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Hazard Perception in Driving: A Systematic Literature Review

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ABSTRACT

Hazard perception is the process of detecting and identifying hazards. Drivers' hazard perception abilities are critical for driving safety. This paper presents a systematic literature review of driver hazard perception, including scientific measures of hazard perception, major human factors affecting hazard perception, and training methods for improving hazard perception skills. Sixty-nine peer-reviewed studies were identified and reviewed. The results showed that common measures of hazard perception include hazard scenario questionnaires, hazard perception reaction time, hazard hit rate, and eye fixation measures such as fixation probability, fixation reaction time, fixation duration, and fixation variance. Major human factors that affect hazard perception include experience, aging, fatigue, distraction, and the use of alcohol and drugs. Various training methods have been developed to train and improve drivers' hazard perception skills. In general, there is evidence in the literature showing the effectiveness of hazard perception training. A combination of complementary training approaches such as instruction, expert demonstration, and active practice with feedback and attention support using picture-, video-, computer-, and simulator-based training methods can improve hazard perception performance in terms of shorter hazard perception reaction time, higher hazard hit rate, and better eye scan patterns (more spread scan, more anticipatory scan). These findings could guide future work developing and designing hazard perception training programs. Three future research areas were identified and discussed, including the need for standardized hazard perception tests, long-term testing of hazard perception training programs, and new hazard perception questions and challenges brought by partially automated vehicles.

Keywords: hazard perception; driving safety; driver training; standardized tests; eye movements.

INTRODUCTION

The cognitive process of driving can be described as three stages including perceiving driving-related information, making decisions, and taking actions to control the vehicle. Hazard perception (HP) is within the perception stage. In the surface transportation literature, a hazard generally refers to "any object, situation, occurrence or combination of these that introduces the possibility of the individual road user experiencing harm" (*1*). It covers many different types of hazards from different sources, such as hazards from the driver (e.g., fatigue, alcohol, and distracted attention), hazards from the traffic (e.g., a leading car that suddenly brakes, a pedestrian crossing the road, and obstacles on the roadway), hazards from the natural environment (e.g., fog, rain, and snow), and hazards from the driver's vehicle (e.g., engine malfunction, tire explosion, and brake malfunction). Depending on the threat imminence level, hazards can be grouped into immediate hazards (or materialized hazards) and non-immediate hazards (or unmaterialized, latent hazards). Immediate hazards can be defined as hazards that required a driver "to take immediate action (e.g., braking or swerving) to avoid a dangerous interaction with another road user," whereas non-immediate hazards can be defined as "hazards that did not require immediate evasive action but required attention in case they developed into immediate hazards" (*2*). Depending on their visibility, non-immediate hazards can be further grouped into potential or overt non-immediate hazards (visible) and hidden or covert non-immediate hazards (not visible) (*3*).

HP is the process of identifying hazards - also used to refer to the skills or capabilities to identify hazards (*4*). Studies have shown that poorer HP skills are associated with higher rates of accident involvement (*5–7*). It has been shown that including HP tests in the driver licensing process has benefits in terms of reducing crash rate and enhancing traffic safety (*8*). HP is related to situation awareness (SA) (*7*). SA is about the degree to which the available information in working memory meets the needs to successfully perform the task (*9*). HP can be considered as the situation awareness regarding hazards (*3*). Corresponding to Endsley's model (*10*), situation awareness regarding hazards in driving is posited to comprise of three components including the ability to constantly perceive hazards on the roadway, the comprehension of the severity of potential adverse events caused by the hazard, and the ability to project the status of the hazard in the near future.

Over the past decades, many studies have examined factors that affect HP. They have found multiple human factors such as driver's knowledge and experience that can affect HP. Studying and understanding HP are important for promoting driving safety. Although novice drivers have learned some basic skills for driving a vehicle and passed the licensing exams, they could still lack proper skill proficiency and skills for HP, which may contribute to their overrepresentation in accidents (*11*). Despite the great amount of literature in this field, there is a lack of a comprehensive review that addresses multiple core aspects pertaining to HP. In the current paper, we aim to provide an organized review as a reference for researchers, by summarizing various approaches of HP measurement and HP training under different hazard scenarios. The objectives include (1) documenting the methods used to measure HP, (2) summarizing various human factors that affect HP, (3) highlighting different training methods developed to improve HP, and (4) discussing potential future research directions.

METHODOLOGY AND SCOPE OF REVIEW

The current paper presents a systematic review of literature on HP in driving. Reviewed studies included both laboratory simulation and real-world driving studies. Articles were included in the review if they met the following criteria – a) demonstrated clear alignment to the purpose of the review in terms of the four objectives specified above; b) presented clear experimental evidence; c) retrievable online; and d) written in English. Articles were excluded from the review if they – a) qualified as non-peer-reviewed literature and b) included small samples.

A comprehensive search of various databases was conducted to identify peer-reviewed, English language publications from indexed electronic and digital sources. The various electronic journals and databases that were scoped include PubMed, TRID (Transportation Research International Documentation), CiteSeer, Scopus, Ref-Works, Web of Science, Mendeley, and Google Scholar. Additional articles were searched, verified, and scoured using a snowballing approach of scoping identified articles for additional references.

The keywords for the search process were driven by a preliminary environmental scan. Specific keywords used in the search process included – "hazard perception"; "hazard anticipation"; "latent hazard anticipation"; "hazard detection"; "hazard perception training"; "latent hazard anticipation training"; "tactical hazard perception"; "strategic hazard anticipation"; "measurement hazard perception"; "situation awareness"; "SAGAT"; "eye tracking in hazard perception"; "age related differences in hazard perception". These key phrases were searched in the "title" and "abstract" fields of the databases identified above.

Following quality assessment (two researchers combed through the sources to ensure adherence to inclusion/exclusion criteria), our systematic search yielded 69 peer-reviewed studies that met all criteria and satisfied the scope of the review. Fifty-six studies were laboratory based (38 studies used videos or images, 15 studies used driving simulators, and 3 studies used questionnaires or focus groups), while the remaining 5 studies were either conducted on the open road or on a closed-loop track. Two studies were laboratory based as well as conducted on-road, and 6 studies were meta-analyses or reviews. Among the 69 studies, 39 focused on measurement of HP, 28 studied the human factors affecting HP, and 25 studies evaluated training-based methodologies to improve HP. The findings from these studies are reported and discussed in the subsequent sections.

MEASURING HAZARD PERCEPTION

Researchers studying HP usually focus on traffic hazards, such as sudden emerging pedestrians or motorcycles. Anticipation and quick identification of traffic hazards are not easy and require knowledge and experience (*12*). HP is often measured using tests showing driver-perspective video of traffic situations. Some videos were real footage recordings (e.g., *13*), whereas others were computer generated video clips (e.g., *14*, *15*). Test-takers are often asked to identify traffic hazards presented in the video. In the instructions to test-takers, hazards are explained as traffic conflicts – situations in which the driver needs to take actions such as braking, steering, or sounding the horn to avoid potentially dangerous interaction with another road user (e.g., *16*, *17*). Using a video-based HP test, for example, a study (*18*) showed that drivers who failed the test were more likely to be involved in crash during a one year period following the test.

Driving simulators have also been used to test HP. Simulators allow researchers to observe drivers' steering, accelerator and brake actions, as well as other operations while simulated hazards are presented. For example, Chan et al. (*19*) measured eye tracking results from both newly licensed and experienced drivers in a driving simulator. The results showed that novice drivers glanced for longer periods of time inside the vehicle, and the eye fixation patterns were similar to the authors' knowledge of results in real-world driving studies. Takahashi et al. (*20*) measured older drivers' responses to hazards in a driving simulator and found the impact of decreased cognitive function on hazard perception and response.

Both video-based and simulator-based HP tests require dynamic driving scenes. Alternatively, picture-based tests that use static images as testing materials have also been examined (*21*, *22*). Static test materials are easier to make, but there was only a weak correlation between static and dynamic test results (*23*), and there has been no evidence to support that static tests can replace dynamic tests. Nevertheless, all these tests are safer than on-road testing because they can reliably recreate traffic hazards and avoid exposing drivers and their assessors to danger during on-road testing (*24*).

To assess HP, researchers have used both questionnaires and behavioral index measures. In some HP tests using multiple-choice questionnaires (*15*, *25*), participants were given pre-recorded traffic scenarios to review and then asked if they were aware of a potential hazard within the observed scenario. If their answer was affirmative, they were presented with a multiple-choice question where each alternative answer contained a short description of a hazardous situation that could have occurred within the scenario. Another scheme is to use SA questionnaire techniques for measuring HP. The Situation Awareness Global Assessment Technique (SAGAT) (*9*) can be used, which involves freezing the video clip prior to the hazard occurring at a pre-determined time unknown to the participant and asking questions to measure awareness about current and near-future situations. For example, researchers have used SAGAT method with questions such as "What was the source of the hazard? What was the location of the hazard? What happens next?" (3Ws). Participants' responses were then numerically scored by awarding 2 points for a correct response, 1 point for a partially correct response, and 0 points for an incorrect response (*26*). Similar questions and scoring methods have been used in several studies (e.g., *27–31*) as well as in the Multiple-Choice Hazard Perception and Prediction test (*32–34*). In one study, researchers (*35*) used questions to measure both detection and cautiousness such as "Had you seen any hazard at the moment when the video was cut?" (detection) and "What manoeuvre would you perform if you were the driver of the vehicle?" (cautiousness). It is important to note that only the detection question is about HP. The cautiousness question is about decision and responses that are beyond the scope of HP.

While questionnaires provide a direct way to measure whether a driver has perceived the hazard, these methods often interfere with the natural flow of driving. In addition, questionnaire methods could not examine how fast drivers can recognize hazards. In this regard, behavioral index measures such as reaction time can be used to quantify HP without interference with the driving task. Previous studies have used behavioral indexes, including reaction time, hit rate, and eye tracking measures for HP.

The reaction time of HP, also called HP time duration or HP latency, is measured from the moment a conflict becomes recognizable to the driver to the moment that it is reported by a button press or a mouse click. For immediate hazards, the timing usually begins when the hazard is visible to the driver. For non-immediate hazards, the timing may start at the moment when test designers believe most drivers should anticipate potential risk from an object or a big object blocking the view to potential hidden hazards. Since non-immediate hazards pose no immediate threat and do not require immediate evasive action, HP reaction time is usually not an important measure for non-immediate hazards (instead, HP hit rate could be used). The validity of each response should be checked to avoid participants guessing or cheating. Some researchers have considered using time windows to exclude very early responses (*26*), but there has been no consensus on how to optimally calibrate these response windows. Although it is usually assumed that HP time duration should not be shorter than simple reaction time duration (typically around 200-300 ms), it is still possible for some drivers who utilize early cues to respond very fast (*24*). Instead of time windows, a better validation approach is to check the intention of responses by recording participants' verbal report for each hazard identification and check if the identified object is a valid target (e.g., *4*, *36*).

The accuracy of HP is often measured as hit rate, which is calculated as the ratio of the total number of correctly identified hazards in a test to the total number of hazards appeared in the test as defined by test designers. From a signal detection theory perspective, correct rejection rate might also be useful, but it is usually very difficult to quantify because it requires knowing the total number of non-hazards appeared in the test scenario. Since essentially all the objects other than hazards are non-hazards, it is difficult to quantity the total number of non-hazards because there are too many. In some studies, only the total number of correctly identified hazards was reported; however, it prevents comparison across studies because different studies may use different numbers of hazards. We recommend comprehensively reporting HP hit rate as well as the total number of correctly identified hazards and the total number of hazards appeared in the test.

Speed-accuracy trade-off is a frequently observed human behavioral characteristics. It means that people can choose to focus on getting either faster reaction speed or higher accuracy, but it is difficult to achieve both at the same time (*21*). Since reaction time and hit rate are two separate measures, some researchers have proposed ways to combine them into a single measure. One of the methods creates a time duration value for missed trials by assigning it the maximum reaction time value observed from the participants (*36*–*38*), so the overall reaction time of HP will cover both hit and miss trials. Another method is to formulate a scoring scheme that reflects both reaction time and hit rate. For example, faster responses in a trial yield higher scores (up to 5 points), and missed or wrong responses yield a score of 0 (*39*). Other researchers have also suggested calculating the z-scores of reaction time and hit rate separately and then getting the average of z-scores for each participant as the combined measure (*40*). However, there has been no consensus on the optimal method for combining reaction time and hit rate measures. Our recommendation is to report both to provide a comprehensive representation of HP performance.

Regarding eye tracking measures for HP, previous studies have used fixation probability, fixation reaction time, fixation duration, and fixation variance. Eye fixation means the maintaining of the visual gaze on a single location. To determine whether a hazard is fixated, a region of interest is defined surrounding the hazard, and then researchers calculate whether a fixation falls within this region of interest. For example, in one study using a video-based HP test (*41*), the region of interest for pedestrian hazards was defined as a rectangle surrounding the pedestrian with an additional width and height of 1° visual angle, roughly representing the area of foveal vision. Fixation measures rely on the assumptions that fixation means hazard perceived, and no fixation mean not perceived. These assumptions are often true but not always true. On the one hand, people may fixate on familiar objects but fail to perceive them due to inattentional blindness (*42*). On the other hand, peripheral vision can also be used to perceive simple objects such as light, simple symbols, and moving cars (*43*–*45*). Therefore, fixation measures for HP should be interpreted with caution, and we recommend the use of verbal confirmation, that is, participants should verbally report the name of the hazard they see.

In the literature, fixation probability, or glance probability, has been used to measure the percentage of hazards perceived by drivers (*12*, *41*, *46*, *47*). A successful fixation, i.e., a fixation that falls in the predefined area of interest, is denoted by '1', while '0' represents failure. Fixation probability is the success rate of fixation over all hazards. Some researchers have emphasized the importance of anticipation in HP and argued that a hazard perceived too late should not be considered as a success. Therefore, they proposed the use of launch zones regarding the position of the driver's vehicle. A launch zone is defined for each hazard and represents the area of the roadway where the driver should begin glancing at the hazard to be able to successfully anticipate and mitigate the threat (*48*). When the launch zone method is used, fixation on a hazard is only counted as a success if the driver's vehicle is within the launch zone defined for the hazard. In general, a higher fixation probability represents better HP. But there has been no established standard about how to set the launch zone for each hazard.

Fixation reaction time, measured as the duration from the onset of a hazard to the moment when participants first fixate on the hazard, has also been used (*12*). Theoretically, fixation reaction time should be shorter than the reaction time of HP measured by manual responses because of the extra time needed for manual processes. The measure of fixation reaction time has an advantage over manual response measure of HP reaction time because fixation reaction does not require any key press and therefore avoids adding interference with natural driving.

Some studies have also reported fixation duration, which refers to the duration of each fixation on hazards (*12*, *41*). Typically the average of fixation duration is around 150-300 ms (*49*). The relationship between fixation duration and HP performance is not straightforward (*50*). In one study (*12*), experienced drivers produced longer average fixation duration than learners; in contrast, another study found that experienced drivers produced shorter average fixation duration than learners (*41*). While longer fixation duration generally means a higher amount of attention devoted to perceiving the hazard, the effectiveness of a fixation also depends on drivers' knowledge and skills. Drivers need to divide visual attention resources (represented by fixation duration) properly across multiple visual targets. Ideally, each fixation duration should be long enough to allow the extraction of important information concerning a potential hazard, but not too long to hinder the processing of other visual targets. It is generally regarded that fixation duration within 100-500 ms is appropriate to process the information (*49*), but the proper duration is affected by many factors such as road environment complexity and lighting conditions (*51*, *52*). Since the optimal fixation duration has not been determined, more studies are needed, and researchers are encouraged to report fixation duration to accumulate data for future meta-analysis.

Another measure related to drivers' visual scan pattern is fixation variance (in degrees of visual angle squared), which refers to the variance of fixation locations (in degree) along the vertical and horizontal median (*53*). Studies have shown that experienced drivers had greater spread of visual search represented by larger fixation variance (*53*, *54*). Since it is generally preferred to have visual attention spread across the visual field to scan more hazards, larger fixation variance is usually regarded as an indicator for better HP.

While the above eye fixation measures are clearly applicable to immediate hazards, their application to non-immediate hazards requires more careful thoughts and definition. In the case of potential or overt non-immediate hazards that are visible but have not materialized into a course of collision with the driver's vehicle, it is important to define the critical time window when the driver needs to scan these visual targets to anticipate and become awareness of these non-immediate hazards, and then valid eye fixations within this time window can be regarded as indication of good HP. In the case of hidden or covert non-immediate hazards that are not visible, such as hidden pedestrians behind a bus or hidden oncoming traffic behind a truck, it is important to define both the critical time window when the driver needs to scan them and the area where such hidden hazards may appear. Eye fixations in this area within this time window are indication of good HP. This does not mean all the big objects such as trucks and bushes should be defined as areas of hidden hazards that need to be scanned. Only the big objects in scenarios with clear cues of hidden hazards should be considered; for example, the cues could be school crossing signs, bus stop with crosswalk, intersection, and left turn waiting area. Eye fixations on non-immediate hazards are sometimes referred to as anticipatory glances (*55*, *56*). Since there is no imminent threat from non-immediate hazards, reaction time measures are usually not considered for non-immediate hazards.

In summary, HP can be measured using both dynamic tests (video-based and simulator-based) and static tests (picture-based). Although picture- and video-based tests are easier to conduct, simulator-based tests are better in terms of capturing multiple sources of mental demands similar to real driving scenarios. In driving simulators, HP can be examined under limited attention resources while some attention resources are used to drive the vehicle as in on-road driving. Video-based tests are generally better than picture-based tests, because HP involves anticipating potential hazards using precursors of hazards (*12*), which are typically lacking in static tests. Table 1 provides a summary of all behavioral measures of HP discussed above with notes and recommended practice.

Table 1. Summary of behavioral measures of hazard perception.

Measure name	**Definition**	**Notes and recommendation**	**References**
Response reaction time	The duration of time from the moment a conflict becomes recognizable to the moment it is reported, usually by pressing a button	It is recommended for drivers to verbally report the hazard they see, to avoid guessing and incorrect objects being identified. Reaction time should be reported together with hit rate.	- Jackson et al., 2009 - Wetton et al., 2011 - Borowsky et al., 2010 - Shahar et al., 2010
Hit rate	The ratio of the total number of correctly identified hazards in a test to the total number of hazards appeared in the test as defined by test designers	It is recommended to report hit rate as well as the total number of correctly identified hazards and the total number of hazards appeared in the test.	- Shahar et al., 2010 - McKenna et al., 2006 - Markkula et al., 2016 - Hoffman & Rosenbloom, 2016
Eye tracking measures			
Fixation probability	The ratio of the number of hazards that have been fixated to the total number of hazards	It is recommended to ask participants to verbally report the name of the hazard they see as a confirmation.	- Borowsky et al., 2012 - Crundall et al., 2012 - Hajiseyedjavadi et al., 2017 - Pradhan et al., 2005 - Samuel & Fisher, 2015
Fixation reaction time	The duration of time from the onset of a hazard to the moment when participants first fixate on the hazard	It has an advantage over manual response measure of HP reaction time because it does not require any key press and therefore avoids adding interference with natural driving.	- Crundall et al., 2012
Fixation duration	The duration of time of each fixation on hazards	Since the optimal fixation duration has not been determined, more studies are needed, and researchers are encouraged to report fixation duration to accumulate data for future meta-analysis.	- Borowsky et al., 2012 - Crundall et al., 2012
Fixation variance	The variance of fixation locations along the vertical and horizontal median.	Since it is generally preferred to have visual attention spread across the visual field to scan more hazards, larger fixation variance is usually regarded as an indicator for better HP.	- Crundall & Underwood, 1998 - Mourant & Rockwell, 1972

HUMAN FACTORS AFFECTING HAZARD PERCEPTION

From the literature, we identified experience, aging, fatigue, distraction, and the use of alcohol and drugs as major factors that impact HP.

Experience

Researchers generally believe that HP skills improve with the accumulation of driving experience (*57*). This is evident in studies that examined the validity of HP tests and driving simulators by comparing performance between novice and experienced drivers (*21*, *24*, *41*, *50*). Many studies have found that experienced drivers have better HP than less experienced drivers, in terms of faster HP reaction time (*13*, *15*, *21*, *22*, *58*), faster fixation reaction time (*12*), higher hazard hit rate (*14*, *15*, *59*), and higher fixation probability (*12*, *47*). The visual scan pattern of experienced drivers showed greater fixation variance (wider spread of fixation locations horizontally and vertically), indicating that they are better at spreading attention to a wider range of visual targets (*53*, *54*). In general, previous studies suggested that the knowledge and skills developed as drivers gain more experience include the visual search strategy to allocate attention across multiple objects, knowledge about the characteristics of hazards, and knowledge about the link between precursors and hazards, all of which are the reasons of better HP performance. These results underly the foundation for HP training.

Factors affecting cognitive process

Since the process of HP relies on visual search, attention resources, and pattern recognition, factors affecting cognitive process will also affect HP performance. In the literature, a group of factors belong to this category, including aging, fatigue, distraction, alcohol, and drugs.

a. Aging

Horswill et al. (*60*) measured HP reaction time from older drivers (118 participants with age 65–84 years, and each had at least 10 years of driving experience). The HP test used edited video recordings from real-world traffic scenarios that contained immediate hazards. The results showed that HP reaction time correlated with age, with older drivers having longer HP reaction time. The drivers' simple reaction time, visual contrast sensitivity, and visual useful field of view were also measured and included in a regression model to predict HP reaction time. The result showed that "contrast sensitivity, useful field of view, and simple reaction time could account for the variance in hazard perception, independent of one another and of individual differences in age" (*60*), which means that within this older age group, the negative impact of aging on HP could be caused by slow down and degradation in the cognitive and vision processes.

b. Fatigue

Examining HP reaction time in a video-based test, researchers (*17*) found that sleepiness significantly increased HP reaction time for novice drivers (aged 17–24 years), whereas HP reaction time from experienced drivers (aged 28–36) was not significantly affected by sleepiness. This result suggests that experienced drivers may have more robust skills for HP that are more resilient to fatigue. Regarding age and experience, it is difficult to control and separate their effects because older drivers typically have more experience than younger drivers (*61*). With older adults (65 years and above), the effect of aging could be stronger than the effect of experience; with younger adult groups, such as the groups in this fatigue study (no more than 36 years old), the effect of experience is expected to be stronger than the effect of aging.

c. Distraction

Distraction during driving may present significant risk to drivers. Distraction could be visual (e.g., reading emails), auditory (e.g., listening to radio news), mental (e.g., thoughts not related to driving), speech (e.g., speaking over the phone), manual (e.g., pressing button on an interface), or the combination of the above. Regarding visual and manual distraction such as texting, studies using driving simulators have found that texting while driving significantly increased HP reaction time (*62*, *63*). For mental distraction, a study using video-based HP tests found that concurrent mental tasks (solving puzzles) also significantly increased HP reaction time (*64*). However, results regarding auditory and speech distraction were mixed. While some studies found that conversation during driving reduced reaction time (*65*–*68*), other studies found that conversation while driving resulted in increased HP reaction time and decreased hit rate (*69*, *70*). In summary, most non-driving in-vehicle tasks are expected to impair HP with the exception for verbal conversation in some driving situations.

d. Driving under influence

Driving under influence (DUI) of alcohol or drugs is a common problem (*71*–*73*). A review study (*74*) showed strong evidence to support that blood alcohol concentration (BAC) 0.05% or higher can significantly impair driving performance and increase crash rate. A recent review (*75*) showed that studies using cannabis dose around 10-20 mg Δ9-tetrahydrocannabinol (THC) all found significantly negative impact on driving performance. The combination of low BAC (0.04%) and low THC (around 70 ng/ml pre-drive) has been found to have an additive effect to produce an additive decrement on driving performance (*76*). While previous studies measured driving performance such as lateral control and speed control, fewer studies have particularly examined the effect of DUI on HP as an aspect of driving performance. A study found HP reaction time was significantly increased by 0.3 s (in 0.025% BAC condition) and 0.7 s (in 0.05% BAC condition) due to alcohol. However, one study found that very light consumption of alcohol (0.015% BAC) increased HP hit rate in comparison to 0% BAC (*77*). Regarding cannabis, a study found no significant impact of cannabis dose around 10-20 mg THC on HP in comparison to the control group with 0.035 mg THC (*78*).

In summary, HP skills develop with driving experience. Research suggests that important knowledge and skills supporting HP include the visual search strategy to allocate attention across multiple locations and targets, knowledge about the characteristics of hazards, and knowledge about the link between precursors and hazards. Previous studies have examined many human factors affecting HP, including experience, aging, fatigue, distraction, and the use of alcohol and drugs. These findings have provided the foundation for the design of HP training programs (*79*, *80*).

HAZARD PERCEPTION TRAINING

In most countries, driver training is provided by experienced driving instructors. Novice drivers' knowledge and skills are usually developed through reading materials, viewing instructors' demonstration, and supervised practice with feedback from instructors (*81*). Traditional driver training often focuses on vehicle control skills. It alone is insufficient to support the development of HP skills (*11*, *82*), and learners in traditional driver training usually cannot experience the full range of hazardous situations. To address this issue, specialized HP training programs have been developed (e.g., *80*).

HP training involves various training materials and is based on several training methodologies and techniques that are summarized as follows. From a skill training methodology point of view, HP skills can be acquired through instructions and active practice. Instructions provide trainees declarative knowledge such as safety facts and what they should and should not do, and then repeated practice allows trainees to apply declarative knowledge in performing the tasks and gradually form procedural knowledge through skill acquisition (*83*).

Instructional training methods generally include instructions, demonstration, and expert commentary. For example, Meir et al. (*84*) used written instructions with pictures of hazardous situations to conceptually teach the types of hazards and where they are most likely to appear. Ivancic and Hesketh (*85*) used video clips that demonstrated HP errors such as failure to identify a hidden car and failure to identify a red light that resulted in collision or police tickets. McKenna et al. (*37*) and Wetton et al. (*86*) used video clips of various traffic situations recorded from the driver's perspective with expert commentary training that explained potential hazards and where to look for them to maximize the chance of identifying them. In another unique study, Castro et al. (*29*) examined the effect of proactive listening to a training commentary. In this training, participants listened to a speech commentary with information about how to allocate their attention in complex driving scenes, and the real consequences of the scenes were revealed at the same time. It resulted in improved HP performance for the participants on a post-intervention What Happens Next (WHN) Assessment. In the work of Isler et al. (*16*), young drivers received video-based road commentary training, and their HP abilities were tested afterwards. Trained young drivers detected and identified significantly more hazards (M= 77.2, SD = 6.5) than the age and driving experience matched control group (M = 62.5, SD = 11.6); the two groups had the same HP performance before the training.

Different types of attention support can be used in instructional training and active practice to reduce participants' cognitive load on driving activities. Practice without any guide or support, equivalent to self-learning without training, is often used as a baseline condition to be compared with different training methods. According to the cognitive load theory (*87*), novice drivers' mental resources are mostly occupied by basic driving tasks such steering and speed control, and they have limited mental resources for learning HP. Therefore, HP training programs should be designed to reduce trainees' cognitive load from activities unrelated to HP training and help trainees focus on self-reflection and learning, for example, by guiding drivers' attention (*88*). As trainees advance in the training process, guidance and support of the trainee's attention can be gradually reduced and eventually removed to allow the adaptation to actual driving.

Video-based and picture-based HP tests can help reduce cognitive load while HP training, because the vehicle control components of driving are not included in these tests. For example, researchers used a video-based HP test that included 63 video clips with different kinds of hazards and traffic environments for training purposes (*84*). The video playing speed may be slowed, for example, at half speed to further reduce task difficulty and cognitive load (*89*). Some researchers have also used methods that freeze video clips at critical moments to ensure enough time for deep thinking and reflection (*86, 89*). Trainees could be probed using questionnaires, similar to SAGAT (*9*), to strengthen their thoughts on what has just happened and what will happen next. Continuous video clips may be simplified into a sequence of pictures (screenshots). For example, Pradhan et al. (*90*) used such 3-second screenshots to present driving scenes from the driver's perspective looking straight ahead, while left or right views were also provided at intersections. Trainees were asked to click on the areas to which they would pay attention for potential hazards. However, screenshots make it difficult for trainees to judge the driving speed. Petzoldt et al. (*91*) developed a computer-based training (CBT) module that complemented existing driver training programs. In the study, video sequences of potentially hazardous driving situations were used followed by multiple-choice questions with adaptive feedback for improving the understanding of the scenarios. The results of a simulator test confirmed that participants using this CBT had quicker glances towards critical cues and relevant areas in their visual field than participants who received paper-based training with similar content or no training at all. This result demonstrated the potential of this CBT module in supporting the development of HP skills.

Figure 1. Example of a computer-based HP training program (*92*). The program provides simulated drives where users can interact by clicking on hazards (e.g., a car pulling out, red solid arrow).

Some training techniques were found useful in training drivers to enhance HP in driving. Repeated exposure to specific hazards has been shown to improve HP. In a study by Kahana-Levy et al (*93*), both inexperienced and experienced drivers participated in a training session that involved viewing repetitions of HP video clips each representing one type of hazard, embedded among filler videos. The eye-movement data and performance in the subsequent transference sessions where novel hazards video clips are used indicated an early fixation on hazards from the trained groups in comparison to untrained groups. The results suggested that repetitive training was effective for both inexperienced and experienced drivers.

Another way to support trainees' skill learning is to direct their attention towards hazards. During normal driving, drivers need to divide attention across multiple task components such as steering control, speed control, road monitoring, and trip planning. Drivers may also engage in thoughts not related to driving, i.e., mind wandering (*94*). One technique that has been used to help trainees focus on HP is commentary training, where participants are asked to continuously verbalize their thoughts regarding hazards that they detect. Participant commentary training was often applied while trainees were watching driver-perspective video clips (*16*, *89*). In one study (*82*), trainees were asked to continuously verbalize their HP process as well as how they would do to avoid risky situations while they drove on the road with an instructor. While the commentary is expected to help trainees focus their attention on perceiving hazards, it creates additional workload to drivers and could be detrimental to driving performance and safety (*95*).

Feedback is also important to learning and self-reflection. Horswill et al. (*96*) showed that adding feedback on drivers' performance in a video-based HP training task resulted in an improvement in HP time performance in comparison to the control group with no feedback. In addition, Chapman et al. (*89*) used visual cues to guide trainees' visual attention to critical areas where hazards were likely to appear. In the video clips, areas of interests were circled in blue or red color. These attention support methods could help trainees in the initial stages of learning.

Through instructional training, trainees can quickly learn a wide range of hazardous situations that would otherwise take a long time to acquire from on-road driving practice. However, instructional training does not provide the deep level of involvement as active cognitive processing does in practice training, and active practice is necessary for the acquisition of cognitive skills (*97*). Therefore, the two approaches should be combined to achieve maximal effects. Wetton et al. (*86*) reported a training package combining video-based "what happens next" exercises and self-generated commentary training. Participants who received full training package had a significantly larger reduction in HP response time ($M = -4.32$ s, $SE = 0.43$) compared to those in the control group ($M = -0.14$ s, $SE = 0.41$). Chapman et al. (*89*) reported a training package that included participant commentary training and practice with task simplification and support (slowing down, freezing, and visual attention guide). The materials were video clips of potentially dangerous driving situations. Training for about 50 minutes produced notable changes in the participants' visual search patterns, and some of the changes were still detectable after a few months (*89*).

To incorporate active practice, feedback, and attention guidance into instructional training, some training programs have used an error-based training approach. For example, Risk Awareness and Perception Training (RAPT) is a computer-based training program that focuses on anticipation of hazards and combines active practice and instructions (*90*, *98*). The practice is based on HP tests using screenshots. The hazards focused on hidden road users and abrupt movement of other road users, for example, a bicyclist or a pedestrian hidden behind a hedge, cars obscured by bushes or other vegetation, cars hidden behind hills, and cars that abruptly change lanes. Trainees were required to click on the areas to which they would pay attention for potential hazards. If they failed to click on the correct areas, plan views (top-down views showing positions of the driver's car and other objects) of hazardous situations and accompanying written instructions were shown to explain potential hazards and where to look for them. It does not mean all big objects such as trees and bushes should be defined as areas of hidden hazards that need to be scanned. Only the big objects in scenarios with clear cues of hidden hazards should be considered; for example, the cues could be school crossing signs, bus stop with crosswalk, intersection, and left turn waiting area.

Trainees receiving training for about 45 minutes had significantly higher hazard hit rate (64.4%) than the untrained control group (37.4%) (*90*), and this increased hit rate due to training did not diminish after about 8 months (*99*). Subsequent versions of RAPT administered on web and tablet were found to be effective (in terms of increased hazard hit rate measured in HP tests) immediately after training and for up to 7 months after training (*92*, *100–102*). However, these studies did not collect data regarding any potential effect on crash rate. Additionally, the effect of the RAPT program has been investigated on newly licensed young drivers (*103*). After 12 months of tracking post-licensure, analyses of pre-test and post-test data indicated performance improvements in trainees who completed the RAPT program. However, the increase in the number of correct responses after the training does not necessarily indicate an increase in risk perception or hazard recognition knowledge. Gender differences were also observed with a decrease in the crash rate for males, but not females. Nevertheless, the findings suggest that RAPT can have a positive influence on the driving safety of young novice drivers.

In comparison to computer-based training programs, simulator-based training can further utilize driving simulation to train and practice HP skills in dynamic driving situations. In computer-based training, the displayed environment and drives are fixed and do not change as a function of the participant's inputs. In simulator-based training, participants take control as the driver of the simulated car, and they could experience in real time the consequences of failing to detect a hazard. Research by Vlakveld et al. (*56*) revealed that simulator-based training can enhance novice drivers' visual search for non-immediate hazards. The participants underwent Simulator-based Risk Awareness and Perception Training (SimRAPT) with elicited crashes and near-crashes in a driver training simulator and were then assessed on an advanced driving simulator. In the post-training evaluation, both near transfer (where the hazards were similar to the trained situations but in a different environment) and far transfer scenarios (where the hazards were different from the trained situations) were tested. Eye tracking results showed that in comparison to untrained drivers, the trained drivers had significantly higher hazard fixation probability (i.e., better HP) in both near and far transfer scenarios. Note that in this study (*56*), drivers' glances towards the general areas where non-immediate hazards may appear and materialize were used as indication of good HP (hazard anticipation).

Moreover, researchers have started to combine multiple training methods to enhance training effectiveness. Isler et al. (*82*) examined a 5-day training package that combined participant commentary training with expert feedback (on-road driving), video-based HP training, and on-road driving practice (without commentary). The results showed that the combined training package produced significant improvement on HP hit rate; in contrast, the vehicle handling training group and the control group showed no such improvement.

Meir et al. (*84*) examined Act and Anticipate Hazard Perception Training (AAHPT). The AAHPT hybrid mode combined instructional training and active practice. The instructional training explained hazards using example situations, where immediate and non-immediate hazards were circled and highlighted for easier identification. The practice training used a video-based HP task that included different kinds of hazards, roads, and traffic environments. Trainees were required to press a response button each time when they detected a hazard.

To comprehensively evaluate the effectiveness of HP training, both near (apply directly to situations learnt in training) and far (apply to a new situation) transfer needs to be considered (*85*, *104*). McDonald et al. (*105*) reviewed 19 studies published between 1980 and 2013 and highlighted evidence to support the effectiveness of various HP training methods regarding both near and far transfer. However, the authors also noted several limitations in these studies, such as a lack of standardized tests and immediate assessments. Only one study evaluated training effects after about 8 months (*99*). Since HP skills are likely to decay at the early learning stage (*86*), long-term skill retention studies are needed to confirm that training effects can sustain over a long period of time.

Regarding the measures used to assess HP training effectiveness, previous studies used HP measures such as HP reaction time, hit rate, and eye tracking measures. These measures focus on measuring only the perception and awareness of hazards by excluding decision making and vehicle control actions that follow the process of perception. However, it is important to note that the assessment of real-world benefits on reducing accidents and crashes will require the examination of all three processes including perception, decision making, and response actions. There is a lack of studies examining whether the expected benefits of HP training can translate into reduction in crash rates (*105*).

In a driving simulator study, Zhang et al. (*106*) examined the effectiveness of a computer-based training program (SAFE-T) (*107*) using hazard mitigation measures including velocity and acceleration when the driver's car is approaching the hazard. The four tested scenarios included Bus Bicyclist, Stop and Turn Left, Opposing Lane Roadwork, and Car in Parking Lane, where other road users such as bicyclists, pedestrians, and vehicles were potential non-immediate hazards (visible), and the driver should slow down for them. The results showed that "the only significant difference between placebo and trained drivers in vehicular control is that trained drivers maintained a larger deceleration when approaching the potential hazard in the Bus Bicyclist Scenario." (*106*). This result suggests that HP training needs to be combined with hazard response and mitigation training to strengthen the effects on driving safety and crash reduction. Future studies need to use more holistic approaches that include all three processes of perception, decision making, and response actions to examine the effect of hazard training on reducing accident and crash rates, using simulator studies or real-world driving data analysis.

In summary, previous studies showed that a combination of complementary training approaches such as instruction, expert demonstration, and active practice with feedback and support is important and effective for HP training (*86*). Table 2 provides a summary of HP training methods reviewed in this paper. In early training stages, more instructions and simpler training methods (e.g., picture- and video-based training) could help reduce trainees' mental workload; in later stages of training, the combination of multiple training methods including simulator-based training could further strengthen the knowledge transfer from training courses to real-world scenarios. Some evidence has been found to support the effectiveness of the reported training programs in terms of improved HP performance. Methodological studies are still needed to establish standard tests and indexes that allow comparison across different training methods. Future studies are also needed to examine long-term effects of training in order to connect the short-term effects to potential reduction in crash rates.

Table 2. Summary of hazard perception training methods reviewed in this paper.

Paper	Content of training (Hazards scenarios involved in training or testing)	Variables (groups)	Evaluation methods	Conclusion
Ivancic and Hesketh, 2000	In a left-hand traffic environment, training scenarios includes: 1) Left lane blocked with oncoming vehicles. 2) Traffic signals at an intersection with cross traffic. 3) Road sign with curved arrow, followed by road curving sharply to the right. 4) Both right lanes blocked with oncoming vehicles. 5) "High wind" road sign followed by speed limit sign. 6) Left lane blocked by a concrete barrier.	Two training groups: Error training group; Errorless training group.	1. Number of errors (either a crash or a police ticket) committed on the transfer tests. 2. Driving speed; 3. The number of strategies recalled; 4. Self-perceived confidence level.	Compared with errorless learning, error training leads to significantly better transfer to driving tests and novel driving situations.
Chapman et al., 2002	In the training, a series of videos based on films which include potentially dangerous driving situations were used as training material. No specific scenarios mentioned in the paper. Participants needed to anticipant the situation, comment on scenarios or do button response during the training.	Two groups of drivers were evaluated: Training intervention group; Control group.	1. Driving measurements: a. Free speed; b. Time Headway. 2. Visual search measures: a. Fixation duration; b. Horizonal variance; c. Vertical variance.	The training intervention produced notable changes in the drivers' search patterns, though some changes were no long detectable after a few months.
McKenna et al., 2006	The training method is commentary drive. The trained group was required to watch a 21-min video of various road and traffic situations, with a recorded commentary from a police driver training program. The commentary referred to potentially hazardous events and how to identify them.	Two groups: Trained group (trained with video and recorded commentary); Untrained group.	Two types of measures done after the training: 1. Risk-taking measures Motorway speed; Questionnaire speed; Video speed; Violation questionnaire; Normal following distance; Uncomfortably close distance; Gap acceptance. 2. Hazards perception measures: Averaged reaction times over each hazard.	Participants who received training responded significantly faster in the hazard perception test than those who did not.
Pollatsek et al., 2006	In the training scenario, 10 scenarios would be presented including left fork, adjacent truck left turn, intersection, etc. Drivers moved symbols to indicate hazards, and they will receive feedback screens of each scenario. In the simulator test, drivers followed a leading vehicle and operated the car just as they did in real world with an eye tracking device mounted.	Two groups: Trained group; Control Group.	In training session, the performance was measured by probability risk recognized. In simulator test session, a series of criteria were developed base on participants' eye fixation behaviors. And a score of 0 or 1 would be given depends on whether the risk was identified.	Trained novice drivers were almost twice as likely as untrained drivers to fixate on the area which contains information about potential hazards for both near and far transfer scenarios.
Pradhan et al., 2009	Drivers were trained using RAPT-3 which contains nine driving scenarios selected from a set used in prior studies. For example, the hidden sidewalk scenario, left fork scenario, left turn (reveal) scenario, right turn (reveal) scenario and abrupt lane change scenario, etc.	Two groups of drivers were involved: Trained with RAPT-3 group; Control group.	A binary scoring method was employed. Drivers were given a score 1 if a target area of potential risk (Area of Interest) was fixated upon by them when they	The trained drivers were significantly more likely to gaze at areas of the roadway that contained information pertinent to risk reduction (64.4%)

			were in the launch zone. A score 0 were given if they don't.	than were the untrained drivers (37.4%). Significant training effects were observed even in far transfer scenarios.
Isler et al., 2009	The hazard perception dual task (both baseline test and post-training test) requires the participants to search for immediate hazards on video-based traffic scenarios while doing a tracking task at the same time. In video-based road commentary training, participants required to provide a running verbal commentary about any hazards they detected.	Three groups for trained drivers: Two groups doing video-based road commentary training. One group needs to provide verbal commentary and one did not. One control group watched commercial tapes. In addition to that, one experienced driver group didn't receive training.	In both dual task post-training testing, two main measures are used: 1. Number of hazards identified. 2. Reaction time.	After the road commentary training, the detected hazards percentage of the young drivers improved to the level of the experienced drivers and was significantly higher than corresponding control group.
Damm et al., 2011	Five prototypical accident scenarios were involved in testing: 1) Overtaking scenario 2) Pedestrian scenario 3) Opposite vehicle crossing scenario 4) Left crossroads scenario 5) Parked vehicle scenario	Three groups of drivers were tested: Traditionally trained; novice early-trained, experienced drivers.	To describe driving behavior: 1. speed 2. Lateral positions (LPs) To evaluate performance: 1. Reaction Time 2. Obstacle avoidance / Collision	No difference was detected across groups regarding RT. But in some scenarios, position control by traditionally trained drivers was more conservative, and early-trained drivers were far more likely to respond with efficient evasive action.
Isler et al., 2011	Only Higher-order driving skill training group received training about HP. For this group, they will receive a series of training including road commentary, video-based hazard perception on a computer, on-road self-evaluation driving exercise, and focus group-based discussions.	All participants are allocated into three groups: Higher-order driving skill training; Vehicle handling skill training; Control group.	1. On-road Driving Assessment: Visual Search; Speed Control; Direction Control. Each of these three skilled is classified into some pre-defined levels. 2. Hazard Perception test: Percentage of Hazards Detected; Percentage of Action to Hazards.	The participants who received higher-order driving skill training showed a statistically significant improvement in HP. The participants who received vehicle handling skill training showed significant improvements in on-road direction control, but showed no improvement in HP.
Taylor et al., 2011	The RAPT training was evaluated in this study. RAPT consisted of 11 scenarios. The training program displayed sequences of photographs from the drivers' first-person perspective in real-world conditions (Amherst, MA). Participants had to click critical locations in the scenario. Participants were assigned to one of two groups to explore the retention effects of training a year following training. Assessments were conducted on-road (13 km field route in Greenfield, MA)	Two groups of young drivers: Trained group (RAPT training); Placebo group One Experienced driver group (no training provided)	Eye movements were analyzed to assess whether participants anticipated a potential hazard.	The effects of training were found to persist over time. Immediately after training, the trained group was found to anticipate 65.8% of the hazards (47.3% for placebo group). Trained group anticipated 61.9% (37.7% for the control group) of the hazards when evaluated up to a year following training.

Vlakveld et al., 2011	A low-cost, fixed-base simulator training program (SimRAPT) was developed and evaluated to improve drivers' ability to anticipate potential hazards. The training contained 10 scenarios (Seven scenarios with latent hazards and three scenarios with no high priority hazards). Participants drove three versions (hazard detection drive, error drive and improvement drive) of each hazard anticipation scenario. In the hazard detection drive, no hazards materialized while in the error drive, the hazard materialized aggressively. In the improvement drive, the latent hazard manifested less aggressively.	Two groups – SimRAPT-Trained group and untrained group.	The eye movements of both groups were measured. 19 scenarios were evaluated of which 7 were near transfer and 12 were far transfer.	The scores of the critical scenarios were internally consistent (alpha = 0.83) implying that the 19 potential hazard scenarios test and measure one concept. Compared to the placebo group, the trained group anticipated significantly more hazards in near transfer scenarios (83.61% vs 56.91%), far transfer scenarios (70.95% vs 53.49 %) and all scenarios (75.60% vs 54.73%) together.
Petzoldt et al., 2013	The CBT video sequence includes 3 aspects: Pretest on theoretical knowledge; An instructional phase; Actual training phase. The actual training phase includes short clips of traffic scenes generated by artificial animations and each video sequence contained two or three relevant situations, whereby sequences were paused at various positions and questions presented.	In training section, three groups of participants completed: (a) The CBT of cognitive driving skills; (b) A paper-based training of cognitive driving skills; (c) No learning intervention.	The main measurement is glance behaviors. A glance sequence is defined as the eye movement from an unspecific hazard indicator directly to a relevant area. The time between the occurrence of the hazard indicator and the first completion of the glance sequence was used as a measurement.	The experiment confirmed that CBT participants exhibited earlier glances towards critical cues and relevant areas than the participants from paper-based training group and control group.
Wetton et al., 2013	The training package used in this study was inspired by the package developed by Poulsen et al. (2010), which included both hybrid commentary and what happens next exercises. In his study, three new packages were developed, which focus on: (1) expert commentary drive exercises; (2) hybrid commentary drive exercises; and (3) what happens next exercises.	Participants are divided into five training groups: What happens next training; Expert commentary training; Hybrid commentary training (i.e., expert plus self-generated commentaries); The full training package (i.e., what happens next plus hybrid commentary training); The placebo control condition.	After the training, reaction time was used as the measurement for Hazard Perception Tests.	All training interventions significantly improved HP response times immediately after the training. The full training interventions resulted in the largest improvement, and the what happens next training intervention led to the least improvement.
Samuel et al., 2013;	In the RA training program, a program-controlled simulation drive was shown to the trainees from the driver's perspective, and trainees can see the surrounding environment and click the hazards they saw. Trainees would receive auditory and visual feedback on whether they have found critical potential hazards. Both near and far transfer scenarios were included in the test simulated hazardous scenarios.	Two groups: Trained group; Untrained group.	A logistic regression model was used within the framework of Generalized Estimating Equations (GEE), including three binary fixed effects: 1. Driver Group (RA and Placebo) 2. Hazard Type (Materialized vs. Un-materialized hazard) 3. Visibility of Hazard Instigator (visible or hidden).	The results showed that trained drivers were more likely to anticipate hazards than their untrained drivers, both in near transfer scenarios and far transfer scenarios.

Meir et al., 2014	Active members observed video-based traffic scenes with button response. Instructional members watched a tutorial including both written material and video-based examples regarding HP. Hybrid members received a theoretical component followed by a succinct active component. In training session, participants observed more materialized situations to strengthen their weakness.	Four groups: (1) Three AAHPT mode group: Instructional, active, hybrid group (2) Control group.	In hazard perception test (HPT), various measurements were applied: 1. Eye tracking measures: Minimum fixation duration; Minimum dispersion considered a fixation; Maximum consecutive sample loss. 2. Other HP measures: RT, Response sensitivity, Searching strategies; Traffic scene classification.	The active and hybrid groups were more aware of potential hazards relative to the control group.
McDonald et al., 2015	A literature review was conducted on hazard anticipation training for young drivers. Studies were only included if they involved an assessment of training outcomes and included at least one younger driver (< 21 years) group.	Only studies with a younger driver (<21) group were included.	A critical review was implemented on 19 peer-reviewed studies. Training programs, outcome measures, study designs, length of follow up and driving experience were captured.	Studies were found to have used a variety of training methods ranging from interactive computer programs and videos to simulation and commentary training. Four studies were found to include an on-road evaluation. Most studies were found to have evaluated short-term outcomes.
Castro et al., 2016	The training uses the complete version of the same 16 videos which were used in the Spanish Hazard Perception test done before, revealing the hazards with a voice containing relevant information about where to allocate attention in the complex driving scene.	Three independent variables: (1) Training condition (Trained and Untrained group) (2) Experience (learners, novices, and experienced drivers) (3) Recidivism condition (non-offenders vs. re-offenders)	A scoring system was developed. For example, when answering 'What is the hazard?', participants got 2 points if they gave an exact description of the hazard (e.g., red car in the left lane), 1 point if they gave a partially correct answer (e.g., a car on the left, but missing critical details) and 0 points for an incorrect answer.	This training shows significant positive effects for all types and groups of participants
Zafian et al., 2016	The Engaged Driver Training System (EDTS) is an iPad-based training program for hazard anticipation and engagement consisting of 8 training scenarios. The user grasps the iPad in both hands as one would with a steering wheel and steering is handled clockwise of counterclockwise by tilting the iPad. Acceleration/deceleration are handled by the right thumb sliding a gas pedal icon up and down a slide bar on the right side of the interface. Similarly, scanning left and right is handled by sliding the eye icon horizontally with the left thumb on a horizontal slide bar. Users can identify hazards by pausing the drive and then tapping on it with their finger. Correct features are highlighted with a glowing yellow outline.	Four groups – Trained teen group, trained parent dyad, placebo teen and parent placebo dyad.	On-road evaluation was conducted in the town of Amherst along a 2.3-mile route with 14 pre-identified scenarios of key interest (included various types of intersections, turns, curves, crosswalks and turns across path situations). A logistic regression model was used within the framework of Generalized Estimating Equations (GEE), including three binary fixed effects: 1. Type of Training (RA and Placebo) 2. Group (Solo and Dyad) 3. Scenarios	The EDTS-trained group was found to be markedly better at anticipating hazards compared to the placebo group (71% vs 44%).

Thomas et al., 2016	This study evaluated the impact of PC-based RAPT on young drivers crashes and traffic violations. Nine training scenarios were evaluated. RAPT was reprogrammed in Adobe Air.	Total of 5251 young drivers (RAPT group or Comparison group). Comparison group received a pre-test but no training.	An analysis of equivalency was utilized to demonstrate that the group assignment was effective at producing equivalent groups. Analyses of pre-test and post-test data was conducted to assess trainee performance. Researchers used Cox regression analysis to evaluate the number of weeks after licensure at which each participant had their first crash (time to first crash).	A significant treatment effect was found for males but not for females. RAPT-trained males showed an approximately 23.7% lower crash rate compared to the male comparison group.
Young et al., 2017	Same with Young et al., 2014, the training video consists of footage of driving around Nottingham (UK) filmed from the perspective of the driver.	Participants were divided into four groups based on whether exposed to commentary during training and whether required to give commentary during testing.	Two measures of behavioral data employed: 1. Percentage of predefined hazards correctly identified 2. Response times. Two measures of eye-tracking data employed: 1. Number of fixations; 2. Mean fixation durations. 3. Vertical and horizontal variance in fixation location.	Giving a live commentary is detrimental to hazard perception. Commentary exposure resulted in an initial increase in the accuracy of hazard perception responses, but this effect only lasted very limited amount of time.
Horswill et al., 2017	Tin the HP tests, participants were asked to watch a series of video clips which contains potential traffic conflict, on a computer screen. Participants in all four groups re-watched all of the video clips used in the first hazard perception test. In graph feedback condition, participants saw a bar graph. In a video feedback condition, participant watched videos with superimposed annotations. And in the last group, the participant got all kinds of feedback.	Four groups are divided by the way of providing feedback: (a) The graph-based feedback; (b) The video-based feedback; (c) Both; (d) No feedback.	In this study, participants' reaction time was used to measure their HP ability. A standard score was gain from the reaction time through a standardization process.	All three types of feedback resulted in an improvement in hazard perception performance. Also, the combination of video-based and graph-based feedback resulted in the largest improvement in hazard perception performance.
Zafian et al., 2017	This study explored the longitudinal evaluation of the EDTS training program. Participants were trained on 8 scenarios as in Zafian et al., 2016. Drivers were evaluated a week after training and a second time, seven months after training.	Two groups – Trained group and Placebo group.	A logistic regression model was used within a GEE framework to analyze the binomially distributed, binary-coded data. Type of training (EDTS or placebo) and type of evaluation (after 1 week or after 7 months) were included as fixed effects in the model.	Seven months after training, the placebo group's hazard anticipation performance was found to have increased to that observed for EDTS-trained teens a week after training. Overall EDTS-trained teens anticipated significantly more latent hazards than placebo-trained teens. These differences were found to be consistent for both near transfer and far transfer.
Unverricht et al., 2018	This paper explored a meta-analysis of all studies that have explored the effectiveness of latent hazard anticipation training programs. The review focused on 19 peer-reviewed training studies	Meta analysis and literature review	Meta analysis explored the role of four moderating factors (mode of delivery – PC-based or non-PC-based,	The meta-analysis suggested that superficial improvement sin training do not necessarily improve training

	that utilized eye movements to measure improvements in drivers latent hazard anticipation following training.		presentation of training – egocentric or exocentric, method of evaluation – on-road or driving simulator, age of sample – teen drivers (16-17 years) or young drivers (18 – 21 years)	effectiveness. Training programs with both ego centric and exocentric training views achieved greater levels of hazard anticipation performance compared to training programs with either view but not both.
Zhang et al., 2018	A study was undertaken to determine whether the effectiveness of a training program at improving hazard anticipation and mitigation skills is moderated by driving style. A computer-based training called SAFE-T was administered and evaluated. SAFE-T consists of four training modules and a total of 12 training scenarios.	Two groups – Trained and untrained groups.	Drivers were classified as careful or careless based both on measures designed to evaluate two general traits (sensation seeking and aggressiveness) and two driving-specific behaviors (aggressive driving behaviors, and driving violations and errors).	Analysis showed that training improved the latent hazard anticipation behavior of careful drivers, but not careless drivers. Across all scenarios, the main effect of training was consistent. Trained careful drivers anticipated 84.4% of the hazards (compared to 58.9% for placebo careful).
Kahana-Levy et al., 2019	Both training phase and transfer phase use real world driving movies filmed from a driver's perspective as material. In training section, each movie was presented three times. In transfer phase, the process of an unmaterialized hazardous scenario becoming materialized was displayed.	Two groups for young-inexperienced drivers: Trained group; Control group. In addition, there was another group of experienced drivers.	Four measures are employed: 1. Number of fixations; 2. Reaction time; 3. Horizontal spread of search; 4. Vertical spread of search.	In training session, young inexperienced drivers gradually increased their focus on visible materialized hazards. In the transfer session, both trained groups focused on hazards earlier compared to untrained drivers.
Horswill et al., 2021	5 types of newly designed activities listed below were involved in the training courses and they were presented in a recursive and progressive order. 1) What happens next. Added real crash clips. 2) Crash Analysis. 3) Commentary drive. Added follow-up presentation to each exercise. 4) Video Review Feedback with feedback provided. 5) Real World Transfer undertaken during real driving between online sessions.	Two groups of participants: Trained group and Waitlist control group.	Two ways of HP measurements: 1. Response Time 2. A scoring system in HP test. 1 score for an answer matched expert's prediction. There are also a few additional measurements of other driving behaviors.	The study found that this training course can significantly improve drivers' hazard perception response time and hazard prediction scores.

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DISCUSSION AND FUTURE WORK

HP is often measured by hazard scenario questionnaires, HP reaction time, hazard hit rate, and eye fixation measures including fixation probability, fixation reaction time, fixation duration, and fixation variance. Previous studies have examined human factors affecting HP including experience, aging, fatigue, distraction, and the use of alcohol and drugs. Various training intervention methods have been used to improve HP. In general, there is evidence in the literature showing the effectiveness of HP training in terms of shorter HP reaction time, higher hazard hit rate, and better eye scan patterns (more spread scan, more anticipatory scan). A combination of complementary training approaches such as instruction, expert demonstration, and active practice with feedback and support improved measured behaviors. Our review identified the following areas for future work.

Standardized HP tests

A variety of different tests and measures have been used in the literature to measure HP. The lack of standard tests prevents the comparison of different training methods across different studies. Transportation authorities need standardized tests for driver licensing programs. Some countries such as United Kingdom and Australia have implemented HP tests in the driver licensing process, but many countries such as China, India and United States have not. The majority of HP tests reported in the literature are video-based, which have the benefits of lower cost and are easier to implement than simulator-based tests. However, simulator-based tests are expected to be more accurate at measuring novice drivers' HP skills because video-based tests do not have the requisite vehicle control components. Novice drivers' skill limitation is more likely to be exposed in driving simulators when they must concurrently work on both vehicle control and hazard perception.

Another limitation of the current HP measures is that they focus on examining a single early moment when a hazard is first attended or recognized. However, as suggested by Markkula et al. (*38*), the process of hazard response is a continuous flow of assessing, responding, and reassessing the situation. Future studies need to develop methods that can continuously measure HP during the entire process of hazard response. More holistic approaches could be used to measure the combination of hazard perception and hazard mitigation processes by including measures such as speed loss and lane keeping measures (*106*, *108*, *109*).

Improving HP training programs

Future studies need to compare different training methods and improve the design of training programs by integrating the most effective training approaches. Most training programs reported in the literature were short (within one hour), and trainees received the training only once. Repeated training with multiple sessions could improve training effects and help the effects to sustain over a longer period of time. Most existing training programs were developed in developed countries such as Australia, United Kingdom, and United States. Traffic situations and rules are different in other countries such as China and India, where drivers have more interaction with other road users including cyclists and pedestrians. This means that training programs need to consider cultural difference and adapt to different countries. In addition, although many researchers have emphasized the need for anticipatory glances on non-immediate hazards to gain HP and being prepared for any non-immediate hazard turning into an immediate hazard, there is a lack of research and data showing the benefits of anticipatory HP training in terms of impact on crash rate. Future studies are needed to establish evidence to support the effectiveness of training in terms of crash outcomes using both simulator studies and road crash data analysis.

While most HP training programs focused on improving anticipation and awareness of non-immediate hazards before they become immediate hazards, fewer studies have designed HP training focusing on proper recognition of immediate hazards. Forensic research and simulator studies (*110–112*) that analyzed driver behaviour in different types of crashes such as left turn across path from opposite direction and lead vehicle front-to-rear (or rear-end) crashes have shown human limitations in recognizing immediate hazards. Even after the immediate hazards are visible to the drivers, drivers may not be able to correctly judge the speed, gap, and future positions of the vehicles for properly realizing the imminent collision. Future studies are needed to improve HP training including speed and gap judgement in this type of immediate hazard scenarios that frequently cause fatal crashes.

New questions brought by autonomous vehicles

Autonomous vehicles are expected to be the future. In partially and fully automated driving, the role of drivers is shifted from operational control to monitoring and supervising. This means a reduced need of vehicle control skills and an increased importance of HP skills. Since autonomous vehicles are equipped with sensors and algorithms that can monitor the environment for hazards, drivers' workload on monitoring hazards is expected to reduce. However, autonomous vehicles may present new hazards when algorithms fail or when the driving scenario exceeds the design limits of the algorithms. A recent study showed that after a period of staying in the automated driving mode, when the automation gives vehicle control back to the human driver, drivers need a long time (at least about 8 seconds) to regain awareness of the environment and be prepared to take over control smoothly (*113*). To successfully perceive hazards in the condition of partially automated vehicles, drivers need to know the capabilities of autonomous vehicles as well as their limitations. Autonomous vehicles bring many new questions regarding HP, and more future studies are needed to answer these questions.

CONCLUSION

Many studies have been conducted to quantify hazard perception in driving and factors affecting it. The major approach is to separate hazard perception from hazard mitigation and analyze them individually. Previous tests and measures are good at measuring hazard perception alone, but more holistic approaches are needed to combine the assessment of hazard perception and hazard mitigation in order to directly connect hazard perception to driving safety and crash rate. Various hazard perception training programs have been developed using pictures, computers, and driving simulators. Their effects on improving the hazard perception process are supported by evidence from measured behaviours, but future studies are needed to further examining the impact on crash data. The current review could provide a quick reference regarding the best practice of HP measures and a summary of existing HP training methods for future researchers and designers of training courses to consider.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: Study conception and design: Shi Cao, Jianwei Niu; Data Collection: Shi Cao, Siby Samuel, Yovela Murzello, Xuemei Zhang; Analysis and Interpretation of results: Shi Cao, Siby Samuel, Wen Ding, Jianwei Niu; Draft Manuscript Preparation: Shi Cao, Siby Samuel, Xuemei Zhang, Jianwei Niu; Revision and Writing Improvement: Shi Cao, Siby Samuel, Yovela Murzello, Wen Ding. This work was supported by National Key Technology R&D Program of China (2014BAK01B01), State Scholarship Fund from China Scholarship Council (201208110144), and Fundamental Research Funds for the Central Universities, China (FRF-TP-14-026A2) to J.N., and Natural Sciences and Engineering Research Council of Canada Discovery Grant (RGPIN-2015-04134) to S.C.

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