WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.145288

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 2 2023

pp. 623 –636

Research paper

Analysis of the influence of warning sounds in expressway tunnels on the mental state and attention of the driver

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Abstract: In recent years, some expressway tunnels have started broadcasting warning sounds, such as fire alarms, to improve driver attention and traffic safety. However, there is few research on it, and in contrast to previous studies, we have considered different evaluation indices and through field measurement to determine the effectiveness of this practice. The characteristics of three warning sound signals, i.e., fire alarm, dynamic music, and voice command, in a tunnel were analyzed using MATLAB. Considering pupil diameter and blink duration as evaluation indexes, the change in the mental state of the driver after hearing a warning sound was analyzed. Based on Markov chain theory, the change in the gaze region and gaze shift of the driver under the condition of a warning sound was analyzed. Results shows fire alarms and voice commands can increase the mental load of drivers, but the degree of impact was not determined. Dynamic music does not affect the mental load of the driver. The fire alarm and dynamic music attracted the attention of the driver; conversely, as the voice command warns the driver to focus on safety, it did not impact the attention of the driver. The research results provide a scientific reference for the selection of warning sounds in expressway tunnels and new research ideas for the prevention of traffic injuries in expressway tunnels.

Keywords: warning sound, expressway tunnel, mental state, visual characteristics

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1. Introduction

Expressway tunnels are often built in mountainous areas because they can significantly shorten the distance between two locations and reduce the elevation of roads. However, compared with open roads, its semi-closed tubular structures and tunnel lighting, which can never be equated to the natural light outside the tunnel, makes the driving environment in the tunnel monotonous and depressing. Furthermore, it is more difficult for driver to judge vehicle's position, prolonging reaction time and stopping sight distance, all those will increase the risk of traffic accident easily [1]. Once traffic accident occurs, it is difficult to rescue because of its semi-closed characteristics, which not only causes traffic interruption, but also will leads to casualties and arousing much social concerns [2].

To improve tunnel traffic safety, some tunnels adopt warning sounds in recent years. However, there are few studies about its impact on driver. Therefore, in this study, the warning sounds played in the tunnel were considered as the research object, and the impact of the warning sounds on the visual characteristics of the driver was studied using the eye movement parameters as the evaluation indices through a field vehicle test, and then the impact on the mental load of the driver was analyzed.

2. Literature review

Drivers can obtain traffic-related information through vision, hearing, touch, smell, and other means. Atesok [3] determined that people can retain 20% of auditory information and 30% of visual information, whereas Sarabi Asiabar [4] identified that 30 and 40% of auditory and visual data are retained, respectively. Although the specific percentage is widely debated [5, 6], we can note that vision is the primary way of obtaining information. Therefore, to improve tunnel traffic safety from the perspective of driver vision, most researchers have conducted considerable research on tunnel lighting technologies, such as lamps, natural light utilization or dimming, landscape lighting, side wall materials [7, 8], and sight guidance technologies that form a multi-frequency pattern through signs, markers, and reflective rings [9, 10].

From the perspective of auditory inputs, research has been conducted on the influence of sound on people. With respect to sound type, Kang [11] applied a special treatment on the road surface to emit a warning sound (which is not rumble strips) when the tire interacts with the road surface to improve the attention of the driver. Fagerlon [12] indicated that the emission of any sound unrelated to real life by the onboard information system will have a negative impact on the driver. He [13] evaluated the effectiveness of three overspeed warning sounds on commercial buses and concluded that a "beep warning" was the most effective. The research conducted by Wei [14] shows that an alarm-type broadcast can improve the distance perception accuracy of the driver, while a vocal broadcast reduces the accuracy. Lin [15] improved driving performance using an audio warning signal in a virtual reality driving environment. While considering the characteristics such as sound pitch and frequency, Sanford [16] tested the recognition accuracy and response time using a Landolt ring and determined that the signal-to-noise ratio of an effective audio alarm should be greater than the detectable value of 10 db. Sonoko [17] analyzed the subjective feelings of people and identified that a change in sound frequency from low to high would give people a sense of danger. The sense of danger would be stronger if the interval between audio signals was shortened. Catchpole [18] indicated that adding a high frequency to an audio alarm can improve its penetrability and direction recognition. Suied [19] identified that the response time of people decreased with the shortening of the time interval between sound pulses. In recent years, under normal operation conditions, some tunnels have started playing alarm sounds, dynamic music, etc. to improve the attention of the driver [20]. For this matter, Yang [21] studied the effects of slow- and fast-music, voice prompts, sirens on ECG, EEG and driving behavior of the driver through indoor simulation tests. In contrast, the current study considered eye movement parameters and through field measurement to determine the mental load and attentiveness of the driver. This study on whether warning sound can avoid distracting the attention of the driver and increase the mental load will be useful in determining novel methods for preventing traffic accidents in tunnels.

In the 1960s, Hess [22] and Kahneman [23] successively published a paper in the Science journal that pupil diameter can not only reflect the mental state of a person but is also closely related to task difficulty. They determined that as the difficulty of a task increases, the pupil diameter increases. Benedetto [24]] concluded that the blink duration is a more sensitive and reliable indicator than the blink rate for evaluating the mental workload of the driver. Thus, the attention level of the driver can be studied using eye points [25].

3. Methods

3.1. Studied tunnel

After a field investigation, a super long (> 3000 m) expressway tunnel of the Baotou Maoming Expressway was selected as the test tunnel. The tunnel is a two-lane one-way road with a length of 7098 m and connected by a subgrade and viaduct (about 219 meters in length and 30 meters in maximum height). The longitudinal gradients are between –2 and 0.5% and two ends of the tunnel are curved sections with radiuses of 2450 and 1263 m, accounting for 8.5% of the total length. The interior zone is straight, accounting for 91.5% of the total length. The tunnel lighting parameters are shown in Table 1.

Table 1. The tunnel lighting parameters

Tunnel zone	Length	Luminance
threshold zone	88 m	75.0 cd/m^2
transition zone 1	74.8 m	22.5 cd/m^2
transition zone 2	88 m	7.5 cd/m^2
interior zone	6787.2 m	1.5 cd/m^2
exit zone	60 m	10 cd/m^2

Note: The above values are from design document.

3.2. Testing personnel and equipment

Nine Chinese drivers were recruited for the test, i.e., six men and three women. All drivers had expressway tunnel driving experience, and their vision or corrected vision was normal.

The SMI Eye Tracking Glasses 2.0 was used to record the eye movements of the driver in real time, such as the pupil diameter, blink duration, scanning amplitude, and fixation point. Wearing it is like wearing glasses without lenses, which has little impact on the driver's behaviour and perception. The iViewETG software was matched with the eye tracker to pre-process the collected data and export the video of the scene as observed by the eyes and the corresponding data to Microsoft Excel.

The test vehicle was a Volkswagen Lavida five-seater sedan. The main test equipment and process are shown in Fig. 1 and Fig. 2, respectively.

Fig. 1. Eye tracker

Fig. 2. Field test of real vehicle

3.3. Test method

The drivers were asked to wear the eye tracker and drive on the Baotou Maoming Expressway section, entering from the interchange near the tunnel entrance and exiting from the interchange near the exit after passing through the tunnel.

3.4. Warning sound

While driving, the broadcasting device attached on the side wall of the tunnel played three types of sounds: voice command (specific content: "please pay attention to safety"), dynamic music (music prelude), and fire alarm (modulated sound). Among these, the voice command was broadcast at approximately 1700 m from the tunnel portal in the east–west direction, the music was broadcast at approximately 1670 m from the tunnel portal in the west–east direction, and two devices were fixed for broadcasting the fire alarm sounds, i.e., at 980 m from the tunnel portal in the east–west direction and 725 m from the tunnel portal in the west–east direction. All warning sound are broadcast at the interior zone of the tunnel, where the luminance is constant, and will not affect driver's visual.

3.5. Processing of eye movement data

Using the video recorded by the eye tracker, we determined the time when the warning sound occurred and exported the corresponding eye movement data. Moreover, as the mental state of drivers fluctuate when driving in a tunnel for approximately 5–6 min, the eye movement data was recorded for the same duration in intervals of 5 s before and after the warning sound was broadcast to ensure that the mental state of the driver was consistent and the fluctuation was only related to the warning sound.

For the filtered pupil diameter, blink duration, and fixation point data, interquartile range method [26] was used to identify outliers because of is very simple and easily explained.

$$\begin{aligned} \text{Upper} &= Q_3 + 1.5 \times (Q_3 - Q_1) \\ \text{Lower} &= Q_1 - 1.5 \times (Q_3 - Q_1) \end{aligned} \tag{3.1}$$

where: Q_1 and Q_3 are the lower and upper quartiles, respectively; *Upper* and *Lower* are the highest and lowest critical values, respectively.

3.6. Gazing area

Shang [27] divided the vision of a driver into five areas: inside the cab, near-distance road section in front of the vehicle, far-distance road section in front of the vehicle, rear-view mirrors (left, right, and inside the vehicle), and other areas (such as the vault and side wall). As the viewing distance of the road in front of the vehicle includes both far and near distances, which cannot be quantified, this study combined them into one area (Area 1). Because the traffic-related information on the right side of the tunnel is greater than that on the left side, the left and right walls (including the vault) were divided into two areas (Areas 2 and 3, respectively) by considering the line formed by the tunnel dome lamps as the dividing line. Finally, after viewing the vision video of the driver, we determined that drivers rarely looked at the rear-view mirrors (left, right, and internal mirrors); therefore, the mirrors and internal cab region were combined into one area (Area 4). The divisions in the specific focus areas are shown in Fig. 3.

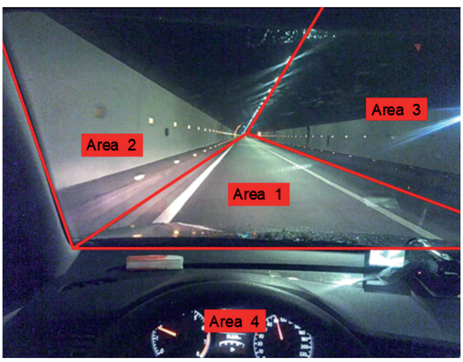


Fig. 3. Divisions in the focus areas

Based on the vertex coordinates of each focus area and coordinates of each focus point of the driver, the geometry of the focus area was drawn and the location of each focus point was marked using MATLAB to identify the focus areas in which each focus point of the driver was located.

3.7. Analysis of one-step fixation transfer characteristics

The Markov chain is a sequence of random variables that can describe the state of a system, while the state of a system at a certain time only depends on its state at the previous time, which is consistent with the behavior of the human eye. Let the discrete state space E of a random sequence $\{X_{(n)},\ n = 0, 1, 2 \ldots\}$ be $\{1, 2, \ldots\}$, if for any non-negative numbers $n_1, n_2, \ldots, n_n (0 < n_1 < n_2 < \ldots n_m)$ any natural number k, any $i_1, i_2, \ldots, i_m$, and $j \in E$ the following condition is satisfied:

$$(3.2)\qquad \begin{aligned} P\{X(n_m + k) = j \mid X(n_1) = i_1,\ X(n_2) = i_2,\ \cdots,\ X(n_m) = i_m\} \\ = P\{X(n_m + k) = j \mid X(n_m) = i_m\} \end{aligned}$$

Then, $\{X_{(n)},\ n = 0, 1, 2, \ldots\}$ is called a Markov chain [28]. The state of the random variable in the Markov chain changes with the time step, and the transition probability can be expressed as $P_{ij}(n, n+k)$, which is abbreviated as $P_{ij}(k)$. When $k = 1$, $P_{ij}(1)$ is called the one-step transition probability and the matrix is:

$$(3.3)\qquad P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} & \cdots \\ P_{21} & P_{22} & \cdots & P_{2n} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

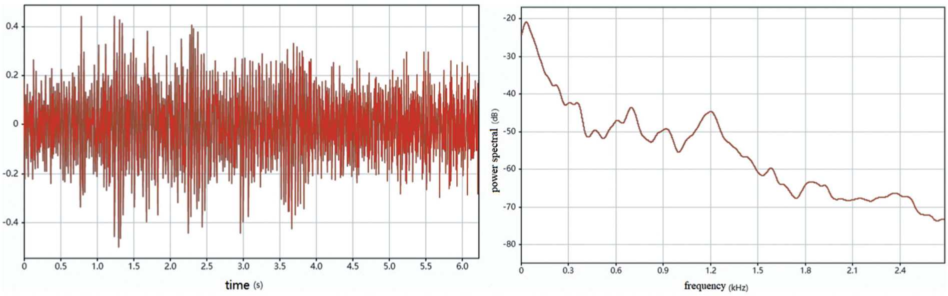
where: $P_{ij} = \dfrac{a_{ij}}{a_i}$, a_{ij} represents the frequency of state i transferring to state j, $a_i = \sum_{j=1}^{n} a_{ij}$ $(i, j = 1, 2, \cdots, n)$.

4. Results

4.1. Warning sound signal characteristics

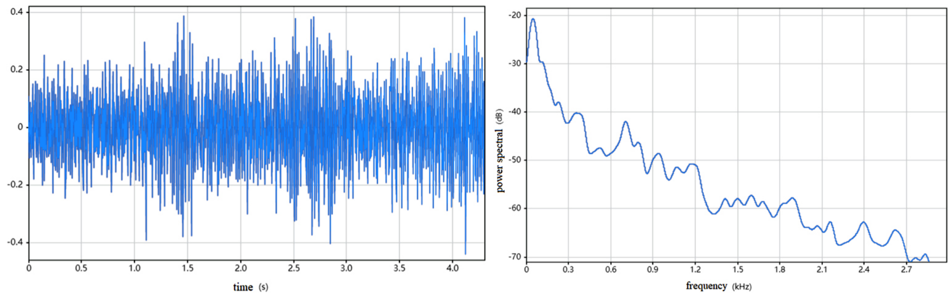
The three collected warning sounds were analyzed using MATLAB 2021b software and processed using Fourier transform, wavelet denoising signal analysis techniques. The waveforms and spectra of the three warning sounds are shown in Fig. 4 to Fig. 6.

The fire alarm frequency exhibited “multiple peaks”, with the highest peak at 30 Hz. The frequency ranges are mainly concentrated in the 520–810 Hz and 1000–1400 Hz bandwidths. The peak frequency of the dynamic music is at 50 Hz with a frequency range of 580–850 Hz. The peak frequency of the voice command is at 40 Hz with a frequency range of 280–430 Hz.



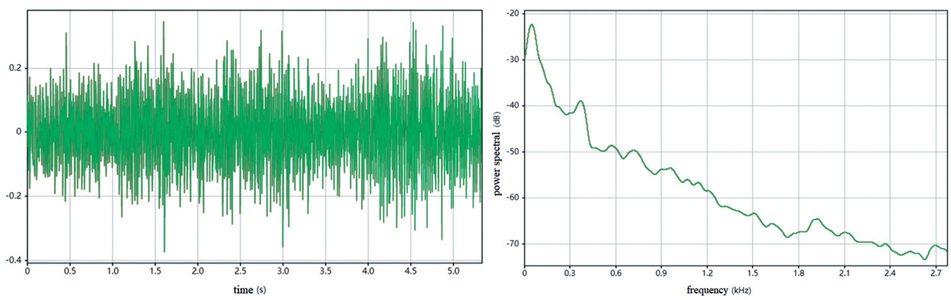
(a) (b)

Fig. 4. (a) Waveform and (b) spectrum diagrams of fire alarm



(a) (b)

Fig. 5. (a) Waveform and (b) spectrum diagrams of dynamic music



(a) (b)

Fig. 6. (a) Waveform and (b) spectrum diagrams of Voice command

Because the playing position of the warning sound is fixed and the vehicle is in motion, the sound heard by the human ear is affected by the Doppler effect, and the characteristics of the collected sound signal also exhibit a frequency shift [29]. Therefore, there was a difference between the frequency characteristics of the three warning sounds that were captured under mobile and static conditions.

4.2. Pupil diameter

After data processing using the Statistical Package for the Social Sciences (SPSS) software, the pupil diameter statistics of drivers before and after hearing the warning sounds and the significance analysis results were obtained, as listed in Tables 2 and 3, respectively.

Table 2. Statistics of the pupil diameter of the driver

	Min (mm)	Max (mm)	Mean (mm)	Standard deviation (mm)
No fire alarm (front)	4.70	5.30	4.99	0.18
Fire alarm	5.10	5.40	5.25	0.09
No dynamic music (front)	4.90	5.50	5.28	0.16
Dynamic music	5.10	5.40	5.27	0.09
No voice command (front)	5.70	6.10	5.92	0.09
Voice command	5.90	6.00	5.96	0.05

Note: "Front" refers to the measurements obtained 5 s prior to the warning sound.

Table 3. T-test of paired samples of the pupil diameter of the driver

Pairing type	Mean (mm)	Standard deviation (mm)	T value	P value
No fire alarm (front) – Fire alarm	–0.26	0.18	–6.75	0.00
No dynamic music (front) – Dynamic music	0.01	0.14	1.02	0.32
No voice command (front) – Voice command	–0.04	0.08	–3.54	0.00

The results listed in Table 1 show that, after the driver heard the fire alarm, the pupil diameter expanded approximately 0.26 mm (5.16%). After hearing dynamic music, the pupil diameter shrunk by approximately 0.01 mm (0.19%). After hearing the voice command, the pupil diameter expanded marginally by approximately 0.04 mm (0.68%). Moreover, the fire alarm and voice command demonstrated a significant impact on the pupil diameter of the driver, whereas the dynamic music did not have a significant impact on the pupil diameter.

The standard deviation of the change in pupil diameter shows that the dispersion of pupil diameter decreased after the driver heard the three warning sounds, and the fluctuation in pupil diameter after hearing the fire alarm, music, and vocal command decreased by 51.49, 43.21, and 42.84%, respectively, indicating that the drivers attempted to maintain a stable state of the eye and reduce the fluctuation of pupil diameter after hearing the warning sound in the tunnel.

4.3. Blink duration

After data processing using the SPSS software, the statistics of the blink duration of the driver before and after hearing the warning sounds were obtained, as listed in Table 4.

Table 4. Statistics of the blink duration of the driver

	Min (mm)	Max (mm)	Mean (mm)	Standard deviation (mm)
No fire alarm (front)	299.20	465.50	374.05	87.43
Fire alarm	332.50	365.80	349.13	19.20
No dynamic music (front)	166.20	930.90	512.99	295.41
Dynamic music	199.50	631.80	384.87	168.32
No voice command (front)	299.30	897.90	422.57	147.88
Voice command	365.70	598.70	419.00	101.47

From Table 4, we can observe that the duration of blinking is shortened to varying degrees after the driver heard the three warning sounds. Specifically, the duration of blinking in the sections where the fire alarm, dynamic music, voice command were broadcast is reduced by approximately 24.93 ms (6.66%), 128.11 ms (25%), and 3.57 ms (0.84%), respectively. A paired t-test (Table 5) shows that the three warning sounds had no significant impact on the blink duration of the driver.

Table 5. T-test of paired samples of the blink duration of the driver

Pairing type	Mean (mm)	Standard deviation (mm)	T value	P value
No fire alarm (front) – Fire alarm	24.93	91.57	0.54	0.62
No dynamic music (front) – Dynamic music	128.11	368.58	0.92	0.39
No voice command (front) – Voice command	6.24	177.42	0.08	0.94

The standard deviation of the blink duration of the driver in the three warning-sound zones decreased by varying degrees. The standard deviation of the blink duration in the sections where the fire alarm, dynamic music, and voice commands were broadcast decreased by 78.04, 43.02, and 31.38%, respectively. The change in the standard deviation of the blink duration indicates that the blink duration fluctuates marginally after the driver hears the warning sound, reflecting that the driver controls the eye movement.

4.4. Focus

Through Eq. (3.3) the one-step transfer probability of drivers in an environment with or without warning sound was obtained as shown below.vadjust

$$
\begin{cases}
P_{\text{fire-front}} = \begin{bmatrix} 0.97 & 0 & 0 & 0.03 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.33 & 0 & 0 & 0.67 \end{bmatrix} \\
P_{\text{fire}} = \begin{bmatrix} 0.96 & 0.01 & 0 & 0.03 \\ 0.5 & 0.25 & 0.25 & 0 \\ 0 & 1 & 0 & 0 \\ 0.67 & 0 & 0 & 0.33 \end{bmatrix} \\
P_{\text{fire-back}} = \begin{bmatrix} 0.98 & 0 & 0 & 0.02 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.67 & 0 & 0 & 0.33 \end{bmatrix}
\end{cases}
\tag{4.1}
$$

$$
\begin{cases}
P_{\text{music-front}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \\
P_{\text{music}} = \begin{bmatrix} 0.95 & 0.02 & 0.02 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \\
P_{\text{music-back}} = \begin{bmatrix} 0.95 & 0 & 0.05 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\end{cases}
\qquad
\begin{cases}
P_{\text{voice-front}} = \begin{bmatrix} 0.98 & 0 & 0 & 0.02 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.67 & 0 & 0 & 0.33 \end{bmatrix} \\
P_{\text{voice}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \\
P_{\text{voice-back}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\end{cases}
$$

The results of Eq. (4.1) show that the focus of the driver was mainly on Area 1 (the road ahead), which is consistent with the statistical results of Shang [26], followed by the interior of the vehicle cabin, and finally the left- and right-side walls. Moreover, the gaze of the driver on both sides of the tunnel was almost concomitant; that is, the driver checked both rear-view mirrors on the sides almost concurrently.

With respect to the one-step transfer path between the focus areas, the focus of the driver was primarily transferred between the frontal view and the area inside the cab. Moreover, every time the driver looked at the areas on the left or right, their gaze generally shifted to the front of the road in the next step.

The three calculation results indicate that, before the warning sounds, the focus of the driver was mainly on the road ahead, followed by the interior of the cab, and no attention was focused on the areas on both sides. However, after hearing the fire alarm and dynamic music, the driver increasingly focused on the left- and right-side walls. Conversely, after hearing the voice command, the driver was focused on the front of the road and did not gaze at other visual areas. After the warning sound disappeared, the driver hardly gazed at both sides.

5. Discussion

The reduction in the standard deviation of pupil diameter and blink duration after the three warning sounds indicates that drivers control their eye movements and reduce fluctuations to cope with the new driving environment after hearing the warning sound.

After hearing the fire alarm and voice command, the pupil diameter of the driver expanded and showed a significant impact on driver attention. When listening to dynamic music, the pupil diameter of the driver decreased. When considering the evaluation index of blink duration, when the driver heard the three warning sounds, the blink duration was shortened, but there was no significant impact on the blink duration. When considering the evaluation results of pupil diameter and blink duration in combination with previous relevant achievements [22–24], we can note that fire alarms and voice commands will increase the mental load of drivers, being consistent with the findings of Yang [21]; however, the difference in the results makes it impossible to judge whether their impact on the mental load is significant. For dynamic music, the two evaluation indicators demonstrated inconsistent results; however, we can conclude that the dynamic music has no significant impact on the mental load of the driver, being consistent with the findings of Yang [21].

The fire alarm and dynamic music significantly increased the gaze of the driver on both sides of the tunnel, whereas the voice command had no effect on the gaze area, indicating that different sounds have different effects on the gaze area of drivers. Pairing analysis was conducted on the fixation point coordinates of the driver (Table 6). The results show that 75% of the pairing types had significant differences, which proved that the addition

Table 6. T-test of paired samples of the fixation point coordinates of the driver

Gazing direction	Pairing type	Mean	Standard deviation	T value	P value
X axis (Horizontal)	No fire alarm (front) – Fire alarm	33.70	58.43	3.00	0.01
	Fire alarm – No fire alarm (back)	–23.48	50.08	–4.32	0.00
	No dynamic music (front) – Dynamic music	–7.42	31.02	–1.37	0.18
	Dynamic music – No dynamic music (back)	–30.00	87.59	–2.32	0.03
	No voice command (front) – Voice command	1.21	40.47	0.17	0.87
	Voice command – No voice command (back)	37.91	43.39	4.87	0.00
Y axis (Vertical)	No fire alarm (front) – Fire alarm	2.85	143.42	0.10	0.92
	Fire alarm – No fire alarm (back)	–22.48	73.37	–2.82	0.01
	No dynamic music (front) – Dynamic music	15.21	22.38	3.90	0.00
	Dynamic music – No dynamic music (back)	53.63	33.98	10.71	0.00
	No voice command (front) – Voice command	–24.78	62.81	-2.20	0.04
	Voice command – No voice command (back)	40.61	35.77	6.32	0.00
	No fire alarm (front) – Fire alarm	2.85	143.42	0.10	0.92

Note: "Back" refers to the measurements obtained 5 s after to the warning sound.

of warning sounds had a significant impact on the x (horizontal), y (vertical) fixation points of the driver. We speculated that most tunnels have only traffic noise; however, broadcasting fire alarms or dynamic music will attract the attention or curiosity of the driver. By increasing the focus of the driver on the two walls of the tunnel, drivers would have a better understanding of what happens in the tunnel. The voice command of "Please pay attention to safety", only reminds the driver to exercise safe behavior; therefore, it does not interfere with the watching behavior of the driver.

6. Conclusions

1. Different warning sounds exhibited different effects on the mental load of the driver. Fire alarms and voice commands increased the mental load of drivers; however, the significance of the impact is unknown. Dynamic music had no significant effect on the mental load of the driver.
2. The type of warning sound also showed different effects on driver attention. Among them, the fire alarm and dynamic music had a significant impact, leading the greater attention of the driver on both sides of the tunnel; however, the voice commands did not affect driver attention.

The major limitation of this study is not a large sample of drivers and one field tunnel which due to warning sounds in expressway tunnels is still in the pilot stage, the application of tunnels is rare and not always in working condition.

Acknowledgements

We acknowledge the National Natural Science Foundation of China (No. 51878107, 52108362) and the Science and Technology Research Project of China Railway Fourth Survey and Design Institute Group Co., Ltd (No. 2017K075-1) for providing funding, and Editage for English language editing.

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Received: 2022-11-18, Revised: 2023-03-28

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