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Research Article

Discrimination of Effects between Directional and Nondirectional Information of Auditory Warning on Driving Behavior

Yuting Zhang, Xuedong Yan, and Zhuo Yang

MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing 100044, China

Correspondence should be addressed to Xuedong Yan; xdyan@bjtu.edu.cn

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This study examines the impacts of directional and nondirectional auditory warning information in a collision warning system (CWS) on driving behavior. The data on driving behavior is collected through experiment, with scenarios containing unexpected hazard events that include different warning content. As drivers approached the collision event, either a CWS auditory warning was given or no warning was given for a reference group. Discriminant analysis was used to investigate the relationship between directional auditory warning information and driving behavior. In the experiment, the CWS warnings significantly reduced brake reaction time and prompted drivers to press the brake pedal more heavily, demonstrating the effectiveness of CWS warnings in alerting drivers to avoid red-light running (RLR) vehicles when approaching a signalized intersection. Providing a clear warning with directional information about an urgent hazard event could give drivers adequate time to prepare for the potential collision. In terms of deceleration, a directional information warning was shown to greatly help drivers react to critical events at signalized intersections with more moderate braking. From these results, requirements can be derived for the design of effective warning strategies for critical intersections.

1. Introduction

Safe driving at intersections is one of the most dynamic and complex tasks for drivers and requires a high degree of visual and spatial processing [1, 2]. According to in-depth analyses of accidents, recognition error is one of the main contributing factors to accidents at intersections [3, 4]. For instance, Vollrath et al. [4] found that a lack of information was the main reason for more than 90% of intersection accidents. In most cases, traffic participants who violate traffic regulations are not easily noticed by those drivers who have the right to cross the intersection. If they fail to yield to these traffic participants, the possibility of collisions increases [5]. In addition, insufficient sight distance or traffic light visibility blockages may lead to conflicts or crashes at intersections [6, 7].

Driving simulators offer a controllable, safe, and cost-effective alternative to real-world driving and have become an established tool in driver behavior research [8, 9]. Furthermore, with advances in in-vehicle collision warning system (CWS) technology, more and more experiments are being conducted to test such systems. Several simulators and on-road studies have suggested that warning information can produce several potential benefits that help drivers to deal with urgent situations at intersections, reducing reaction times to hazardous situations [10–14], reducing collision involvement [15, 16], and thereby enhancing drivers' safety.

Several recent studies based on driving simulators have indicated that the effectiveness of CWSs is affected by various parameters [17–21]. For example, Chang et al. [17] compared two kinds of warning forms in alerting red-light running (RLR) vehicles: beeping sounds and speech messages. It was found that drivers had shorter response times and slower speeds in vehicles installed with warning systems. Baldwin and May [19] considered the impacts of loudness and semantics in auditory warnings and found that the less urgent signal word "Notice" presented at the level of 85 dB and the high-urgency signal word "Danger" presented at the level of 70 dB resulted in significant reductions in crash probability. Meanwhile, Yan et al. [21] found that auditory warning information could help drivers detect RLR vehicles in a more timely fashion and that early warnings provided drivers with more adequate time and space to decelerate so as to avoid collisions with the conflicting vehicles. The auditory warning is designed not only to attract attention but also to provide additional information about the nature of the hazardous event, such as directional information with the direction in which the hazard is [22]. Previous studies have shown participants to have shorter response times when the stimulus is presented with clear directional help [23, 24]. Liu and Jhuang [20] indicated that auditory warning with the help of directional information significantly improved drivers' performance in making accurate simulated-response task decisions and that the response time to the tasks was shorter when a warning with directional information was given.

The studies mentioned above indicate that drivers can benefit greatly from auditory warnings that include the direction of the danger. To date, there have been few promising studies discriminating between the effects of directional and nondirectional auditory warnings on driving behavior and crash avoidance performance at signalized intersections. Therefore, more research is needed. The current study addresses two points, using a driving simulator to evaluate the effects of in-vehicle warning information displayed with and without directional information on drivers' response and decision performance. Firstly, the difference between directional and nondirectional warning information on the drivers' collision avoidance performance is investigated in depth. Secondly, discriminant analysis, which has been widely used in climate classification, agricultural zoning, and the division of land types, is used to analyze the relationships between directional and, respectively, nondirectional information and driving behavior.

Therefore, the current research aims to evaluate the effects of directional and nondirectional auditory warning information on driving behavior. The results obtained could contribute to better-designed warning content for in-vehicle warning systems, which would in turn enhance road driving safety.

2. Methods

2.1. Principles of Collision Warning Systems. Suppose that, at a signalized intersection, when a vehicle is approaching the intersection in the green phase, a violating vehicle crosses the intersection during a red light. In this urgent situation, CWSs are useful for ensuring safe driving. In in-vehicle CWSs, all vehicles approaching the intersection can be dynamically monitored by sensors such as GPS navigation systems, vision systems, and WIFI cards installed in the car. Due to the availability of supportive wireless technologies and advanced sensory technologies within vehicles, all the data about the road conditions, including the positions of vehicles, speeds, deceleration, and real-time to collision, can be acquired. These sensors can help drivers to respond effectively by sending appropriate messages between vehicles. When a vehicle with an in-vehicle CWS is approaching an intersection during the red phase, it should follow the traffic rules and stop in front of the stop line. When the distance from that vehicle to the stop line is larger than the stopping distance, or the vehicle is predicted to run a red light with high probability, it will be detected as a RLR vehicle. Once a RLR vehicle has been detected, a vehicle that has the right to cross the intersection will receive an auditory warning of danger through wireless communications equipment. Figure 1 shows the flow chart of CWS at the signalized intersection.

2.2. Discriminant Analysis

2.2.1. Goals and Assumptions of Discriminant Analysis. The goals of discriminant analysis are clearly clarified by Meloun et al. [25]. It is used to determine whether there are statistically significant differences between the average score of discriminators for two or more predefined classes, to classify objects into preset classes based on their score for the set of discriminators, and to determine which of the discriminators is reflected significantly in the differential average score profiles of two or more classes.

Three assumptions are required when discriminant analysis is applied [26]. The first is that discriminatory variables are assumed to be normally distributed. It is necessary to confirm this assumption so as to use tests of the significance of individual discriminatory variables and discriminatory functions. The second is that groups of statistical units are strictly defined. In general, groups can be defined by objective factors or by statistical methods. The third is the significance of the selected discriminatory variables. Specifically, in order to derive the Fisher discriminant function, to ensure conformity of variances, the intracovariance matrix must be calculated and it must be verified that the intracovariance matrices are not the same, so that the derived quadratic discriminant function can be used for classification. The degree to which a violation of these assumptions affects the significance of the tests and the estimation of classification error will depend on the number of discriminatory variables and the group sizes [25].

2.2.2. Discriminant Analysis Criteria. Satisfying the discriminant analysis criteria can be seen as a key task of discriminant analysis. The object of discriminant analysis is to derive the discriminant function or functions that separate the data into two or more groups in a statistically significant way. The goal is to find a linear combination of p observed variables $x_1, x_2, x_3, \ldots, x_p$ as follows:

$$Y = b^T x, \quad (1)$$

where b^T is equal to $b^1, b^2, \ldots, b^p$, and the vector of parameters helps to separate the considered groups in such a way that the intergroup variability is as large as possible and the intragroup variability is as small as possible.

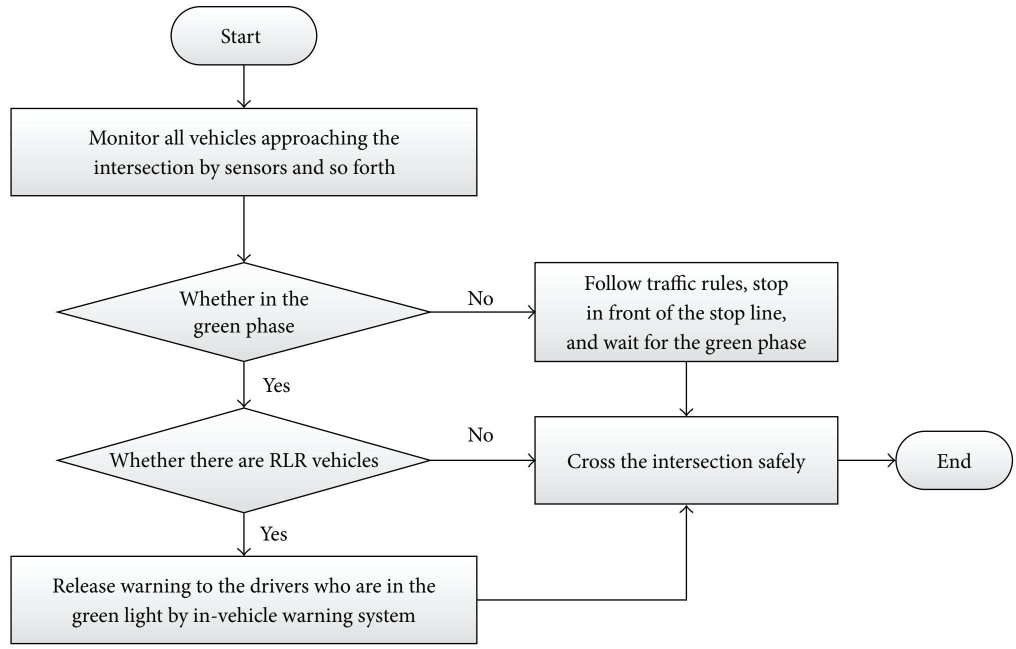

Figure 1: Flow chart of CWS.

The total variability of the original observed variables is expressed by matrix T:

$$T = \sum_{h=1}^{H} \sum_{i=1}^{nh} (x_{ih} - \overline{x}) (x_{ih} - \overline{x})^T, \quad (2)$$

where x_{ih} represents a vector of values of i which is statistical unit in h group; $\overline{x}$ represents the average value over the groups. A similar matrix E is used to express intragroup variability, and a matrix B to express intergroup variability. The matrix T is equal to the sum of squares of $Q_B(Y)$ and $Q_E(Y)$, and the largest intergroup and smallest intragroup variability of the variable Y can be achieved by maximizing the following ratio:

$$F = \frac{Q_B(Y)}{Q_E(Y)} = \frac{b^T B b}{b^T E b}. \quad (3)$$

F is known as Fisher's discriminatory criterion. In order to determine the value of Y, it is necessary to specify the elements of the vector b so as to maximize the discriminatory criterion that will distinguish between the groups.

If the set of units described by p variables is divided into two groups, only one discriminant is sufficient to express the variability of the original variables based on Fisher's discriminatory criterion [27], but for Bayes' discriminant analysis criterion, two discriminants are needed. Bayes' discriminant analysis criterion is expressed as follows:

$$X \in G_i, p_i f_i(X) \geq p_j f_j(X), \quad (4)$$

where p_i represents the a priori probability of each group and $f_i(X)$ the probability density function corresponding to each group.

The discriminatory score can be used to classify n objects into H groups. The Mahalanobis distance can also be used as a criterion for the selection of discriminators. Each object will be included in the group to which it is closest in terms of distance from the centroid of the group. It is expressed as follows, for the generalized measure of the distance between two groups 1 and 2:

$$D_{1,2}^2 = (n - g) \sum_{i=1}^{m} \sum_{j=1}^{m} w_{ij} (\overline{x_{i1}} - \overline{x_{i2}}) (\overline{x_{j1}} - \overline{x_{j2}}), \quad (5)$$

where m represents the number of discriminators in the model, $\overline{x_{i1}}$ is the average of discriminator i in class 1, and w_{ij} is the i, j element of the inverse covariance matrix [28].

In addition, a high positive or negative value of the structural variables indicates that the monitored variable is characteristic of the given discriminant. The sign (+/−) determines whether the values of the original variable lead to an increase or a decrease in the value of the discriminatory score.

2.3. Experimental Data. The RLR precrash scenarios are simulated using the BJTU driving simulator. The design of the experimental RLR precrash scenario is shown in Figure 2. When the test vehicle (simulator) is 7 s from the conflict point at the intersection, a RLR vehicle is triggered to start by the time to collision (TTC sensor, which calculates the time from the simulator to the conflict point in real time, and is set to cross the intersection with a velocity of 20 m/s). Once the time from the conflict point reaches a predesigned value (4 s), an auditory warning is triggered to the test vehicle (simulator) that is crossing the intersection during a green phase. The auditory warning without directional information is "please watch out for the vehicle running the red light" and the auditory warning with directional information is "please

Table 1: Results of discriminant analysis.

Variable	Classification function coefficient			Sig.
	No warning	Nondirectional warning	Directional warning	
Brake reaction time	1.564	1.378	1.235	0.010*
Deceleration	0.784	0.982	0.950	0.028*
Crash rate	4.065	−0.415	−0.219	0.000*
Constant	−6.114	−5.389	−4.804	—

*The corresponding variable has significant difference on the variable among three groups (no warning, non-directional information or directional information) at the 0.05 significance level.

watch out for the vehicle running the red light on your right." At the same time, the driving simulator collects essential data on driving behaviors, such as the location of the simulator, the real-time speed, and deceleration.

A total of 45 subjects (53% males) participated in the study. The participants ranged from 31 to 39 years of age (mean age 35 years). Each driver experienced three kinds of warning: no warning, a warning without directional information, and one with directional information. The drivers' performances are represented by brake response time, deceleration, and crash rate. Two variables are needed to calculate these driving behaviors. First, brake reaction time is measured from the time when a RLR vehicle is triggered in the driving scenario (when the simulator vehicle is 7 s from the conflict point) to the time when the test driver presses the brake pedal. According to the definition used in this study, the brake reaction time is not an absolute time value, but the same baseline time is chosen; it is still able to reflect how quickly drivers take action to avoid a collision. Second, deceleration in this study is defined as the change in velocity, which is measured during the collision avoidance process from the time when the traffic event is triggered to the time when avoidance is achieved or the driver leaves the conflict point.

3. Results

In this study, the discrimination between the effects of directional and nondirectional information on drivers' collision avoidance behavior at a signalized intersection is investigated. Thus, the sample is divided into three groups based on the warning given: (1) no warning, (2) auditory warning with nondirectional information, and (3) auditory warning with directional information. Drivers' brake reaction times, deceleration, and whether or not they crash are selected to represent their collision avoidance performance.

3.1. Discriminant Analysis of Directional Information. Table 1 lists the results of the discriminant analysis. At the 0.05 significance level, we have no reason to reject the null hypothesis of equal mean values of the variables (brake reaction time, deceleration, and crash rate). That is, there is a significant difference between the means of the variables in the three groups, which reveals that the warning condition (no warning, nondirectional information, or directional information) exhibits a significant influence on the brake reaction time, deceleration, and crash rate.

The discriminant functions are as follows, where Y_1 is the group given no warning, Y_2 the group given a nondirectional warning, and Y_3 the group given a directional warning; t represents the brake reaction time of the driver, a represents the deceleration that the driver applies, and c indicates whether or not a crash occurs ($c = 0$ means no crash occurs and $c = 1$ means a crash occurs). Consider

$$\begin{aligned} Y_1 &= 1.564t + 0.784a + 4.065c - 6.114, \\ Y_2 &= 1.378t + 0.982a - 0.415c - 5.389, \\ Y_3 &= 1.235t + 0.950a - 0.219c - 4.804. \end{aligned} \tag{6}$$

3.2. Analysis of Driving Behavior. According to the above results, the brake reaction times of the drivers, the deceleration applied by the drivers, and their crash rates all differ significantly between the three warning conditions. Over the 135 experimental intersections, a total of 17 crashes (12.6%) are observed. Of the 17 crashes, none occurs under either of the CWS auditory warning conditions (as Figure 3 shows), which indicates that the CWS can greatly reduce crash risk.

Figure 4 indicates that the scenario with no warning leads to the longest mean brake reaction time and the highest standard deviation. The brake reaction times when auditory warnings are given are shorter and have lower standard deviations, indicating that drivers react differently to the collision event and that the warning is effective in reducing their reaction times. Also, the mean brake reaction time when a directional information warning is given is a little smaller than that in the case of the nondirectional information warning, indicating that directional information will help to reduce the mental processing required of drivers, thus reducing the brake reaction time in the event of a traffic event at a signalized intersection. Figure 5 shows the mean deceleration applied by drivers as a result of the traffic event. The group given no warning, which has the high crash rate (38.6%), also has the lowest deceleration, indicating that the drivers given no warning information pressed their brake pedal too late to avoid an accident. However, the provision of an auditory warning increases the deceleration applied by the driver, demonstrating that such warnings tend to cause drivers to apply the brakes more heavily. Interestingly, the experimental results show that the mean deceleration in the case of a directional information warning (3.45 m/s/s) is smaller than that in the case of a nondirectional information warning (3.93 m/s/s), indicating that a directional warning

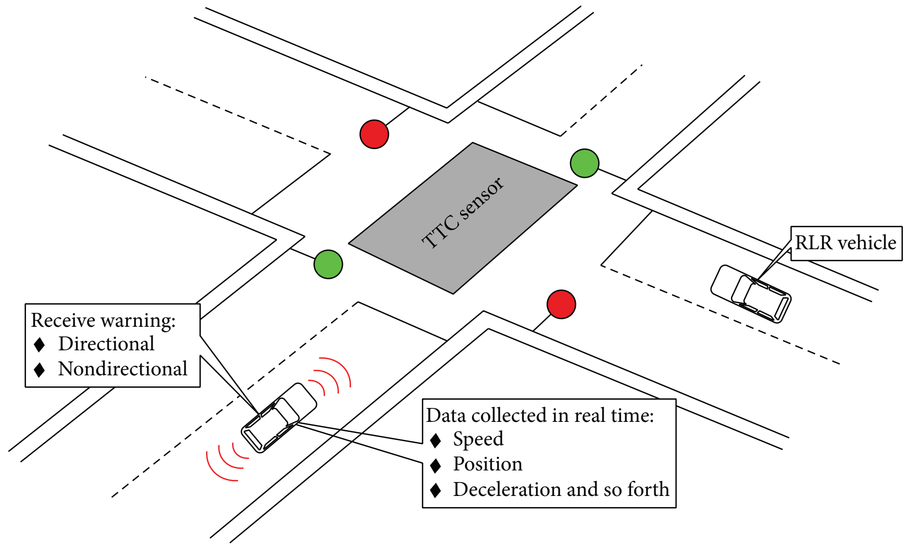

Figure 2: Design of experimental scenario.

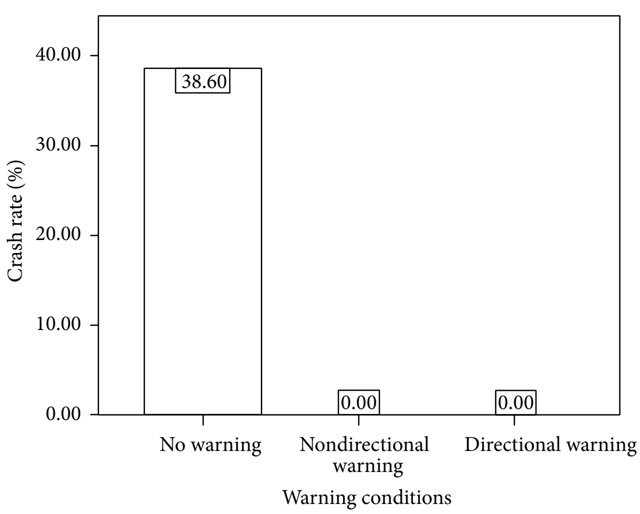

Figure 3: Crash rates under different warning conditions.

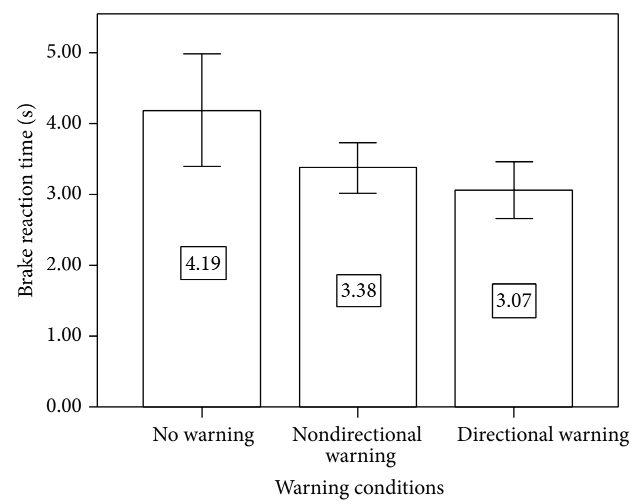

Figure 4: Mean brake reaction times under different warning conditions.

may not only reduce the possibility of a collision but also help the driver to take more comfortable and appropriate braking action to avoid the collision.

Additionally, at the end of the experiment, the participants were asked to complete a questionnaire about the subjective effectiveness of CWS warnings. Figure 6 shows the results of the subjective ratings of contribution brought by directional information of auditory warnings. All participants agreed that the CWS warning could help improve driver behavior. Around 60% thought that CWS warnings with directional information were of great benefit for avoiding collisions.

4. Discussion and Conclusion

This study has investigated driving behavior under different types of CWS warning information. Regarding brake reaction

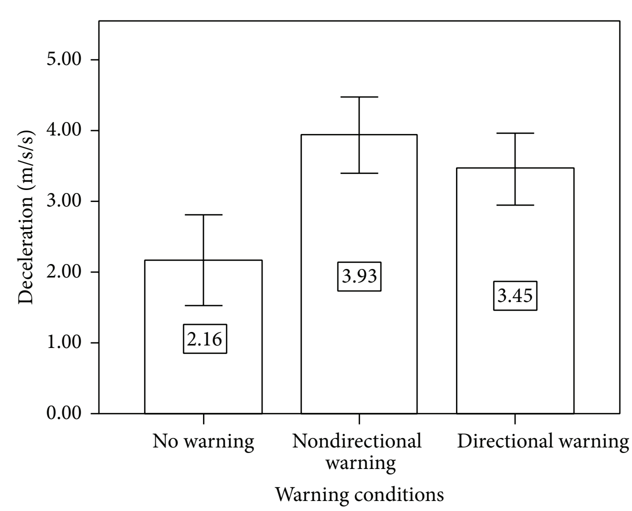

Figure 5: Mean deceleration under different warning conditions.

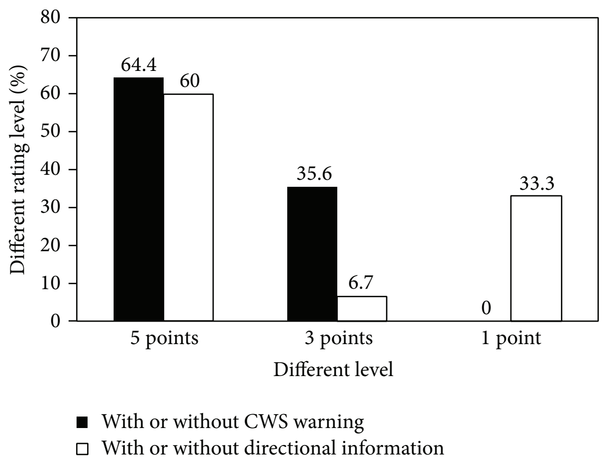

Figure 6: Results of subjective ratings of different warning conditions. (note: 5 points indicates that CWS or directional information makes a big contribution to reducing traffic collisions; 3 points indicates a small contribution; 1 point indicates no contribution).

times, the results have shown that, when given an auditory warning, drivers will take less time to apply the brakes compared to when given no warning. Deceleration is the smallest in the group given no warning, which also exhibited the highest crash rate. A possible reason is that, within a limited time and distance to the conflict point, only drivers that slow down quickly enough will successfully avoid collision. The experimental results indicate that the decelerations applied by drivers provided with a CWS warning are consistently larger, similar to results found by Yan et al. [21].

An extremely high percentage of crashes occur when CWS warnings are not provided. Thus, whether the warning contains directional information or not, the release of a warning can improve drivers' ability to respond to a RLR collision situation. That is, faster reaction times and lower crash risk are exhibited when a CWS warning is given in a critical intersection situation, consistent with the results of previous studies [1, 17]. Additionally, from a subjective rating point of view, all of the participants believed that CWS warnings would contribute to a reduced crash risk at intersections.

Interestingly, the experiment showed that directional information given in an auditory warning has a significant impact on the drivers' brake reaction time and deceleration rate. With respect to the brake reaction time, directional information can help drivers to react to an emergency event more quickly. With regard to the deceleration rate, it seems that drivers who receive a nondirectional information warning still have to observe the surrounding traffic because they do not know the direction from which the RLR vehicle is coming. Thus, directional information would seem to be extremely important in terms of informing the driver of the direction of the danger source. On hearing the CWS warning, a driver will react quickly to avoid a collision even if no directional information is given. However, in such a situation they may feel more pressure, leading them to press down on the brake pedal more heavily. In contrast, the drivers who received directional information seem to have been more leisured and had comparatively more time to take braking action. Studies with similar conclusions have indicated that, when the warning contains directional information about the danger, the driver can pay attention to the danger more easily and effectively [29, 30]. The subjective ratings also showed CWS warnings with directional information to be of higher benefit.

The investigation of directional and nondirectional information in auditory warnings carried out in this study is expected to help reduce the brake reaction times of drivers. The application of directional information in auditory warnings given in emergent driving situations will give drivers sufficient time to respond to urgent situations and take moderate deceleration action. Besides this, the results contribute to an existing literature indicating that auditory warnings can help to reduce collisions at critical intersections and that the content of the auditory warnings is a key factor in the effectiveness of CWS [16, 31].

The results of this study suggest that auditory warnings with directional information should be adopted as they are useful for improving drivers' ability to avoid collision events and cross intersections more safely. The results can be used to improve the effectiveness of CWS warnings in real traffic situations. A larger amount of directional information will lessen the information-processing burden on drivers. Drivers who are distracted easily may benefit particularly from auditory warnings with directional information. However, if the time of the warning is inappropriate, then whether a directional warning will make a difference to the driver is not clear. Thus, the time at which a warning is released may be a key factor, along with directional information, in improving existing CWS warnings and should guide future CWS design. As a result, although the results of this investigation provide an important step towards understanding the different effects of directional and nondirectional auditory warning information in applied settings, additional work is needed to examine the effects of the combination of directional information and information release time on driving behavior.

Conflict of Interests

The authors do not have a direct financial relation with any commercial entity mentioned in their paper that might lead to a conflict of interests for any of the authors.

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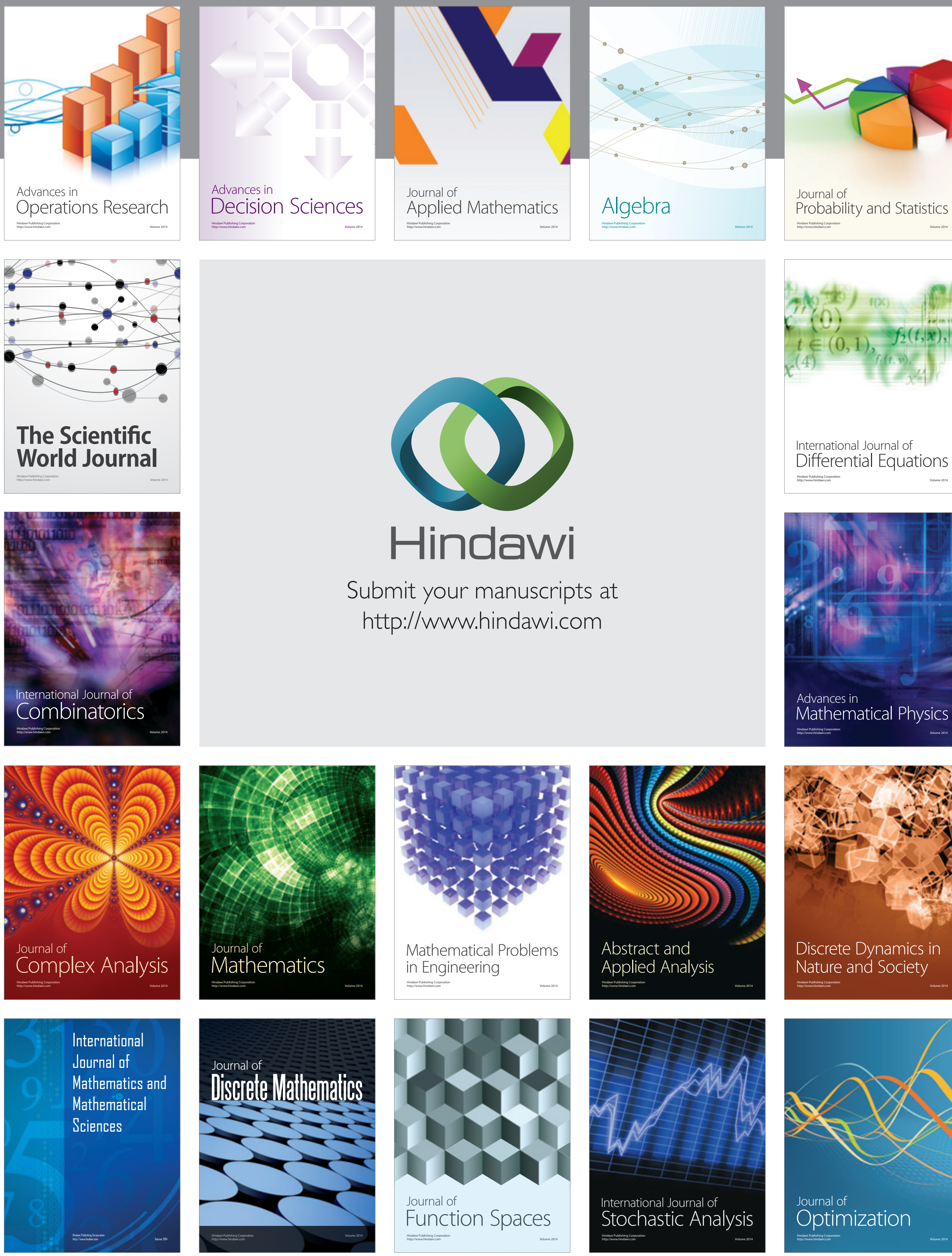

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