptation, Pedestrian, EV
I-INCE Classification of Subject Number: 13

1. INTRODUCTION

The quiet operation of electric vehicles (EVs) has led to the enforcement of artificial warning sounds for their detection at lower speeds, over safety concerns. Warning sound systems have been subsequently developed with a sound design that aims to increase the detectability of EVs, while in compliance with the standards imposed by the relevant regulations [1]. Although such sounds are usually designed with the general spectral qualities of an urban sound scape in mind, neither the widely produced designs nor the legislation itself consider the variability in human reaction time and detectability when faced with different road scenarios [2]. This situation may pose a potential problem in failing to render a vehicle audible in certain cases; or, equivalently, causing the vehicle to be unnecessarily intrusive in quieter environments.

It could therefore prove invaluable to develop a system that modifies the signal emitted according to the environmental background noise, so as to ensure that the warning sound remains sufficiently audible under changing environmental conditions. This would

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mean that the vehicle could be rendered detectable in both quiet and noisy environments without unnecessarily increasing its overall sound output levels, therefore limiting pass-by noise. While some research has already gone into adaptive warning sounds [3], these systems have currently only adapted the overall level of the sound. Through a full implementation of the proposed system, however, it may be possible to modify not only the level, but also the spectral content of the warning sound, taking into account the masking effects stemming from the environmental noise.

This paper presents the proposed method and components required to implement the spectrally adaptive EV warning sound system. A preliminary version of the proposed approach is implemented in simulation and its ability to adapt the spectral content of a previously designed warning sound signal [4] to the acoustic environment is investigated.

2. ADAPTIVE WARNING SOUND SYSTEM OVERVIEW

An environmentally adaptive warning sound system should, as its primary principle, be able to analyse the sonic environment that the EV finds itself in, and make modifications to the warning sound that is to be emitted according to the information it has gathered. Figure 1 displays the basic sequence that this system follows from receiver, to the processing and finally to the warning sound emitter. In detail these are:

- A sound receiver, which could be a single microphone or an array thereof, either dedicated solely to the warning sound system, or possibly doubling up as a component of a different vehicle system. The receiver should be able to detect environmental noise successfully without being affected by factors such as wind due to the speed of the vehicle.
- The signal processing software to estimate the level and spectral content of the environmental noise, determine the audibility thresholds and adapt the gain equalisation of the warning sound so that it is appropriately audible.
- A sound emitter for the generation of the warning sound; this could potentially be a single loudspeaker, a directional system [5], [6], [7], or a different kind of suitable sound source.

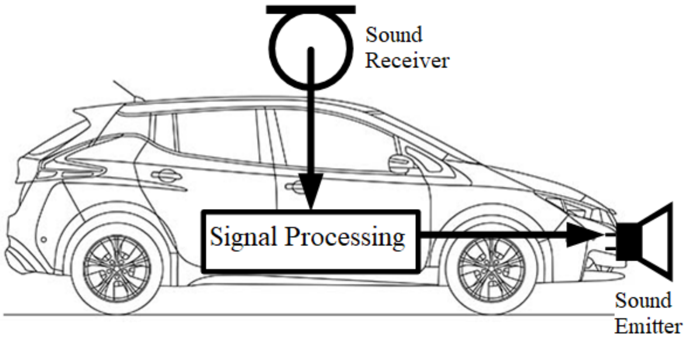


Figure 1: The basic implementation principle of the environmentally adaptive warning sound system.

At the core of the proposal is the signal processing block, which includes the processes and algorithms to adapt the base warning sound so that it is detectable, whilst contributing minimally to environmental noise levels. The signal processing block is the main focus of this paper, and can initially be developed largely independently from the two other components. Figure 2 illustrates the principles of operation for the proposed system through a processing block diagram. The symbols used in the diagram to denote sound pressures and signals are listed in Table 1. The function of the system is intended to function through the following sequence:

1. The receiver measures an overall pressure, which corresponds to the environmental noise, p_{Er}, plus the warning sound, p_{Wr}, emitted from the vehicle, and sends this signal to the Signal Processing Block.
2. The estimated warning sound component at the receiver, $\hat{p}_{Wr}$, is then subtracted from the received signal in order to isolate the signal corresponding to the environmental noise, $\hat{p}_{Er}$.
3. Further processing can be performed at this stage to estimate the environmental noise level, $\hat{p}_E$, at the position of the intended target.
4. The above estimated environmental noise signal is then sent to the Warning Sound Adaptation Block. Here, thresholds of audibility due to the ambient wide band background noise, $\hat{p}_E$, are estimated using a masking model. The base warning sound, s_W, is then adapted using the information obtained from the masking model, by adjusting the amplitude of its frequency components so that it will be rendered appropriately audible at the position of the target.
5. The adapted warning sound signal, $\tilde{s}_W$, is then simultaneously sent to the emitter and to be further processed:
    a. The emitter receives the signal, $\tilde{s}_W$, from the processing block, and produces the sound output.
    b. At the same time, a model of the transfer response between the emitter and the receiver is applied to $\tilde{s}_W$ so that it may be subtracted as the warning sound component, $\hat{p}_{Wr}$, from the overall input signal, $\hat{p}_{Er}+\hat{p}_{Wr}$.

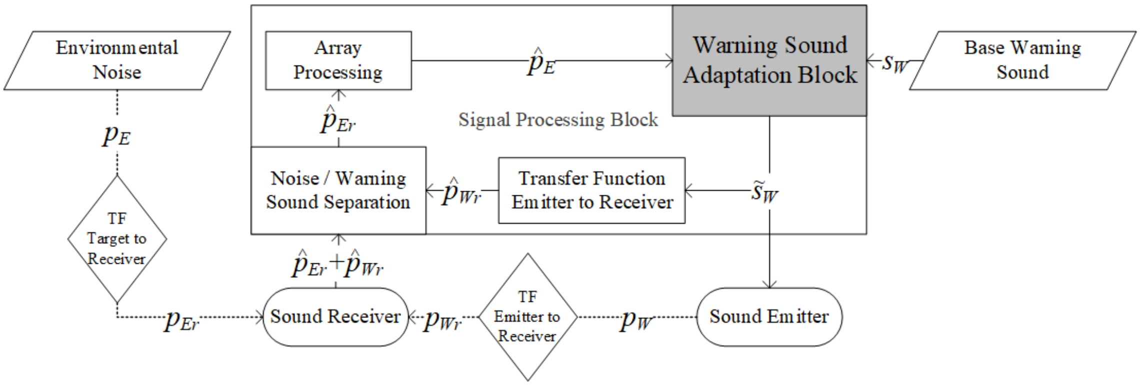


Figure 2: Block diagram of the proposed environmentally adaptive sound system

Table 1: Nomenclature for the block diagram (Figure 2) of the proposed sound system

Symbol	*Content*
p_E	Environmental SPL at target location
p_{Er}	Environmental SPL at receiver location
p_W	Warning sound SPL at emitter location
p_{Wr}	Warning sound SPL at receiver location
$\hat{p}_E$	Estimated environmental SPL at target location
$\hat{p}_{Er}$	Estimated environmental SPL at receiver location
$\hat{p}_{Wr}$	Estimated warning sound SPL at receiver location
s_W	Base warning sound signal
$\tilde{s}_W$	Adapted warning sound signal

At the current state of development, the adaptive sound system has not been integrated within a vehicle and does not include the processing stages covering the separation of the warning sound from the received signal, or the determination of spatial information related to the environmental noise. The current focus is, therefore, on the signal processing stage of the system that adapts the warning sound, based on the assumption that a measure of the environmental noise is available. The Warning Sound Adaptation Block will be described in more detail in the following section.

3. WARNING SOUND ADAPTATION

The key component of the adaptive warning sound system is the sound adaptation block shown in Figure 2, which is responsible for the audibility evaluation of the warning sound in the current sonic environment, and its respective adaptation. These two subcomponents are described in the following subsections.

3.1 Environmental Masking Estimation

For the effective adaptation of the warning sound, the audibility thresholds across frequency for the current environmental noise must first be estimated. This can be done through the implementation of a masking model, which primarily involves filtering the input environmental noise signal through a filter bank designed to emulate the processes of the human auditory system [8]. The resulting filtered signals can then be analysed to obtain the audibility thresholds which are used to define the required level of the warning sound over frequency.

For the study presented in this paper, the masking estimation is performed using a one-third octave band filter bank. Although a simplified approximation to the actual processes that occur in the human ear and define the auditory thresholds, using this type of filter bank provides a low computational cost and complexity in implementation. Moreover, current regulations evaluate sound and define the minimum SPL thresholds for a warning sound system per one-third octave band [9]. These factors justify the suitability of a one-third octave filter bank at this early stage of investigation.

Filters need to be constructed so that they cover the entire spectrum occupied by the components of the warning sound, including the changes in frequency content that occur during acceleration of the EV. At the end of this process, the power and respective sound pressure level calculated within each of the frequency bands of interest contain the information necessary to adapt the warning sound. However, as the one-third octave bands do not exactly match the fundamental frequency components of the warning sound, the algorithm may implement high gain values at frequencies where the warning sound is not intended to include components. For this reason, a maximum limit is defined for the assigned gain values. This also serves to stop the system from attempting to overcome an extraordinarily loud environmental noise situation.

3.2 Warning Sound Generation and Adaptation

The spectral content of the warning sound is adapted so that its level remains greater than that of the environmental noise within each one-third octave frequency band. The difference in level between the warning sound and environmental noise in each band must be specified such that the warning sound is sufficiently audible. Definition of what difference is required is not trivial and would need to be determined through context specific psychoacoustic experiments [10].

The required adaptation can be either integrated within the sound generation process by adjusting the gain coefficient of each component during its synthesis. Alternatively, adaptation can be performed for any pre-existing warning sound signal by implementing the same audibility estimation used for the environmental noise and calculating the gain required in each band to reach the required difference in level. The signal can then be adapted by filtering it again through a bank of filters with the updated gain coefficients for each band and summing the outputs of these gain adjusted filters.

4. SIMULATION BASED APPLICATION STUDY

This section will present an investigation into the application of the proposed adaptive warning sound system to a previously developed warning sound [4]. The warning sound will firstly be described, before it is adapted for different environmental noise conditions using the proposed strategy.

4.1 Base Warning Sound Signal

The warning sound used in this application study of the adaptive system was designed during a previous project researching EV warning sounds, specifically to be detectable without causing annoyance to the recipient [4]. It consists of three frequency components, centred around 300 Hz, 517 Hz and 630 Hz respectively, with each characterised by a different type of frequency and amplitude modulation. Figure 3 shows the diagram describing the warning sound generation process: each component goes through a stage of modulation in amplitude and phase, before receiving a gain adjustment; after this, all components are added together to form a signal constituting the warning sound. Figure 4 contains the spectrogram of the base warning sound, where the three components and their different types of modulation over time are visibly distinguishable.

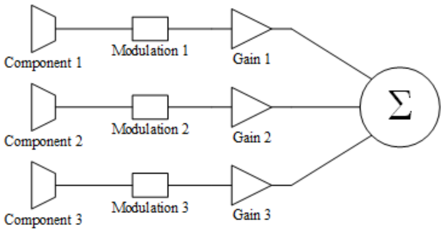


Figure 3: Diagram of the warning sound synthesis and integrated gain equalisation process, for an example comprising of three fundamental frequency components.

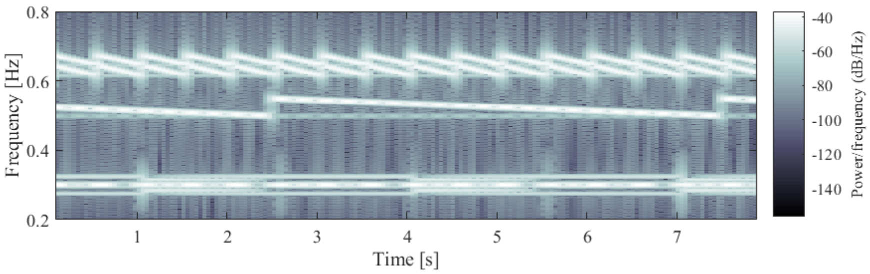


Figure 4: Spectrogram of the warning sound used in the presented implementation of the adaptive system.

In the current investigation of the system, the base warning sound is loaded from a pre-existing sound sample. The modulation and gain stages displayed in Figure 3 are, therefore, not interfered with during the adaptation process. The required gain adjustment is instead performed using a one-third octave graphic equaliser. The base warning sound signal is filtered through the one-third octave filter bank and its power within each band is compared with that of the environmental noise. The gain values are then calculated so that the adapted warning sound has a power greater than the environmental noise within the corresponding band by a specified amount. The maximum allowable gain in each band is limited to avoid over-amplification of low-level warning signal components and to avoid adaptation for to extraordinarily loud environmental noise. In the presented study, a +5dB difference between the warning sound and the environmental noise in each band is set and a maximum gain of 20 dB is enforced. The adaptation of the gain coefficients is performed over time, so that each component is adjusted dynamically to reflect any changes in the sonic environment.

The reasons for choosing this specific warning sound to test the adaptive system are its frequency content, which is clearly structured in separate bands, and the fact that these frequencies lay in a range where urban noise typically displays an abundance of components, making the task of adapting the sound depending on such a sonic background most relevant. In addition, the methods used for the synthesis of this warning sound have been thoroughly documented and made available to the public, allowing for its precise reproduction through the algorithms contained within the adaptive system. One final thing to note about this warning sound, however, is that it does not display the acceleration-related frequency shift that is normally required by the regulations. Although it makes for a more convenient implementation at this instance, this last factor is something that needs to be considered in future development stages.

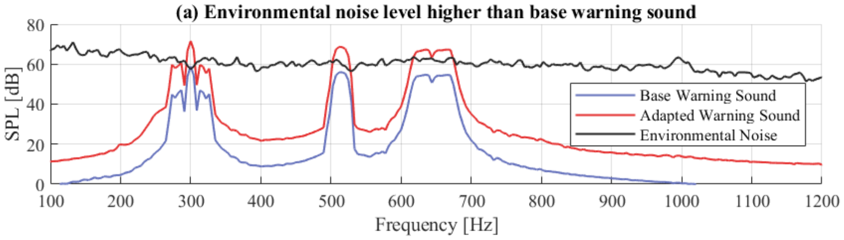
4.2 Environmentally Adaptive Warning Sound Testing

The adaptive system is evaluated by comparing the base warning sound, defined as the warning sound without the gain adjustment stage described in Section 4.1, to the adapted warning sound. The assumed environmental noise has been provided by a number of monaural field recordings taken in central and suburban areas of Southampton during clear weather conditions, i.e. no rainfall or strong winds, using a portable recording device.

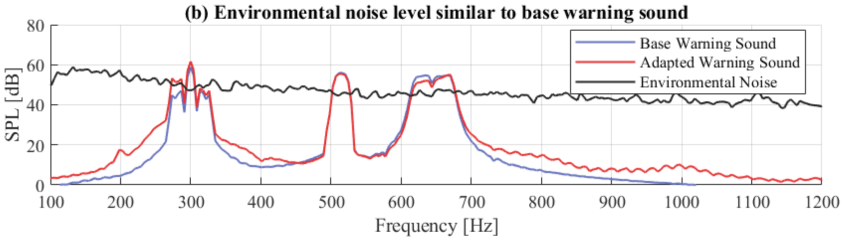
A block-based processing strategy is employed, where the data is partitioned into non-overlapping data blocks. Each block is then filtered using the one-third octave based filter bank, which in this case consists of the filters centred around 251 Hz, 316 Hz, 501 Hz and 630 Hz, in accordance with the ANSI S1.11-2004 standard. This frequency range is enough to cover the spectrum of the warning sound used. After the power of the environmental noise within these bands has been estimated, the gain coefficients for each frequency component of the warning sound are updated and the adapted signal is produced by adding together these components. As mentioned in Section 2.3, the gain coefficients are defined so that the SPL of the warning sound is 5dB greater than the environmental noise within the respective band.

Figure 5 shows the average sound pressure level across frequency calculated within a 0.5s long buffer for the environmental noise, base warning sound and adapted warning sound, in three different example cases. In (a), the level of the environmental noise is higher than the threshold compared to the based warning sound across all three bands, leading to an increase in the gain applied to all components of the warning sound. Case (b) presents a segment of time during which the level of the base warning sound is close to the intended threshold imposed by the environmental noise. In this case, while the two lower frequency components have had minimal gain adjustment, the 630 Hz component is boosted noticeably more due to the spectral characteristics of the environmental noise. Lastly, in (c), the environmental noise is lower in level than the desired threshold across the three bands, and the adaptation algorithm has thus reduced the gain applied to all components of the warning sound.

(a) Environmental noise level higher than base warning sound



(b) Environmental noise level similar to base warning sound



(c) Environmental noise level lower than base warning sound

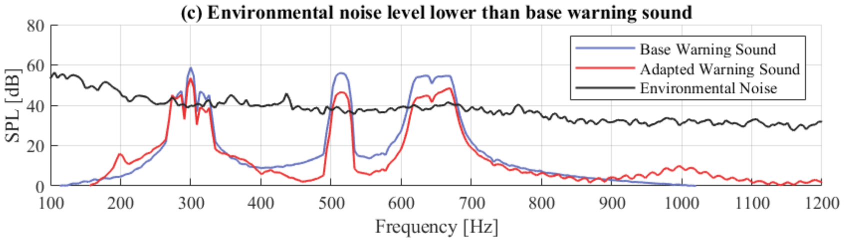


Figure 5: Sound pressure level across frequency for environmental noise, base warning sound and adapted warning sound in different noise scenarios.

One factor in the adaptation process that has a significant effect on the adapted output signal is the size of the buffer chosen to partition the input signal, which also determines the update rate of the gain values. Figure 6 shows the waveforms of a ten second sample of environmental noise, the warning sound with no component specific gain adjustment, and the adapted warning sound. In case (a), the buffer has a length of 0.5s, while in (b) a length of 0.1s.

The response obtained through the shorter buffer replicates fluctuations in the amplitude of environmental noise with a higher precision. Moreover, there is a smaller delay in this response, as the greater buffer size means that the adaptation algorithm waits for a longer time period before determining the required gain values. It is also clear from these results, however, that there are fluctuations in the amplitude of the environmental noise that neither adapted waveform follows, which suggests that they stem from events at frequencies outside of the range specified by the filter bank used.

Figure 7 shows the calculated gain values for each of the three components as functions of time, when using a 0.5s buffer in (a) and a 0.1s buffer in (b). In the latter case, the gain values display a relatively large variation between short time intervals, as the adaptation algorithm tends to match both signals. Perhaps noteworthy is that with a larger buffer the gain values are mostly negative, meaning that the signal is attenuated for a greater part of this particular section of environmental noise. The gain distribution is visibly more even between negative and positive values with the shorter buffer.

Although this analysis might indicate that the shortest possible buffer would yield the most effective adaptation, the optimum buffer length would be most suitably determined through listening tests. Large and rapid fluctuations in the warning sound spectral content might ultimately render the warning sound less detectable to the human listener or unnecessarily annoying.

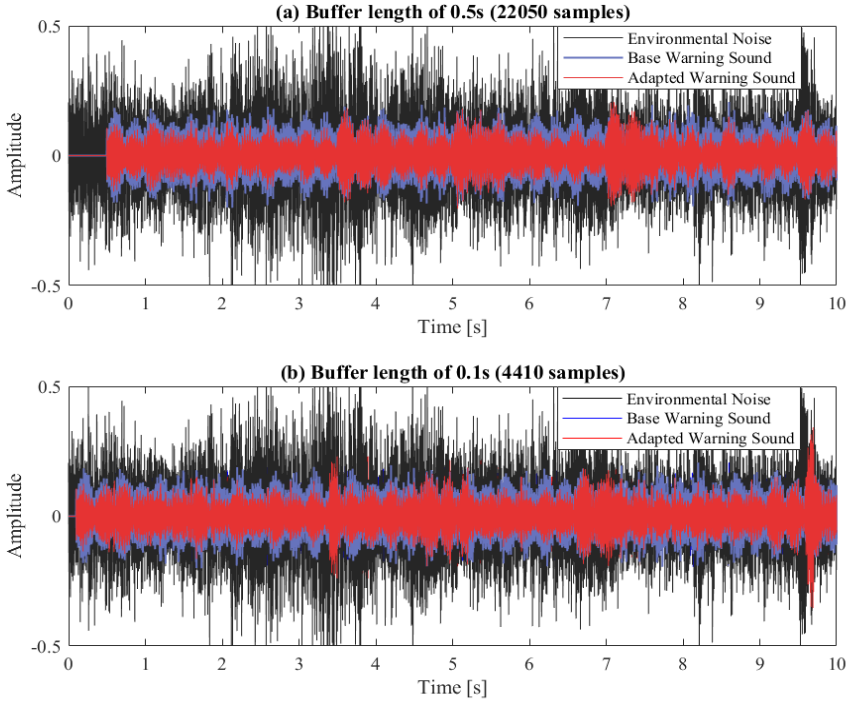


*Figure 6: Time history of the base warning sound, the environmental noise sample, and the resulting adapted warning sound for buffer lengths of 0.5s (*a*) and 0.1s (*b*).*

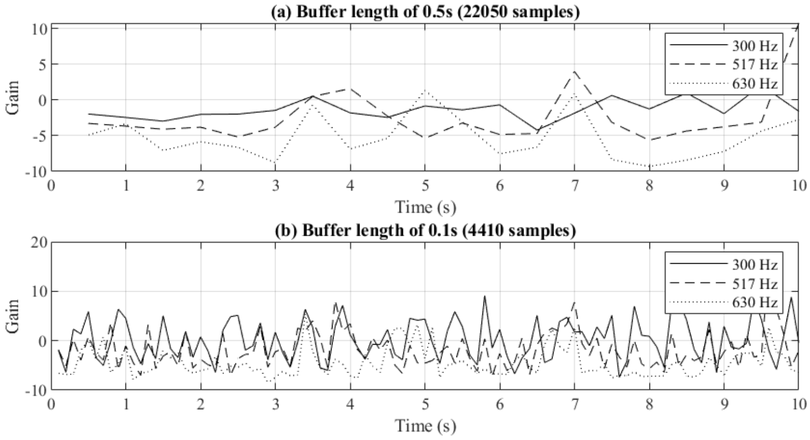


Figure 7: Gain values for each frequency component of the adapted warning sound in time, given the presence of environmental noise and the use of different buffer lengths.

4. CONCLUSIONS

The environmentally adaptive warning sound system is intended to adjust the overall level and spectral content of a warning sound according to the sonic environment, so that it is rendered audible yet not intrusive. For its operation, such a system would require, apart from the warning sound emitter itself, a signal processing unit as well as a sound receiver, which may potentially be shared with another system belonging to the vehicle.

An overview of the system structure separates it into a signal processing block, which includes the initial and final stages of signal processing to the environmental noise and base and adapted warning sound signals respectively, and a core sound adaptation that implements the sound adaptation process. At its current stage of development, the adaptation algorithm uses a one-third octave band filter bank with the number and centre frequencies of the filters chosen so as to cover the spectrum occupied by the warning sound. The warning sound itself is generated within the system, allowing for precise adaptation through the gain adjustment of its individual components during the synthesis process.

The implementation of the algorithm shows that the system is successful in attenuating or amplifying the warning sound per frequency component, depending on spectral content of the current environmental noise. The use of a shorter buffer leads to an increase in responsiveness of the adapted sound, but may also impact the annoyance and detectability of the warning sound.

Plans for the further development of the adaptive system involve the addition of the transfer function and array processing blocks to the algorithm, and the use of different audibility estimation methods, from simple filter banks to auditory masking models. Along with buffer size and under the constraints of computational cost, these components of the adaptation system will evaluated for their effectiveness in rendering an EV sufficiently detectable through a series of listening tests.

5. ACKNOWLEDGEMENTS

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