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Research Paper

Evaluating the Effects of Speech-Based Auditory Warnings on Safe Driving Behavior among Young Drivers

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Abstract

This study evaluated the effects of speech-based auditory warnings on safe driving behavior in high-risk situations using a high-fidelity driving simulator. Utilizing a within-subject design, 36 young drivers navigated an urban scenario under two conditions: "with" and "without" auditory warnings. Warnings consisted of brief Persian voice messages (e.g., reduce your speed, hazard ahead) delivered at predefined critical moments before hazardous events. Behavioral and vehicle-related indicators including collisions, speed limit exceedances, velocity, braking intensity, accelerator pedal input, engine RPM, and seat-belt use were recorded via simulator logs and analyzed using paired statistical tests. The auditory warnings significantly enhanced safety metrics: mean collisions with vehicles, pedestrians, and fixed objects decreased by 80%, 76%, and 56%, respectively, while speed limit exceedances dropped by 53%. During critical events, warnings prompted lower speeds, reduced accelerator input, lower engine RPM, and increased braking intensity. Seat-belt compliance also improved; however, as no explicit seat-belt warning was provided and the condition order was fixed, this remains an exploratory finding. Overall, this pilot study suggests that speech-based auditory warnings can significantly improve key indicators of safe driving behavior among young drivers in simulated environments. Nonetheless, generalizing these short-term findings to real-world driving requires future research with randomized or counterbalanced condition order and larger sample sizes.

Keywords: Speech-based Auditory Warning, Driving Simulator, Driver Behavior, Young Drivers

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1. Introduction

Road traffic crashes are among the most important challenges in transportation safety and public health worldwide. According to the World Health Organization's Global Status Report on Road Safety 2023, approximately 1.19 million people die each year as a result of road traffic crashes, and road traffic injuries remain a major cause of death, particularly among children and young people aged 5 to 29 years (WHO, 2023). Therefore, reducing crash risk and improving drivers' safe behavior have become central priorities in traffic safety policy and research.

Among the factors contributing to road crashes, driver behavior and perceptual, decision-making, and control-related errors play a substantial role. Factors such as distraction, fatigue, inappropriate speed, delayed reaction, and failure to detect hazards in time can increase the likelihood of crashes (Treat et al., 1977). Accordingly, in recent years, the development of driver assistance systems and in-vehicle warning systems has received considerable attention, particularly for enhancing drivers' situational awareness and reducing reaction time. Warning systems can alert drivers to potential hazards through visual, auditory, tactile, or multimodal stimuli (Ju, Chuang, & Wallraven, 2022). Although visual warnings can provide precise and observable information, they depend on visual attention and may increase drivers' cognitive load in certain situations. In contrast, auditory warnings can attract drivers' attention to hazardous situations without requiring them to shift their gaze away from the road. Among auditory warnings, speech-based messages have particular potential for high-risk driving situations because they can communicate information in a direct, meaningful, and easily understandable manner (Liu, Wu, Ma, & Yang, 2023). Previous studies have shown that auditory and multimodal warnings can reduce drivers' reaction time, limit risky behaviors, and improve decision-making in critical situations (Ju et al., 2022; Kaizuka & Nakano, 2020; Liu et al., 2023). However, the effectiveness of such warnings depends on several factors, including warning timing, message content, message length, sound intensity, urgency level, and suitability to the driver's situation. In addition, excessive, inappropriate, or delayed warnings may increase cognitive load, cause auditory annoyance, or reduce drivers' sensitivity to warnings over time. Therefore, the design and empirical evaluation of speech-based auditory warnings, particularly under controlled simulated conditions, are of considerable importance. Despite the growing body of research on in-vehicle warning systems, three specific gaps remain. First, most empirical studies have been conducted in non-Iranian settings, and limited evidence is available on speech-based auditory warnings adapted to the Persian language and the driving context of Iranian drivers. This contextual gap is particularly important for young drivers, who are considered a high-risk group because of their relatively limited driving experience, greater tendency toward risk-taking, and higher likelihood of perceptual and decision-making errors (Faridiaghdam, Mirzahossein, Rassafi, & Khanpour, 2025). Moreover, the comprehension, perceived urgency, and behavioral effectiveness of speech warnings may vary according to language, message familiarity, and cultural context. Second, previous studies have frequently examined nonverbal alerts, auditory icons, multimodal warning systems, or specific applications such as forward-collision warnings. Consequently, the independent contribution of semantically meaningful speech-based messages to driving behavior remains insufficiently understood. Third, much of the existing literature has focused on a single hazard type or a limited number of outcomes, such as warning recognition, reaction time, or crash occurrence. Therefore, less is known about whether speech-based warnings are associated with a coherent pattern of change across multiple direct safety outcomes and vehicle-control responses. The present pilot study addresses these gaps in three ways. First, it evaluates brief Persian speech-based auditory warnings among predominantly young Iranian drivers, thereby providing context-specific evidence from a population and linguistic setting that have received limited empirical attention. Second, it examines speech warnings as a distinct auditory intervention rather than as one component of a multimodal warning system. Third, it evaluates multiple hazard types and simultaneously considers direct safety outcomes, including collisions and speed-limit exceedances, together with vehicle-control indicators such as speed, braking intensity, accelerator pedal input, and engine RPM. This integrated assessment extends previous research by examining whether speech-based warnings are associated with coordinated behavioral and vehicle-control adjustments across different critical situations. Given the fixed order of the experimental conditions, however, the contribution of the study should be interpreted as preliminary evidence of association rather than definitive causal evidence.

The main objective of this study is to evaluate whether presenting speech-based auditory warnings at critical moments in a driving simulator may be associated with reductions in risky behaviors and improvements in safer driving responses. It is expected that auditory warnings will be associated with fewer collisions, fewer speed limit exceedances, lower speed, lower accelerator pedal input, lower engine RPM, and higher braking intensity. Seat-belt use is also examined as a complementary and exploratory indicator. However, given the pre–post design, the fixed order of the two conditions, and the absence of an independent control group, the findings are interpreted as preliminary and pilot evidence.

Based on the theoretical background, identified research gaps, and the expected effects of speech-based auditory warnings on driving behavior indicators, the conceptual framework of the present study is presented in Table 1.

2. Literature Review

Vehicle safety and driver behavior are central topics in traffic safety research and intelligent transportation systems. In general, vehicle safety technologies can be classified into passive and active safety systems. Passive safety focuses on reducing injury severity after a crash has occurred, whereas active safety aims to prevent crashes or reduce their likelihood through systems such as emergency braking, stability control, collision warnings, and other driver assistance systems (Ostermaier & Sandner, 2023; Toshev & Minchev, 2023). In this context, in-vehicle warning systems are considered an important component of active safety because they can draw the driver’s attention to potential hazards before a critical situation occurs and provide an opportunity for a safer response.

In-vehicle warnings can be presented through visual, auditory, tactile, or multimodal formats. Visual warnings usually provide precise and observable information, but they depend on the driver’s visual attention and may be limited in situations where drivers need to keep their gaze on the road. In contrast, auditory warnings can communicate hazard-related information without requiring drivers to shift their gaze, making them suitable for emergency situations. However, the effectiveness of auditory warnings depends on several characteristics, including sound type, message content, message length, sound intensity, urgency level, and warning timing. Previous studies have shown that auditory warnings can contribute to faster hazard detection and behavioral adjustment by drivers (Liu et al., 2023; Sabic, Mishler, Chen, & Hu, 2017).

Table 1. Conceptual framework of the expected effects of speech-based auditory warnings on driving behavior indicators

Independent variable	Behavioral or vehicle-related indicator	Expected direction of change in the warning condition
Speech-based auditory warning	Number of collisions with vehicles, pedestrians, and fixed objects	Decrease
Speech-based auditory warning	Number of speed limit exceedances	Decrease
Speech-based auditory warning	Speed during critical events	Decrease
Speech-based auditory warning	Accelerator pedal input	Decrease
Speech-based auditory warning	Engine RPM	Decrease
Speech-based auditory warning	Braking intensity	Increase
Speech-based auditory warning[a]	Seat-belt use	Possible increase; interpreted as a complementary and exploratory indicator

Note. [a] No seat-belt-specific auditory warning was presented in this study. Seat-belt use was recorded only as a complementary and exploratory behavioral indicator; therefore, any between-condition change should not be interpreted as a direct effect of the warning content.

Sabic et al. (Sabic et al., 2017) examined different types of in-vehicle auditory warnings, including speech, spearcons, and auditory icons, and showed that warning type can affect recognition speed and response accuracy. Although this study is valuable for auditory warning design, it was conducted as a warning recognition task in a human–computer interaction setting and did not assess actual driving behavior or vehicle dynamics. Therefore, while this source is useful for understanding auditory warning design, it is not sufficient for evaluating driver behavior in high-risk driving scenarios.

In the context of driving simulators, Wu et al. investigated the effectiveness of auditory forward collision warning alerts and showed that auditory warning characteristics can influence drivers' avoidance behavior, reaction time, and response intensity. This study demonstrates the importance of auditory warnings in collision prevention; however, its focus was mainly on forward collision scenarios and it did not examine other behavioral and vehicle-related indicators such as accelerator pedal input, engine RPM, or protective driving behavior. Similarly, Ju et al. showed in a virtual reality study that acoustic cues can increase drivers' situational awareness in accident-prone situations. However, that study focused on acoustic and visual cues in a virtual reality environment and did not specifically examine Persian speech-based messages or Iranian drivers.

Another body of literature has focused on warning design characteristics, including urgency, timing, and multimodal presentation. Kaizuka and Nakano showed that the urgency level of audiovisual collision warnings can affect drivers' response time and steering accuracy. Wang et al. examined multimodal warning design for in-vehicle robots and showed that message content, speech rate, and coordination between speech and visual cues can affect driving safety and driver workload. Yue et al. also emphasized, in a driving simulator study, that warning timing and warning level may produce different effects on driver behavior across scenarios such as approaching a bus stop, roadside parking, and pedestrian crossings. These studies indicate that warning effectiveness does not depend merely on the presence of a warning; rather, message design, urgency level, and timing play determining roles.

In addition to warning-related studies, research on young drivers is also of particular importance. Faridiaghdam et al. (Faridiaghdam et al., 2025), in a driving simulator-based study, showed that situational awareness, driving skills, risky violations, and crash history are interrelated among young drivers. This finding supports the selection of the target population in the present study, as young drivers are often considered an important group in traffic safety research due to their lower driving experience and higher likelihood of perceptual and decision-making errors. However, that study did not examine an intervention such as auditory warning.

The review of previous studies indicates that, despite substantial evidence on the effects of auditory and multimodal warnings on driver behavior, several research gaps remain. First, many studies have been conducted in non-Iranian contexts, and empirical evidence regarding auditory warnings adapted to the language and culture of Iranian drivers is limited. Second, in many studies, auditory warnings have been examined in the form of alarms, beeps, or nonverbal cues, while the independent role of speech-based auditory messages has received less attention. Third, most studies have focused on a limited number of outcomes, such as reaction time, warning recognition, or forward collision, whereas the simultaneous evaluation of indicators such as collisions, speed limit exceedances, speed, braking intensity, accelerator pedal input, engine RPM, and seat-belt use can provide a more comprehensive picture of drivers' responses to warnings.

Accordingly, the contribution of the present study lies not merely in testing whether an auditory warning produces a statistically significant response, but in examining whether localized and semantically explicit Persian speech messages are associated with a consistent pattern of safer behavior across multiple hazardous situations. By combining collision-related outcomes with speed and pedal-based vehicle-control indicators, the study provides a broader behavioral profile of drivers' responses than studies limited to warning recognition, reaction time, or a single forward-collision scenario. Nevertheless, because the no-warning condition always preceded the warning condition, the findings are positioned as pilot evidence that should be verified through randomized or counterbalanced experimental designs. The position of the present study relative to previous research is summarized in Table 2.

3. Methodology

This study used a within-subject experimental design with a pre–post structure. In this design, each participant completed an urban driving scenario under two conditions: first, the control condition, referred to as "no-warning condition," and then the intervention condition, referred to as "with speech-based auditory warning." The purpose of this design was to compare within-participant behavioral changes between the two conditions while reducing the influence of individual differences such as driving style, skill level, and responsiveness.

Given the exploratory and pilot nature of the study, the two experimental conditions were administered in a fixed sequence for all participants: the no-warning condition was completed first, followed by the speech-based auditory warning condition. This sequence was selected to reduce the possibility of carryover from the warning condition to a subsequent no-warning condition. In particular, prior exposure to semantically explicit warning messages could have informed participants not only about the locations of the hazardous events but also about the expected behavioral response, such as reducing speed or preparing to brake. Such prior knowledge could have contaminated performance in a later no-warning trial.

Table 2. Summary of previous studies on in-vehicle warnings and the position of the present study

Reference	Warning type or study focus	Study context	Main finding	Relevance to the present study and remaining gap
(Sabic et al., 2017)	Auditory warnings, including speech, spearcons, and auditory icons	Warning recognition task in a human–computer interaction setting	The type of auditory warning can affect recognition speed and response accuracy.	Useful for auditory warning design, but it did not use a driving simulator or assess behavioral or vehicle-related driving indicators.
(Wu, Boyle, Marshall, & O'Brien, 2018)	Auditory forward collision warning alerts	Driving simulator	Auditory warning characteristics can influence drivers' avoidance behavior, reaction time, and response intensity.	Highlights the role of auditory warnings in collision prevention, but mainly focuses on forward collision and does not examine indicators such as accelerator pedal input, engine RPM, or seat-belt use.
(Ju et al., 2022)	Acoustic and visual cues	Virtual reality-based driving simulator	Acoustic cues can increase drivers' situational awareness in accident-prone situations.	Relevant to the role of auditory stimuli in improving situational awareness, but it did not examine Persian speech-based messages or Iranian drivers.
(Kaizuka & Nakano, 2020)	Audiovisual collision warnings with different urgency levels	Simulated avoidance maneuver study	Warning urgency can affect drivers' response time and steering accuracy.	Emphasizes the importance of warning urgency, but does not focus on speech message content or warning language.
(Wang et al., 2022)	Multimodal warnings including speech and visual cues	Driving simulator and in-vehicle robot	Message content, speech rate, and coordination between speech and visual cues can affect driving safety and driver workload.	Relevant to speech message design, but speech was examined as part of a multimodal system rather than as an independent Persian auditory warning.
(Yue et al., 2025)	In-vehicle warning strategies	Driving simulator	Warning timing and warning level can produce different effects on driver behavior across driving scenarios.	Emphasizes warning timing and warning level, but does not focus on Persian speech-based warnings or young Iranian drivers.
(Faridiaghdam et al., 2025)	Situational awareness, driving skills, violations, and crash history	Driving simulator	Situational awareness, driving skills, risky violations, and	Supports the selection of young drivers as the target population, but does not

Reference	Warning type or study focus	Study context	Main finding	Relevance to the present study and remaining gap
	among young drivers		crash history are interrelated among young drivers.	examine an intervention such as auditory warning.
Present study	Persian speech-based auditory warnings	Driving simulator in Iran	Evaluates the effects of warnings on collisions, speed limit exceedances, speed, braking intensity, accelerator pedal input, engine RPM, and seat-belt use.	Focuses on young Iranian drivers, Persian speech-based messages, and the simultaneous analysis of multiple behavioral and vehicle-related driving indicators.

Nevertheless, the fixed sequence introduces an important methodological limitation. Because the same route and hazardous events were encountered twice, participants may have performed differently in the second run because of practice with simulator controls, greater familiarity with the route, anticipation of previously encountered hazards, or reduced anxiety and cognitive demand after the first exposure. These order-related influences cannot be separated statistically from the warning condition because the condition order was neither randomized nor counterbalanced. Consequently, the observed between-condition differences may reflect the combined influence of the auditory warnings and repeated exposure to the scenario. The findings are therefore interpreted as preliminary within-participant associations rather than definitive causal effects of the warnings.

3.1. Participants

The study population consisted of young drivers with basic driving experience. Participants were selected from students at Imam Khomeini International University using convenience sampling. A total of 36 individuals participated in the study, including 24 men and 12 women. The mean age of participants was 24.19 years, with a standard deviation of 4.59 years. Thus, most participants belonged to the young driver age group.

The inclusion criteria were having a driving license or basic driving experience, sufficient vision and hearing, the ability to operate the driving simulator, and no severe sensitivity to simulated environments. Before the experiment began, the general objectives of the study were explained to the participants, and all participants provided informed consent. They were also assured that the recorded data would be used solely for research purposes and that their personal information would remain confidential.

Considering the pilot nature of the study, the time limitations of the experimental procedure, and the time required for each simulator session, a sample size of 36 participants was selected as an initial and feasible sample. The purpose of this sample size was to provide preliminary evidence regarding the effects of speech-based auditory warnings and to establish a basis for future studies with larger samples and higher statistical power.

3.2. Apparatus and Experimental Environment

The experiment was conducted using a driving simulator. The simulator included a steering wheel, accelerator pedal, brake pedal, display, and driving scenario software. The simulated environment represented an urban driving route in which traffic conditions and hazardous events were predefined. For the purposes of this study, a “critical event” was operationally defined as a preprogrammed and time-stamped hazardous situation that required an immediate vehicle-control response, such as reducing speed, releasing the accelerator, or braking, to avoid or reduce the likelihood of a collision. Three critical events were included: (1) a pedestrian suddenly entered the vehicle's travel path; (2) a lead vehicle stopped abruptly, requiring an immediate car-following response; and (3) a fixed obstacle obstructed the travel path. The events were presented at predefined points in the same sequence and under identical route, traffic, speed-limit, and environmental conditions for all participants in both experimental conditions. The simulator timestamp marking the onset of each event was used to align the corresponding behavioral and vehicle-control data.

In each scenario, the driving route, event arrangement, traffic intensity, speed limits, and environmental conditions were identical for all participants. The simulator software automatically recorded behavioral and vehicle-related driving data. These data included speed, accelerator pedal input, braking intensity, engine RPM, number of collisions, and number of speed limit exceedances. Accelerator pedal input and braking intensity were recorded on a normalized scale from 0 to 1, where 0 indicated no pedal use and 1 indicated maximum pedal pressure. Speed was recorded based on the simulator output in centimeters per second. Engine RPM was extracted in revolutions per minute.

The critical events and warning delivery points were predefined and time-stamped in the software. This procedure ensured that the timing of events and the extraction windows for behavioral indicators were aligned and comparable between the no-warning and warning conditions as much as possible. Figure 1 shows the driving simulator used in this study.

3.3. Characteristics of the Speech-Based Auditory Warnings

In the intervention condition, speech-based auditory warnings were played at predefined points before drivers encountered hazardous situations. The warnings were designed as brief Persian voice messages, aiming to attract the driver's attention to the upcoming hazard and provide sufficient time for a safer response. Examples of the warning messages included "reduce your speed," "hazard ahead," and "be careful."

The warning messages were designed based on three principles: brevity, clarity, and relevance to the hazardous situation. Each message lasted approximately two seconds to avoid excessive message length and increased cognitive load. Warning timing was set in an anticipatory manner; that is, the message was presented before the driver reached the hazardous point, allowing sufficient time for speed reduction, braking, or behavioral adjustment. The sound intensity of the messages was kept uniform and clearly audible for all participants to minimize between-participant differences caused by auditory stimulus intensity.

In this study, the warnings were specifically designed for critical driving situations, and no separate message regarding seat-belt use was provided. Therefore, seat-belt use was recorded as a complementary and exploratory behavioral indicator, and changes in this variable were interpreted with caution.

3.4. Variables and Indicators

The independent variable of the study was the presence or absence of speech-based auditory warnings, defined at two levels: "no-warning condition" and "with speech-based auditory warning." Because each participant experienced both conditions, the comparison of indicators was conducted within participants.

The dependent variables consisted of a set of behavioral and vehicle-related driving indicators. These indicators were selected to cover both direct safety outcomes and drivers' control-related responses.

Figure 1. Driving Simulator

First, the number of collisions was recorded in three categories: collisions with other vehicles, collisions with pedestrians, and collisions with fixed objects. These indicators were considered direct safety outcomes.

Second, the number of speed limit exceedances was recorded. This indicator reflected the extent to which drivers exceeded the speed limits defined in the scenario and was analyzed as a risky driving behavior.

Third, drivers' speed during three critical events was extracted. For each event, the mean speed within the corresponding event window was calculated based on the time-stamped simulator logs. A reduction in speed within these windows was considered an indicator of a more cautious response to the hazard.

For each critical event, speed, braking intensity, accelerator pedal input, and engine RPM were extracted from an event-specific interval defined by the simulator timestamps marking the beginning and end of the hazardous event. The same temporal boundaries were applied to all participants and in both experimental conditions. This interval was selected to capture the driver's immediate vehicle-control response to the developing hazard while minimizing the inclusion of unrelated driving behavior before the event and recovery behavior after the immediate response. The mean value of each continuous indicator within the predefined event window was used in the statistical analysis.

Fourth, braking intensity was examined during the three critical events. This indicator was recorded on a normalized scale from 0 to 1, and an increase in the warning condition may indicate a more active response to the hazard.

Fifth, accelerator pedal input was extracted during the critical events. A reduction in this indicator in the warning condition may reflect a lower tendency to continue accelerating or maintain risky behavior at the moment of hazard exposure.

Sixth, engine RPM was recorded for each critical event. This variable was used as a complementary vehicle-related indicator for analyzing acceleration patterns and vehicle control.

Seventh, seat-belt use was recorded as a binary variable, classified as either "unfastened" or "fastened," in each experimental condition. This indicator was used to assess one of the basic individual safety behaviors. Because the auditory warnings did not directly refer to seat-belt use, this variable was analyzed as a complementary and exploratory indicator.

3.5. Experimental Procedure

At the beginning, a short orientation session was held for each participant. During this session, the general purpose of the study was explained how to operate the driving simulator, the experimental procedure, and participants' rights. Informed consent was then obtained, and the inclusion criteria, including the ability to operate the simulator, sufficient vision and hearing, and absence of severe sensitivity to the simulated environment, were checked.

Before the main test began, individual simulator settings were adjusted for each participant. These settings included seat height, appropriate distance from the steering wheel and pedals, display field of view, and warning sound level. Participants then completed a short practice drive on a standard route without critical events to become familiar with vehicle dynamics, steering and pedal sensitivity, and the simulator environment. This stage was included to reduce the influence of initial unfamiliarity with the simulator.

After the practice stage, each participant completed the main scenario twice. In the first run, the scenario was conducted no-warning conditions, and the driver's behavioral data were recorded under the control condition. After the first run, a short rest break was provided. The same scenario was then conducted under the second condition, with speech-based auditory warnings. In this condition, warning messages were played at predefined points before participants reached hazardous situations.

In both runs, the route, critical events, speed limits, traffic arrangement, and environmental conditions were identical. The start and end of the scenario, the occurrence of critical events, and the timing of warning messages were automatically recorded in the software reports. During the experiment, an experienced observer was present to ensure correct implementation of the instructions, absence of secondary tasks, avoidance of unnecessary conversation, and adherence to standardized experimental conditions. To reduce procedural bias, environmental conditions such as lighting, room temperature, ambient noise, and instruction wording were kept similar for all participants.

3.6. Data Preparation and Quality Assurance

After the experiments were completed, the simulator log data were checked for completeness, readability, and potential recording errors. Files with serious defects, interrupted recording, or corrupted data were considered for exclusion from the analysis. The temporal alignment of critical events between the two conditions was also examined to ensure that behavioral and vehicle-related indicators were extracted from comparable time windows. For continuous variables such as speed, braking intensity, accelerator pedal input, and engine RPM, extreme outliers were identified and flagged using an absolute standardized score greater than 3. Given the pilot nature of the study and the limited sample size, extensive data removal was not performed. When outliers were present, sensitivity analyses with and without these values could be reported as supplementary analyses to determine the extent to which the main findings were influenced by extreme values.

Because the data were automatically recorded by the simulator software, errors related to manual recording or inter-rater differences were minimized. In addition, the definitions of critical events, warning delivery points, and data extraction windows were specified before analysis to reduce the possibility of bias in data selection.

3.7. Validity and Reliability Assessment

To ensure the content validity of the auditory warnings, the message texts and their delivery timing were designed based on the literature on auditory warnings, in-vehicle warning systems, and driver behavior. The proposed messages were then reviewed by a five-member expert panel in the fields of traffic safety, driving psychology, and warning systems. The experts evaluated each warning in terms of necessity, relevance to the hazardous situation, message clarity, brevity, and avoidance of unnecessary stress.

For the quantitative assessment of content validity, the content validity index (CVI) and content validity ratio (CVR) were used. The results showed that the CVI values of the designed warnings were above the acceptable threshold of 0.78. Given the number of experts, only warnings that were judged to have sufficient necessity and relevance were retained in the final version. Accordingly, the final messages were considered content-valid for use in the experimental scenarios.

In terms of face validity, the driving scenarios, critical events, traffic arrangement, and speed limits were reviewed by experts and the research observer. Necessary adjustments were made to the location of events, event sequence, and warning timing to make the scenarios as realistic, repeatable, and consistent with the study objectives as possible.

To examine the reliability of data recording, preliminary trials were conducted before the main data collection to assess the stability of simulator performance, the accuracy of log recording, and the repeatability of critical events. In a short-interval test–retest assessment, correlation coefficients for key indicators, including speed, braking intensity, accelerator pedal input, engine RPM, and the number of speed limit exceedances, were above 0.70, indicating acceptable measurement stability in the simulator environment (Polit & Beck, 2006). Given the pilot nature of the study, the validity and reliability results were interpreted mainly as evidence supporting the quality of the experimental setup and as a basis for larger future studies.

3.8. Ethical Considerations

Before participating in the experiment, the general purpose of the study was explained to the participants, and informed consent was obtained. Participants had the right to withdraw from the study at any stage. Personal information and recorded data were kept confidential, and the analyses were conducted at the group level. In addition, because the experiment was conducted in a simulator environment, participants were not exposed to real driving risk. If discomfort, dizziness, or simulator-related symptoms occurred, the test could be stopped for the participant.

3.9. Data Analysis

The simulator data were organized for each participant under the two conditions: “no-warning condition” and “with speech-based auditory warning.” Descriptive statistics, including mean, standard deviation, frequency, and percentage, were first calculated for the study variables. Paired statistical tests were then used to compare behavioral and vehicle-related indicators between the two conditions.

For continuous variables, including speed, braking intensity, accelerator pedal input, and engine RPM, the distribution of the differences between the two conditions was first examined. If the normality assumption for the paired differences was met, the paired-samples t-test was used. If this assumption was violated, the nonparametric Wilcoxon signed-rank test was used as an alternative or complementary analysis.

For count variables, including the number of collisions and the number of speed limit exceedances, the Wilcoxon signed-rank test was also used as a complementary analysis in addition to mean comparisons, because these variables were count-based and might not follow a normal distribution. For comparing seat-belt use between the two conditions, McNemar’s test was used because this variable was binary and paired.

The statistical significance level was set at 0.05. To provide a consistent interpretation of practical significance, effect sizes and confidence intervals were reported alongside all significance tests. For continuous variables analyzed using paired-samples t-tests, Cohen’s dz was used as the standardized effect-size metric because all measurements were obtained from the same participants under two experimental conditions. Cohen’s dz was calculated based on the mean paired difference and the standard deviation of the paired differences.

For count-based outcomes analyzed using the Wilcoxon signed-rank test, a nonparametric paired effect-size measure was used because these variables do not represent continuous normally distributed outcomes. For the binary seat-belt use outcome, the absolute paired difference in proportions was reported because it provides a direct interpretation of the behavioral change. Therefore, although different effect-size measures were selected according to the measurement scale of each outcome, a consistent reporting framework based on effect magnitude and confidence intervals was applied throughout the manuscript.

4. Results

This section first presents the descriptive characteristics of the participants and then reports the results of comparing behavioral and vehicle-related driving indicators between the "no-warning condition" and "with speech-based auditory warning" conditions. The raw data from the two conditions were matched pairwise for 36 participants. For quantitative variables, means and standard deviations were calculated, and paired statistical tests were used to compare the two conditions. Given the count-based nature of some variables, such as the number of collisions and speed limit exceedances, the Wilcoxon signed-rank test was also conducted as a complementary analysis. For continuous variables, the Wilcoxon test was additionally reported to examine the robustness of the results with respect to the normality assumption of paired differences. For the binary variable of seat-belt use, McNemar's test was used. The significance level was set at 0.05 for all analyses.

4.1. Descriptive Characteristics of Participants

The study sample consisted of 36 young drivers. In terms of gender, 24 participants, equivalent to 66.7% of the sample, were men, and 12 participants, equivalent to 33.3%, were women. The mean age of the participants was 24.19 years, with a standard deviation of 4.59 years. The youngest participant was 18 years old, and the oldest was 37 years old. Regarding age groups, 3 participants, equivalent to 8.3%, were younger than 20 years; 21 participants, equivalent to 58.3%, were between 20 and 25 years old; and 12 participants, equivalent to 33.3%, were older than 25 years. This distribution indicates that most participants belonged to the young driver group (Table3).

4.2. Comparison of Collisions and Speed Limit Exceedances

The results showed that the mean number of collisions in all three categories - collisions with other vehicles, collisions with pedestrians, and collisions with fixed objects - was lower in the auditory warning condition than in the no-warning condition. The number of speed limit exceedances also decreased in the auditory warning condition.

Table 3. Descriptive characteristics of participants

Variable	Category	Frequency	Percentage
Gender	Female	12	33.3
Gender	Male	24	66.7
Gender	Total	36	100
Age	Younger than 20 years	3	8.3
Age	20–25 years	21	58.3
Age	Older than 25 years	12	33.3
Age	Total	36	100

The mean number of collisions with other vehicles decreased from 0.694 in the no-warning condition to 0.139 in the warning condition, corresponding to an 80.0% reduction. The mean number of collisions with pedestrians decreased from 0.805 to 0.194, indicating a 75.9% reduction. Similarly, the mean number of collisions with fixed objects decreased from 0.444 to 0.194, corresponding to a 56.2% reduction. The number of speed limit exceedances also decreased from 2.361 to 1.111, indicating a 52.9% reduction (Table 4).

Because these indicators were count-based, the Wilcoxon signed-rank test was also conducted as a complementary analysis. The Wilcoxon results were consistent with the paired-samples t-test results and confirmed significant reductions in all four indicators. Therefore, the observed reductions in collisions and speed limit exceedances were not solely dependent on the normality assumption and were also supported by nonparametric analysis.

4.3. Comparison of Mean Speed during Critical Events

The results for mean speed during the three critical events showed that drivers' speed was lower in the auditory warning condition than in the no-warning condition across all three events. In the first event, mean speed decreased from 1031.785 to 509.491 cm/s, corresponding to a 50.6% reduction. In the second event, speed decreased from 1050.901 to 426.320 cm/s, indicating a 59.4% reduction. In the third event, speed decreased from 1135.002 to 576.007 cm/s, corresponding to a 49.3% reduction.

The paired-samples t-test results showed that the reduction in speed was statistically significant for all three events. The Wilcoxon signed-rank test was also significant for all three events, confirming the paired-samples t-test results. Cohen's dz indicated large observed effects across the three events, particularly in the third event, where the effect size was higher than in the other events. This finding suggests that the auditory warning condition was associated with lower entry speeds into hazardous zones (Table 5).

4.4. Comparison of Braking Intensity during Critical Events

Braking intensity increased significantly in the auditory warning condition across all three critical events. In the first event, mean braking intensity increased from 0.087 in the no-warning condition to 0.337 in the warning condition, corresponding to a 288.4% increase. In the second event, braking intensity increased from 0.064 to 0.523, indicating a 717.5% increase. In the third event, braking intensity increased from 0.121 to 0.414, corresponding to a 243.4% increase (Table 6).

The paired-samples t-test results showed that the increase in braking intensity was statistically significant for all three events. The Wilcoxon signed-rank test also confirmed these increases. The increase in braking intensity, together with reductions in speed, collisions, and accelerator pedal input, suggests that the auditory warning condition was associated with more active control responses to hazards.

4.5. Comparison of Accelerator Pedal Input during Critical Events

Accelerator pedal input decreased in the auditory warning condition across all three critical events. In the first event, mean accelerator pedal input decreased from 0.233 in the no-warning condition to 0.138 in the warning condition, corresponding to a 40.8% reduction. In the second event, accelerator pedal input decreased from 0.187 to 0.138, indicating a 26.3% reduction. In the third event, this indicator decreased from 0.188 to 0.110, corresponding to a 41.5% reduction (Table 7).

The paired-samples t-test results showed that the reduction in accelerator pedal input was statistically significant for all three events. The Wilcoxon signed-rank test also confirmed the significance of this reduction across the three events. This finding suggests that the auditory warning condition was associated with a lower tendency among drivers to continue accelerating or maintain pressure on the accelerator pedal in critical situations.

4.6. Comparison of Engine RPM during Critical Events

Engine RPM also showed a significant decrease in the auditory warning condition across all three critical events. In the first event, mean engine RPM decreased from 2755.983 rpm in the no-warning condition to 1741.706 rpm in the warning condition, corresponding to a 36.8% reduction. In the second event, engine RPM decreased from 2754.930 to 1703.470 rpm, indicating a 38.2% reduction. In the third event, engine RPM decreased from 2573.364 to 1743.801 rpm, corresponding to a 32.2% reduction (Table 8).

The paired-samples t-test results were significant for all three events, and the Wilcoxon signed-rank test also confirmed these reductions. The decrease in engine RPM, together with reductions in accelerator pedal input and speed, suggests that the auditory warning condition was associated with a moderation of acceleration patterns and a reduction in more aggressive vehicle-control behavior during hazardous moments.

4.7. Comparison of Seat-Belt Use

McNemar's test was used to examine changes in seat-belt use between the two experimental conditions. In the no-warning condition, 18 participants, equivalent to 50.0% of the sample, had fastened their seat-belts, while the other 18 participants had not. In the auditory warning condition, the number of participants with fastened seat-belts increased to 28, equivalent to 77.8%, while the number of participants with unfastened seat-belts decreased to 8, equivalent to 22.2%.

Among the 18 participants who had not fastened their seat-belts in the no-warning condition, 10 fastened their seat-belts in the auditory warning condition. In addition, none of the participants who had fastened their seat-belts in the no-warning condition unfastened them in the auditory warning condition. McNemar's test indicated that this change was statistically significant, $p = 0.002$.

Accordingly, the rate of seat-belt use increased from 50.0% to 77.8%, representing an absolute increase of 27.8 percentage points and a relative increase of approximately 55.6%. However, because no specific warning message about seat-belt use was provided in this study and the order of the two conditions was fixed, this finding should be interpreted as a complementary and exploratory indicator (Table 9).

Table 4. Comparison of collisions and speed limit exceedances between the two conditions

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Number of collisions with other vehicles	0.694 ± 1.142	0.139 ± 0.351	0.556 decrease (0.190 to 0.921)	3.084	0.004	0.514	0.002
Number of collisions with pedestrians	0.805 ± 0.624	0.194 ± 0.401	0.611 decrease (0.393 to 0.829)	5.686	<0.001	0.948	<0.001
Number of collisions with fixed objects	0.444 ± 1.423	0.194 ± 0.856	0.250 decrease (0.016 to 0.484)	2.168	0.037	0.361	0.034
Number of speed limit exceedances	2.361 ± 1.854	1.111 ± 1.833	1.250 decrease (0.611 to 1.889)	3.973	<0.001	0.662	0.001

Table 5. Comparison of mean speed during critical events

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Mean speed in event 1	1031.785 ± 306.924	509.491 ± 209.936	522.294 decrease (371.456 to 673.131)	7.03	<0.001	1.172	<0.001

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Mean speed in event 2	1050.901 ± 343.930	426.320 ± 257.490	624.581 decrease (440.449 to 808.712)	6.886	<0.001	1.148	<0.001
Mean speed in event 3	1135.002 ± 271.074	576.007 ± 203.149	558.996 decrease (485.369 to 632.622)	15.413	<0.001	2.569	<0.001

Table 6. Comparison of braking intensity during critical events

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Braking intensity in event 1	0.087 ± 0.162	0.337 ± 0.299	0.250 increase (0.128 to 0.373)	4.157	<0.001	0.693	<0.001
Braking intensity in event 2	0.064 ± 0.115	0.523 ± 0.227	0.459 increase (0.360 to 0.557)	9.443	<0.001	1.574	<0.001
Braking intensity in event 3	0.121 ± 0.142	0.414 ± 0.169	0.294 increase (0.230 to 0.358)	9.291	<0.001	1.549	<0.001

Table 7. Comparison of accelerator pedal input during critical events

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Accelerator pedal input in event 1	0.233 ± 0.180	0.138 ± 0.101	0.095 decrease (0.027 to 0.163)	2.823	0.008	0.47	0.009
Accelerator pedal input in event 2	0.187 ± 0.151	0.138 ± 0.129	0.049 decrease (0.004 to 0.094)	2.209	0.034	0.368	0.023
Accelerator pedal input in event 3	0.188 ± 0.201	0.110 ± 0.056	0.078 decrease (0.013 to 0.144)	2.424	0.021	0.404	0.022

Table 8. Comparison of engine RPM during critical events

Variable	No warning, M ± SD	Warning, M ± SD	Change (95% CI)	t	p	Cohen's dz	Wilcoxon p
Engine RPM in event 1	2755.983 ± 662.208	1741.706 ± 759.590	1014.278 decrease (664.249 to 1364.306)	5.883	<0.001	0.98	<0.001
Engine RPM in event 2	2754.930 ± 889.335	1703.470 ± 549.468	1051.460 decrease (708.850 to 1394.070)	6.23	<0.001	1.038	<0.001
Engine RPM in event 3	2573.364 ± 606.990	1743.801 ± 591.902	829.563 decrease (578.366 to 1080.760)	6.704	<0.001	1.117	<0.001

Table 9. Comparison of seat-belt use between the no-warning and auditory warning conditions

Seat-belt status before warning / after warning	Unfastened after warning	Fastened after warning	Total
Unfastened before warning	8	10	18
Fastened before warning	0	18	18
Total	8	28	36

McNemar’s test: $p = 0.002$; absolute paired increase = 27.8 percentage points (bootstrap 95% CI: 13.9 to 41.7)

4.8. Summary of Findings

Overall, the descriptive and inferential results showed that the speech-based auditory warning condition was associated with significant improvements in several behavioral and vehicle-related driving indicators compared with the no-warning condition. In terms of direct safety outcomes, the number of collisions with other vehicles, pedestrians, and fixed objects, as well as the number of speed limit exceedances, decreased significantly. Regarding control-related indicators, speed, accelerator pedal input, and engine RPM during critical events decreased, while braking intensity increased.

The consistency between the paired-samples t-test and Wilcoxon signed-rank test results indicates that the overall pattern of findings was robust across statistical approaches. In other words, even when an appropriate nonparametric test for paired data was used, the reductions in collisions, speed limit exceedances, speed, accelerator pedal input, and engine RPM, as well as the increase in braking intensity, remained statistically significant.

The rate of seat-belt use was also higher in the auditory warning condition. However, because no dedicated seat-belt warning message was provided and the order of the two conditions was fixed, this finding should be interpreted cautiously as a complementary and exploratory result.

Taken together, these findings support the main hypothesis of the study that speech-based auditory warnings may be associated with reduced risky behaviors and enhanced safer control responses under short-term simulated driving conditions. Nevertheless, because of the pilot nature of the study, the absence of an independent control group, and the possibility of learning or route-familiarity effects in the second run, these results should not be interpreted as definitive evidence of a causal relationship.

These findings should be interpreted in relation to the sequential study design. Because the warning condition was always administered during the second run, part of the observed improvement may have resulted from practice with the simulator, route familiarity, anticipation of the critical events, or reduced anxiety after the first exposure. Therefore, although the results consistently favored the warning condition, the present design does not allow the magnitude of the warning-specific effect to be isolated from potential order and repeated-exposure effects.

5. Discussion

The present study aimed to evaluate the effects of Persian speech-based auditory warnings on indicators of safe driving behavior among young drivers using a driving simulator. Based on the conceptual framework of the study, it was expected that auditory warnings delivered at critical moments would be associated with fewer collisions, fewer speed limit exceedances, lower speed, lower accelerator pedal input, lower engine RPM, and higher braking intensity. Seat-belt use was also examined as a complementary and exploratory indicator. The findings showed that, in the auditory warning condition, most behavioral and vehicle-related indicators changed in the expected direction. Overall, the results suggest that speech-based auditory warnings, under controlled and short-term simulated driving conditions, may be associated with reduced risky behaviors and enhanced safer control responses among young drivers.

Taken together, the findings are better interpreted as a coordinated pattern of hazard-related behavioral adjustment rather than as a set of isolated changes in individual indicators. In the warning condition, drivers showed lower speed, reduced accelerator pedal input, lower engine RPM, greater braking intensity, fewer speed-limit exceedances, and fewer collisions. One plausible explanation is that the anticipatory auditory messages increased the perceptual salience of the upcoming hazard and redirected drivers' attention toward information relevant to immediate vehicle control. Because auditory information can be received without requiring drivers to shift their gaze away from the road, the warnings may have supported earlier hazard recognition while preserving visual attention for the driving environment. This interpretation is consistent with Ju et al. (Ju et al., 2022), who found that acoustic cues can enhance situational awareness in accident-prone driving situations, and with Wu et al., who reported that auditory forward-collision warnings can influence avoidance behavior, reaction time, and response intensity.

Warning timing may also have contributed to the observed reductions in speed and collisions. In the present study, the messages were presented before participants reached the hazardous locations rather than at or after hazard onset. This anticipatory timing may have provided an additional interval for drivers to recognize the developing risk, evaluate its potential consequences, and initiate an appropriate control response. The lower entry speeds observed across all three critical events suggest that drivers may have approached the hazardous zones with a larger safety margin in the warning condition. This interpretation is consistent with Yue et al., who showed that warning timing and warning level can produce different behavioral effects across driving scenarios. It also supports the view that warning effectiveness depends not only on whether a warning is presented but also on whether it is delivered early enough to permit meaningful behavioral adjustment.

A second possible mechanism concerns the semantic content of the speech messages. Unlike nonverbal alarms, which primarily signal that a problem exists, speech-based warnings can communicate both the presence of danger and the response expected from the driver. For example, a message such as "reduce your speed" may reduce uncertainty about the required action and facilitate a more direct transition from hazard detection to response selection. This may help explain the simultaneous reduction in accelerator pedal input and engine RPM and the increase in braking intensity. Sabic et al. showed that the type of auditory warning can influence recognition speed and response accuracy, while Wang et al. emphasized that message content and speech characteristics can affect driving safety and driver workload. The present findings extend these observations by suggesting that semantically explicit Persian messages may be associated with measurable changes in vehicle-control behavior during simulated hazardous events.

The combined changes in pedal use, engine RPM, and speed also suggest a coordinated vehicle-control sequence. Reduced accelerator input likely limited continued propulsion, while lower engine RPM and speed indicate a moderation of the vehicle's movement before or during hazard exposure. Increased braking intensity may then represent a more active attempt to increase deceleration and avoid collision. However, greater braking intensity should not automatically be interpreted as safer behavior, because intense braking can also indicate delayed or abrupt responding. In the present study, it is interpreted more cautiously as part of a targeted hazard response because it occurred together with lower speed, reduced acceleration, and fewer collisions. This interpretation is broadly consistent with

Kaizuka and Nakano, who showed that warning urgency can influence the timing and accuracy of drivers' control responses.

The reduction in speed-limit exceedances may reflect a broader change in risk regulation rather than only an immediate reaction to individual hazards. Repeated presentation of brief warnings may have temporarily increased the perceived seriousness of the driving task or heightened drivers' general awareness of risk, leading them to adopt a more conservative driving style during the warning run. This mechanism may be particularly relevant among less-experienced drivers, for whom external cues may compensate for less developed hazard anticipation and control strategies. Faridiaghdam et al. demonstrated that situational awareness, driving skill, risky violations, and crash history are interrelated among young drivers. The present results suggest that situation-specific speech warnings may provide external support for safer short-term responses in this population.

Nevertheless, the proposed attentional, cognitive, and behavioral mechanisms were not measured directly in the present study. No independent measures of visual attention, hazard perception, reaction time, perceived urgency, cognitive workload, or risk perception were collected. Therefore, these explanations should be regarded as theoretically plausible interpretations of the observed behavioral pattern rather than confirmed mediating mechanisms. In addition, because the warning condition was always completed second, part of the observed pattern may reflect learning, route familiarity, hazard anticipation, or reduced simulator anxiety. Future studies should directly measure the proposed mechanisms and use randomized or counterbalanced designs to determine whether attentional capture, risk appraisal, and response selection mediate the effects of speech-based warnings on driving behavior.

The finding related to seat-belt use should be interpreted separately from the coordinated hazard-response pattern described above. The results showed that the rate of seat-belt use increased in the auditory warning condition. However, no specific warning message regarding seat-belt use was provided in this study. Therefore, this change cannot be directly attributed to the content of the auditory warning. The increase may have resulted from a general increase in perceived risk, a more serious attitude toward the experiment during the second run, greater familiarity with the simulator, or the fixed order of the conditions. Accordingly, seat-belt use should be regarded as a complementary and exploratory indicator in this study. Future research should examine this issue more directly by including a dedicated seat-belt warning, an independent control group, and randomized condition order.

Sabic et al. showed that auditory warning type can affect recognition speed and response accuracy, but their study was conducted in a human–computer interaction setting and did not assess actual driving indicators. The present study extends this direction by examining speech-based warnings in a driving simulator and showing their association with behavioral and vehicle-related driving indicators. Wu et al. demonstrated the effectiveness of auditory forward collision warnings, while the present study examined multiple hazard types and several driving indicators simultaneously. Ju et al. highlighted the role of acoustic cues in improving situational awareness, and the present findings support this interpretation. Studies by Kaizuka and Nakano, Wang et al., and Yue et al. emphasized the importance of urgency, content, speech rate, coordination of cues, and warning timing. By using brief, clear, and anticipatory Persian speech messages, the present study suggests that these design principles may also be applicable to young Iranian drivers.

An important point in explaining the findings is the role of language and message content. Many in-vehicle warnings use nonverbal sounds, beeps, or alarms. These warnings usually signal danger but do not necessarily communicate the expected behavior directly. In contrast, speech-based warnings can both signal the hazard and specify the appropriate response. For example, the message “reduce your speed” directly communicates the expected action. This feature may be particularly useful for young drivers, who may have less experience in detecting and managing hazardous situations. However, the effectiveness of speech-based warnings depends on careful design. If messages are too long, ambiguous, delayed, overly frequent, or mismatched with the level of hazard, they may increase cognitive load, cause auditory annoyance, or reduce drivers’ sensitivity to warnings. Therefore, the present findings should not be interpreted to mean that any auditory warning is necessarily beneficial. Rather, they suggest that short, clear, situation-relevant, and timely speech messages may be associated with improvements in selected driving indicators in a simulator environment.

The focus of the present study on young Iranian drivers is also theoretically and practically important. Young drivers are often considered a key group in traffic safety research because of their lower driving experience, higher likelihood of perceptual and decision-making errors, and sometimes greater tendency toward risky behaviors. Faridiaghdam et al. showed that situational awareness, driving skills, risky violations, and crash history are interrelated among young drivers. The present findings are in line with this perspective and suggest that a simple and relatively low-cost intervention, such as speech-based auditory warning, may be associated with short-term improvements in selected indicators of safe driving behavior in this group. This may have implications for designing driver assistance systems tailored to novice or young drivers.

From an applied perspective, the results of this study may be useful for designing Persian-language in-vehicle warning systems adapted to driving conditions in Iran. Compared with some more complex technologies, speech-based auditory messages may have relatively simple and low-cost implementation potential. Such messages could be used as complementary warnings in situations such as approaching a pedestrian, reducing distance from a lead vehicle, entering an intersection, encountering a fixed obstacle, or exceeding a speed limit. However, the design of such systems should be based on principles of cognitive ergonomics. Messages should be brief, clear, timely, nonintrusive, and proportional to the level of hazard.

Despite the positive findings, the results should be interpreted in light of several limitations. The most important limitation of the present study is the fixed sequential administration of the experimental conditions. All participants completed the no-warning condition first and the speech-based warning condition second. This order was selected to reduce carryover contamination, because exposure to the warning condition could have revealed both the locations of hazardous events and the appropriate behavioral responses before a subsequent no-warning trial. However, using a fixed order created an alternative source of bias. During the second run, participants had already become familiar with the simulator controls, the route configuration, and the approximate locations and nature of the critical events. They may also have experienced lower anxiety, reduced cognitive demand, and greater confidence in operating the simulator. In addition, prior exposure to the hazards may have enabled participants to anticipate them before they occurred.

These learning, practice, route-familiarity, and hazard-anticipation effects may have contributed to the improved performance observed in the warning condition and may therefore have inflated the apparent warning-associated differences. Because all participants experienced the same sequence, the effects of condition and order were completely confounded and could not be separated in the analysis. Accordingly, the observed reductions in collisions, speed, speed-limit exceedances, accelerator input, and engine RPM, as well as the increase in braking intensity, cannot be attributed exclusively to the speech-based auditory warnings. Future confirmatory studies should use randomized or counterbalanced condition orders, preferably with equivalent but nonidentical scenario versions, or include an independent parallel control group to distinguish warning effects from repeated-exposure effects.

The second limitation concerns the simulator environment. Driving simulators allow hazardous conditions to be controlled, scenarios to be repeated, and data to be recorded accurately. However, drivers' behavior in a simulator may differ from their behavior on real roads. In real-world driving, factors such as social pressure, the presence of other drivers, weather conditions, road quality, real distractions, and the more serious consequences of errors can influence driver behavior. Therefore, the generalization of the findings to real-world driving should be made cautiously, and field or semi-field studies are needed to confirm the results.

The third limitation relates to the sample size and composition. The sample consisted of 36 young drivers who were mostly students. Although this sample size is acceptable for a pilot study and provides preliminary evidence regarding the association between auditory warnings and changes in driving behavior, it is not sufficient for generalizing the findings to the broader population of Iranian drivers. Future studies should include larger and more diverse samples in terms of age, gender, driving experience, crash history, driving style, and risk-taking tendency.

The fourth limitation concerns the characteristics of the warnings themselves. In this study, a specific set of brief Persian messages was used, and the separate effects of tone of voice, speaker gender, sound intensity, speech rate, message length, urgency level, and precise warning timing were not examined. However, the literature indicates that these characteristics can substantially influence warning effectiveness (Wang et al., 2022; Yue et al., 2025). Future studies should compare different versions of speech-based warnings to determine which combination of content, tone, timing, and sound intensity produces the best safety-related outcomes.

The fifth limitation is the short-term nature of the assessment. In this study, warning effects were examined within a single experimental session. In real-world use, drivers may become habituated to warnings or less sensitive to them over time. This phenomenon, often referred to as warning fatigue or reduced warning sensitivity, is an important issue in the design of warning systems. Therefore, future research should examine the long-term effects of auditory warnings, the possibility of habituation, driver acceptance, cognitive workload, and auditory annoyance.

Overall, the findings of the present study indicate that Persian speech-based auditory warnings, under short-term simulated driving conditions, were associated with improvements in a set of safe driving behavior indicators among young drivers. The warnings produced a relatively coherent pattern of behavioral adjustment, including fewer collisions, fewer speed limit exceedances, lower speed, lower accelerator pedal input, lower engine RPM, and higher braking intensity. However, because of the limitations related to the study design, simulator environment, sample size, and fixed condition order, the results should be interpreted as preliminary and pilot evidence. The main value of this study is that it shows how localized, brief, and situation-relevant speech-based warnings may represent a practical direction for developing driver assistance systems and improving the safety of young Iranian drivers.

6. Conclusion

This pilot study examined whether brief Persian speech-based auditory warnings were associated with safer driving responses among predominantly young Iranian drivers in a simulated urban environment. The study contributes to the existing literature by examining semantically explicit speech warnings in a Persian-language context, considering multiple hazardous situations, and evaluating direct safety outcomes together with vehicle-control indicators.

Across the experimental conditions, the warning condition was associated with fewer collisions and speed-limit exceedances, lower speed, reduced accelerator pedal input, lower engine RPM, and greater braking intensity. The effect-size estimates and confidence intervals indicated that several of these differences, particularly those related to speed, braking intensity, and engine RPM, were practically meaningful rather than merely statistically significant. Taken together, the findings suggest that brief, clear, and anticipatory speech messages may support more cautious short-term vehicle-control responses in simulated hazardous situations.

These findings should nevertheless be interpreted as preliminary associations rather than definitive causal effects. The principal limitation is that all participants completed the no-warning condition first and the warning condition second. Consequently, the warning condition was confounded with practice, route familiarity, hazard anticipation, and reduced simulator anxiety. Additional limitations include the small convenience sample, the simulator-based setting, the short-term assessment, and the absence of direct measures of attention, cognitive workload, perceived urgency, or warning acceptance.

The primary next step should be a confirmatory experiment using randomized or counterbalanced condition order, preferably with equivalent alternative scenarios or an independent parallel control group. Addressing this design limitation is necessary to separate warning-specific effects from repeated-exposure effects. Subsequent studies should recruit larger and more diverse samples, compare warning characteristics such as message content, timing, urgency, speech rate, and voice, and examine workload, acceptance, habituation, and auditory annoyance. Field-based or naturalistic driving studies will ultimately be required to determine whether the observed simulator-based associations generalize to real-world driving.

Subject to these limitations, the study provides preliminary evidence that localized Persian speech-based warnings may represent a practical direction for the development of context-sensitive in-vehicle warning systems for young and less-experienced drivers.

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