safety

Review

Hazard Perception–Response: A Theoretical Framework to Explain Drivers' Interactions with Roadway Hazards

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Abstract: Research suggests that novice drivers are most susceptible to errors when detecting and responding to hazards. If this were true, then hazard training should be effective in improving novice drivers' performance. However, there is limited evidence to support this effectiveness. Much of this research has overlooked a fundamental aspect of psychological research: theory. Although four theoretical frameworks were developed to explain this process, none have been validated. We proposed a theoretical framework to more accurately explain drivers' behavior when interacting with hazardous situations. This framework is novel in that it leverages support from visual attention and driving behavior research. Hazard-related constructs are defined and suitable metrics to evaluate the stages in hazard processing are suggested. Additionally, individual differences which affect hazard-related skills are also discussed. This new theoretical framework may explain why the conflicts in current hazard-related research fail to provide evidence that training such behaviors reduces crash risk. Future research is necessary to empirically test this framework.

Keywords: driver behavior; traffic safety; attentional processes; perception-action; individual differences; experience; crashes

1. Introduction

It is well established that drivers' skills in detecting and responding to dangerous driving scenarios (i.e., hazards) are directly related to their crash probability [1,2]. Much of the existing research is concerned with providing evidence that the increased crash risk among young novice drivers results from decrements in detecting and responding to hazards—for example [3–6]. In fact, researchers generally support this claim without measuring crash risk. However, we do not discredit that crash risk is highest among young novice drivers. Regardless of age and driving experience, there has been limited interest in exploring other factors which may affect drivers' hazard detection and response skills such as visual attention [7,8], offender drivers [9], emotional valence and arousal [10], route familiarity [11], and knowledge of traffic laws [7]. Additionally, researchers disagree about which behaviors predict hazard-related skills. For example, studies have shown that performance decrements are due to inefficient attention allocation [3,4], inadequate mirror usage [6], or poor speed management [5].

Even more problematic, hazard-related constructs are inconsistently defined and empirical results are infrequently supported by theory. Hazard-related constructs are often used interchangeably such as hazard detection [12], hazard perception [1,12–15], hazard anticipation [16], and hazard awareness [5,17]. Not only are these discrete constructs [18], but studies using the same terms also provide opposing definitions. For example, hazard perception is defined as detecting hazards [1]; detecting hazard anticipation cues [13]; detecting and responding to hazards [15]; the latency in detecting and responding to hazards [14]; or a process which involves situation awareness [9]. Furthermore, several studies have failed to define the construct being measured e.g., [8,12]. These issues highlight the need to distinguish hazard-related constructs to clarify the state of existing knowledge.

In this paper, we propose a theoretical framework to explain hazard detection and response relying on support from visual perception and driving hazard literature. In doing so, we also discuss limitations of existing frameworks, define hazard-related constructs, discuss individual differences affecting drivers' hazard skills, and suggest suitable metrics to evaluate each stage in the proposed framework.

2. Review of Existing Hazard Processing Frameworks

Five existing frameworks attempt to explain the hazard detection process including (1) Model of processes underlying driving behavior in response to potential hazards [19], (2) Model of responding to risk [20], (3) Model of hazard cognition [21], (4) Recognition-primed decision-making for hazard behavior [22], and (5) Hazard avoidance framework [23]. Each framework is briefly explained below (see Table A1 in the Appendix A for a more thorough description of each framework).

2.1. Model of Processes Underlying Driving Behavior in Response to Potential Hazards

The *model of processes underlying driving behavior in response to potential hazards* was developed in Australia to explain the deficiencies of novice drivers in hazard response [19]. As described in the model, the hazard response process includes assessing whether a response is necessary and, if so, executing a maneuver to avoid a crash. The author of this model states that novice drivers commit errors in hazard response due to insufficient risk threshold (i.e., the level of risk willing to accept) and miscalibration of the skills required to avoid a crash [19]. However, more recently, a study found that novice drivers accurately calibrate their skills in responding to hazards [24]. In summary, this model is limited in that it fails to incorporate the processes preceding decision-making, such as detecting and perceiving a hazardous situation and instead only explains hazard perception in terms of risk-taking. In fact, a study found that drivers' risk perception is unrelated to their hazard perception performance [25].

2.2. Model of Responding to Risk

The *Model of responding to risk*, developed in the United Kingdom, incorporates the relationships among risk, hazard perception, and control [20]. This model explains that drivers engage in top-down processing when determining whether a response is warranted. In other words, a driver must have experience dealing with similar hazards or be able to anticipate the hazard in order to make an accurate response. Therefore, this model cannot explain decision-making when a driver encounters an abrupt or hidden hazard (i.e., hazards which cannot be anticipated). Additionally, this model only accounts for the decision-making process involved in hazard response and disregards other fundamental processes, similar to the *Model of processes underlying driving behavior in response to potential hazards* [19].

In an effort to validate the *Model of responding to risk*, the authors of the model performed an empirical study, but the results did not support the framework [20]. Specifically, the authors empirically tested their model to evaluate the role of psychological influences such as fluid intelligence and personality factors on the performance of a hazard perception task and a subjective driving assessment task. The results of these studies produced inconclusive results. They found that spatial attention and driving skills predicted hazard detection skills (stage 1). However, when empirically tested, they found that age and an experimenter's rating of participants' driving performance (attentive, safe, skillful) predicted hazard detection. Threat appraisal (stage 2) was found to be predicted by personality traits and perceived driving skills. The latter was measured subjectively and compared to an experimenter's rating of their skills. The authors found that action selection (stage 3) was predicted by fluid intelligence, and implementation (stage 4) was predicted by motor abilities such as eye-hand movement. When performance on a hazard perception task was evaluated, the authors found that drivers with high scores could be categorized as

'good drivers' [20]. However, such categorization does not provide any value or significant importance to the proposed theory.

2.3. Model of Hazard Cognition

The original publication describing the *Model of hazard cognition* [21] was written in German, and we were unable to obtain English translation. Therefore, our interpretation of this model comes from a secondary source [26] (p. 23). The *Model of hazard cognition* was developed to explain information processing of hazard scenarios and assumes that drivers detect hazards using bottom-up processing ([21] as cited by [26]). Thus, according to this model, drivers cannot rely on prior experience to aid in detecting hazards. To date, two empirical studies have been performed to validate this model, but neither successfully explain driver's information processing of hazard scenarios [26].

2.4. Recognition-Primed Decision-Making Model for Hazard Behavior

The authors of the *Recognition-primed decision-making model* for hazard behavior [22] modified the original recognition-primed decision-making model [27] to explain hazard-related behaviors among novice drivers. Specifically, the authors of the revised model [22] were interested in assessing whether driving instructors in the U.K. agreed with their proposed stages when evaluating the performance of learner drivers. Although driving instructors believed that these stages are important in hazard processing, there is no empirical support to validate this model. Similar to the Model of responding to risk [20], this model does not support hazard processing for abrupt or hidden hazards, which engage in bottom-up processing [26]. Instead, Recognition-primed decision-making model for hazard behavior [22] assumes that drivers perceive and respond to hazards using top-down processing and thus drivers without prior experience (i.e., novices) are incapable of processing hazards. Although several studies suggest that novice drivers have poor hazard perception skills (e.g., [28]), novice drivers are still capable of detecting at least some hazards [29].

2.5. Hazard Avoidance Framework

Similar to the *Model of processes underlying driving behavior in response to potential hazards* [19], the *Hazard avoidance framework* [23] seeks to explain why novice drivers commit errors when interacting with hazards. This framework describes visual processing of roadway hazards in reference to the spatial location of the driver [23]. Furthermore, cognitive processes are compartmentalized into distinct spatial locations rather than a fluid process—a shortcoming of this framework. In addition, similar to the other frameworks, there are no validation studies supporting the framework.

2.6. Summary of Existing Frameworks

The five frameworks discussed each intended to explain the processing of detecting and responding to a hazard while driving. These existing frameworks support the results of the breadth of literature, that novice drivers have poor hazard performance. However, it is evident that other drivers have poor hazard performance (e.g., offender drivers [9], older drivers [13], drivers with poor visual attention [7,8]), and these results cannot be supported by the existing frameworks.

3. Proposed Framework: Hazard Perception–Response

3.1. Taxonomy

In developing a framework to explain the process of detecting and responding to hazardous driving events, it is imperative to first define hazard-related constructs.

3.1.1. Hazard

"The term "hazard" is deemed to provide a qualitative description of (dangerous) traffic situations (i.e., objects or object constellations) or events which hold a certain injurious

potential on account of their specific aspects (properties, features, states)" [26] (p. 25). A hazard has also been defined as "the possibility that a mass, i.e., a vehicle, might undergo a change in velocity or direction by colliding with a moving or non-moving object or by swerving off the road," [30] (p. 1). For simplicity, we define a hazard as *an unsafe, strange, or dangerous driving event* [7]. Here, we define strange as something out of the ordinary or unusual, such as a pedestrian walking on a highway.

3.1.2. Hazard Detection

Hazard detection has been defined as a mental model developed by looking and perceiving a potential hazard and deciding whether there is an actual hazard [28]. However, detection and decision-making are separate processes. Leveraging support from visual attention literature [31], we define hazard detection in a driving context as *the process of selectively attending and localizing a potential driving hazard*. This is analogous to what is known in the attention literature as pre-attentive attentional guidance [32]. This construct is further explained in the proposed framework.

3.1.3. Hazard Awareness

Researchers have suggested that hazard awareness depends on risk perception and involves identifying a hazard, determining if a response is necessary, and then selecting a response [17]. However, the term awareness simply implies consciousness rather than a process associated with response and selection. Therefore, we define hazard awareness as *a state of consciously attending to a hazard including deciding whether the scenario is hazardous and the knowledge or understanding about the scenario*. Thus, this implies that hazard detection precedes hazard awareness. Knowledge or understanding of the scenario includes identifying features of the hazard and making judgments about the speed and trajectory of the hazard in relation to the driver.

3.1.4. Hazard Perception

As previously mentioned, there are at least five conflicting definitions for hazard perception [1,9,13–15]. For example, hazard perception has been defined as involving "elements of both driving skills (e.g., hazard perception latency) and subjective experience (e.g., quantifying the dangerous potential of hazards" [19] (p. 226). However, in support of visual attention literature [33], we define hazard perception as *the cumulative process of hazard detection followed by hazard awareness*.

3.1.5. Hazard Anticipation

Hazard anticipation has been defined as awareness of an environmental risk, a visual search to guide detection and recognition, predicting whether a hazard will materialize, and responding [16]. We largely agree with this definition but modify the definition of hazard anticipation as the *recognition of cues which may signal and aid in the prediction of a hazard using top-down processing*. Similar to the issue raised with existing definitions of hazard awareness (e.g., [17]), the term anticipation does not signify processes involved in response-selection.

3.2. Hazard Perception–Response Framework

The proposed framework, *Hazard Perception–Response Framework*, attempts to explain the perceptual and cognitive processes involved in detecting and responding to hazardous events while driving. The components of this framework are explained below and displayed in Figure 1.
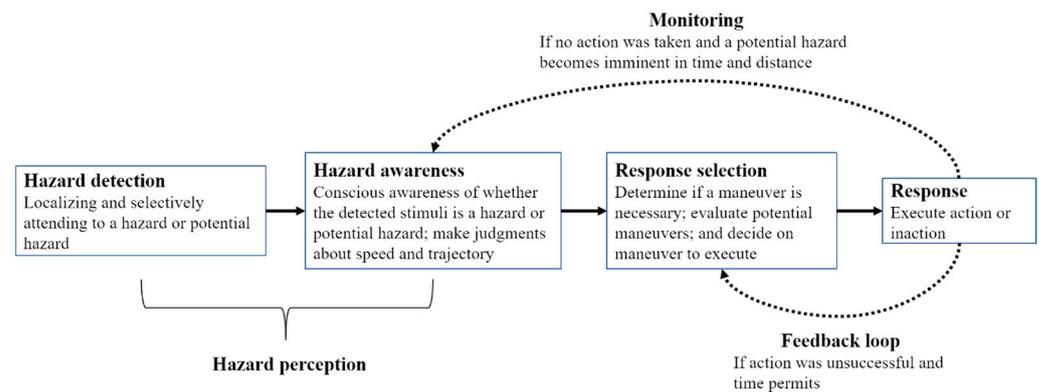
Figure 1. Hazard perception–response framework.

3.2.1. Hazard Detection

The *hazard detection* stage includes localizing and selectively attending to a hazard or potential hazard. Spatial processing allows the driver to localize the stimuli selected for attention [34]. Depending on the characteristics of the hazard, attentional guidance can occur exogenously or endogenously. Exogenously-driven attention, a form of bottom-up processing, occurs automatically and is driven by salient events [34] such as a materializing hazard. According to the selective attention framework [35], when stimuli are salient, visual orienting guides attention to the unexpected event.

On the other hand, endogenously-driven attention is driven by top-down processing [34] where visual selection is affected by predictability [36]. Moreover, this type of information processing explains how drivers selectively attend to anticipation cues (in line with the *Model of responding to risk* detection stage [20]) or engage in visual scanning for potential unmaterialized hazards [36,37]. In other words, visual search is consistently engaged when locating relevant information and aids in visual selection of hazards [35].

Researchers have revealed that individuals can selectively attend stimuli without conscious awareness and provide evidence that visual perception and visual awareness are distinct processes which occur serially [34,38]. For example, individuals can covertly attend to objects (as in this stage), but fail to gain conscious awareness of the attended objects—a phenomenon termed inattentional blindness [39]. Studies evaluating this phenomenon revealed that individuals failed to gain awareness of salient stimuli [40], such as the occurrence of an abrupt hazard while performing a demanding driving task. On the other hand, researchers have found that, as route familiarity increased, drivers were less likely to detect hazards, which could have otherwise been anticipated [11]. Other researchers suggest that this is likely due to mind wandering, where attention is focused on internal thoughts rather than on the driving task [41]. These studies provide further support in delineating the *hazard detection* stage and the proceeding *hazard awareness* stage. Because of this, the *hazard detection* stage does not discern whether drivers are consciously aware of the attended stimuli.

Finally, performance at this stage is particularly important because the information selected for attention affects processing efficiency and accuracy, response latency, and whether the information will be stored in long-term memory for later retrieval [34].

3.2.2. Hazard Awareness

During the *hazard awareness* stage, the driver is consciously aware of the attended stimuli and is able to identify whether it is hazardous (i.e., materializing) or potentially hazardous. In addition, drivers are able to make judgments about the speed and trajectory of stimuli in relation to their vehicle.

3.2.3. Response Selection

During the *response selection* stage, the driver determines whether a maneuver is necessary. If the *hazard awareness* stage determines that the scenario is potentially hazardous, an action is likely unnecessary. Alternatively, if the scenario is identified as hazardous (i.e., materializing and will interact with the driver if no action is taken), then a response is necessary. Regardless, if an action is deemed necessary, the driver will evaluate potential actions and decide on a maneuver to execute [22]. Potential actions are evaluated in terms of maneuvers to either avoid interacting with the hazard or to reduce the severity of a crash (if it cannot be avoided).

3.2.4. Response

During the *response* stage, the driver will potentially execute an action as determined in the *response selection* stage.

There are five possible outcomes following the driver's response:

1. An action is taken and interaction with the hazard is avoided (successful response).
2. No action is taken, but the driver did not interact with the hazard (successful response).
3. An inadequate action is taken, which results in a crash (unsuccessful response).
4. An inadequate action is taken; however, time permitting, the driver may engage in a *feedback loop* (described below).
5. No action is taken because the event is identified as *potentially* hazardous (i.e., a response will be necessary if the hazard materializes). In this case, the driver can continue to monitor the potential hazard in the event that it becomes hazardous (i.e., *monitoring* stage; described below).

3.2.5. Feedback Loop and Monitoring Stage

These components of the Hazard Perception–Response Framework are only executed under specific conditions. If, during the response stage, the driver performs an inadequate maneuver and time permits, they have the option to select and execute an alternative response through the feedback loop. On the other hand, if the driver determines that the scenario presented only a potential hazard (one which did not materialize) and did not execute a maneuver, the driver may continue to assess the likelihood that the potential hazard will materialize through the monitoring stage. If the hazard becomes imminent based on time and distance, the driver will reengage in the hazard awareness stage. Both the feedback loop and monitoring stage are regulated by working memory, specifically, the central executive. Baddeley, Della Sala, Robbins, and Baddeley (1996) state that the central executive, a component of working memory, is primarily responsible for the manipulation of information in working memory by filtering irrelevant information, changing task strategies, and storing and accessing information in long-term memory [42].

4. Performance Metrics and Factors Affecting Performance

Table A2 in the Appendix A highlights metrics to evaluate drivers' performance at each stage of the Hazard Perception–Response Framework as well as factors (i.e., individual differences and hazard characteristics) affecting performance.

4.1. Hazard Detection

Performance in the *hazard detection* stage depends on whether hazard detection is exogenously- or endogenously-driven. Specifically, detection driven by exogenous attention occurs when hazards are salient or materializing. Accuracy in detecting such hazards is affected by individual differences in visual attention (i.e., orienting). In support, researchers have found that individuals with better visual orientation detected more hazards, regardless of other individual differences (e.g., driving experience) [43].

On the other hand, endogenously-driven hazard detection occurs when hazards can be predicted through anticipation cues. Research suggests that more experienced

drivers are better at perceiving anticipation cues than novice drivers [13]—perhaps due to endogenous attentional guidance [36]. Likewise, researchers have revealed that, as driving experience increases, visual scanning/searching increases [44], and attentional tunneling decreases [45]. However, these results could merely reflect the increased mirror use with increased driving experience [6] rather than differences in visual attention abilities. In another view, more experienced drivers have been shown to be more knowledgeable of traffic laws [7], which could possibly aid in visual search. Therefore, increased driving experience may instead guide visual attention to hazards such as in detecting anticipation cues or due to familiarity.

In addition to hazard detection accuracy, detection latency is also affected by hazard characteristics and individual differences. Exogenous attentional capture of salient hazards is automatic and therefore processing time occurs quickly [38,46]. Researchers have even found that peripheral hazards are perceived just as quickly and as accurately as foveal hazards when the level of dangerousness is high (e.g., materializing hazards) [8], one reason being that such hazards are salient and engage bottom-up processing. On the other hand, processing time for hazards with low saliency (i.e., endogenously-driven) is affected by the hazard location (i.e., foveal or peripheral). Regardless of the hazard location, detection latency is also affected by factors driving individual differences in visual attention such as age. For example, the age-related declines in visual processing speed (as measured by Useful Field of View) have been shown to predict the likelihood of some traffic crashes [47].

4.2. Hazard Awareness

If a hazard is accurately detected, then success at the *hazard awareness* stage is hypothesized to be affected by individual differences in visual attention abilities (i.e., multiple object tracking), knowledge of traffic laws, and driving experience. In multiple object tracking tasks, individuals are asked to visually attend to several stimuli simultaneously and then determine whether a presented stimulus was the target [35]. This mechanism of visual selective attention may be related to deciding whether the scenario is hazardous or potentially hazardous.

It is likely that drivers who are more knowledgeable about traffic laws are better able to differentiate behaviors or scenarios deviating from that of normal or safe driving scenarios. For example, drivers who understand traffic laws about turning left at a green signal (in the absence of a green arrow) are likely more aware of drivers who violate such laws and thereby have greater accuracy in identifying hazards. To evaluate these hypotheses that individual differences in visual selective attention and knowledge of traffic laws predict hazard awareness, we performed additional analyses on the data from Barragan and Lee (2021) [7], who measured these variables. Hazard awareness was significantly predicted by knowledge of traffic laws [$t(396) = 4.31$, $p < 0.001$], visual search [$t(396) = 5.67$, $p < 0.001$], and visual orienting [$t(396) = 2.68$, $p = 0.008$]. However, hazard awareness accuracy was not predicted by driving experience. Though, driving experience has been shown to affect the processing time of hazards, such that experienced drivers identify hazards quicker than novice drivers [43]. Thus, driving experience may play a role in perceptual, but not attentional processing, contrary to several lines of research [44,45].

4.3. Response Selection

If a hazard is accurately identified, then accuracy in *response selection* is proposed to be affected by individual differences in response bias (i.e., liberal vs. conservative), knowledge of traffic laws, and visual attention (i.e., filtering). In support, research has revealed that conservative drivers respond to fewer hazards and take longer to respond to hazards than liberal drivers [1]. Additionally, drivers' knowledge of traffic laws may assist in selecting an appropriate maneuver to avoid interacting with the hazard. In performing additional data analyses from Barragan and Lee's (2021) study [7], we found that knowledge of traffic laws predicted accuracy in response selection, $t(396) = 4.19$, $p < 0.001$. Finally, individual differences in visual attention, specifically filtering (filtering out irrelevant visual

information), should also affect accuracy and efficiency in response selection [34]. Although these additional data analyses did not reveal that driving experience predicts response selection accuracy, research should further evaluate this. In line with the *Recognition-primed decision-making model for hazard behavior*, more experienced drivers may rely on prior experience and responses with similar hazards to determine the appropriate response [22].

4.4. Response

If the driver decides on a suitable response to avoid interacting with the hazard, then success at the *response* stage is hypothesized to be affected by individual differences in selective attention (i.e., multiple action monitoring), motor movement, and driving skills. Researchers have defined multiple action monitoring as attending to several related tasks simultaneously such as steering while controlling speed (via accelerator and brake) [35]. Thus, performance on this type of visual attention task should predict whether the driver successfully avoids a crash (as long as an adequate maneuver was selected).

Individual differences in motor movement directly affect response latency. For example, young novice drivers outperform (faster response time) older experienced drivers in hazard response due to age-related declines in motor movement [13]. When correcting for age effects, researchers have revealed that novice drivers respond slower than experienced drivers when encountering a hazard [48]. This may be due to insufficient behaviors such as speeding or greater steering variability [48]. Likewise, experienced drivers may perform better due to greater experiential practice executing driving maneuvers [49] rather than due to superior hazard response skills. However, the effects of driving experience on response time to hazards, as presented here, is only speculative, given that most research evaluates response time as a keyboard press rather than driving behavior.

5. Application of the Hazard Perception–Response Framework: A Hypothetical Case Study

For this hypothetical case study, we chose to evaluate a prevalent incident that involves a driver encountering a pedestrian who attempts to cross the road at an intersection without a crosswalk. The prevalence of errors in processing pedestrian behavior is fatal. Specifically, in 2017, it was estimated that one pedestrian dies every 88 min from being struck by a vehicle [50]. It has also been noted that pedestrians are 1.5 times more likely to be killed in a motor vehicle accident than a passenger vehicle occupant [51]. The hazard processing framework for this hypothetical case study is in Figure 2 below.
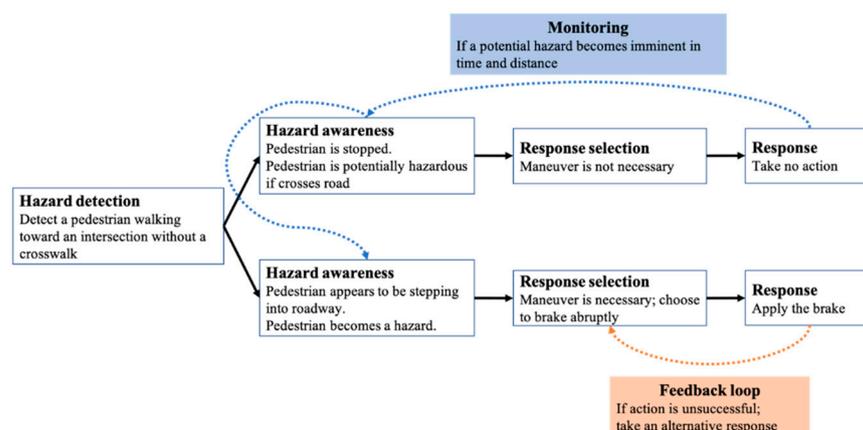

Figure 2. Hazard perception–response framework for the hypothetical case study.

During *hazard detection*, the driver localizes the stimuli selected for attention, which is the pedestrian walking toward an intersection. In this scenario, attentional guidance occurs endogenously using top-down processing. Specifically, the driver attends to the pedestrian who is walking toward the intersection and predicts that the individual will likely cross

the road even in the absence of a crosswalk. The driver then becomes consciously aware of the pedestrian during the *hazard awareness* stage and determines that the situation is potentially hazardous. Given that the hazard is not yet materializing, the driver determines that a maneuver is not necessary in the *response selection* stage and their *response* is to not act. Because no action is taken and the driver determines that the situation is potentially hazardous, they will continue to monitor the situation during the *monitoring* stage.

Then, when the potential hazard begins to materialize, it becomes hazardous and the driver will reengage the *hazard awareness* stage. In this case, the hazard begins to materialize when the pedestrian steps into the roadway to cross the intersection. During the *response selection* stage, the driver will evaluate potential actions and decide on a maneuver to execute. Potential actions in this scenario are to make a lane change or brake. However, a lane change is not an adequate choice because the pedestrian could change their speed. Therefore, the driver decides to apply the brake abruptly in order to avoid striking the pedestrian. Finally, during the *response* stage, the driver applies the brake.

During the feedback loop, if the driver's maneuver is unsuccessful or the direction of the walking pedestrian has changed, the driver may need to take an alternative maneuver, such as making a lane change. However, if the driver does not have adequate distance or time to execute an alternative maneuver, the situation becomes more dangerous and possibly fatal.

6. Discussion

Simply evaluating differences in performance that is not theory-driven is limited by the ambiguity of interpretation [52]. Although this is widely understood in psychological research, studies evaluating drivers hazard-related performance have failed to acknowledge this. Despite this shortcoming, it is well established that novice drivers perform poorly in hazardous situations, which causes them to be most susceptible to automobile crashes [3–6]. Researchers claim these results suggest that experience provides a protective effect, whereby, in certain situations, performance is not degraded. For example, the results of one study showed that experienced drivers in a sleepiness-induced group still outperformed novice drivers in the non-sleepiness-induced group on a hazard perception task suggesting that sleepiness has more of an effect on novice drivers [53]. There are, however, situations in which more experienced drivers do not outperform novice drivers such as under stress or fatigue. One study evaluated risk-taking under stress and found that experienced drivers compared to novices committed more errors while driving [54]. Additionally, researchers have shown that individual differences other than driving experience cause impaired hazard performance including offender drivers [9], older drivers [13], and drivers with poor visual attention [7,8].

Despite the evidence, several hazard training programs have been developed, all claiming to be successful in reducing crash risk among novice drivers' (cf. [16]). However, there is limited evidence that these training programs are effective. In fact, there is also limited evidence linking novice drivers hazard-related skills and crash risk. If researchers are correct in claiming that errors in hazard detection and response do contribute to crash risk, then improving these skills through training should decrease crash frequency. One potential solution is to perform studies that are theory-driven.

Therefore, we developed a theoretical framework to provide a clearer understanding and interpretation of existing hazard perception literature. The proposed framework, *Hazard Perception–Response*, provides specific predictions about vulnerable populations and individual differences in performance, which can be tested empirically. As suggested in Table A2, visual attention skills are predicted to affect performance during each stage of the framework. One study found that drivers who have poor visual attention skills have degraded hazard perception performance [7]. This could be tested at the response stage to determine whether drivers with poor visual attention commit more errors or respond slower to a hazard compared to drivers with better visual attention. The *Hazard Perception–Response Framework* can also be applied in the design of warnings and alerts for

autonomous vehicle systems. For example, when the system detects a hazard or a potential hazard begins to materialize, the automated system can alert the driver to take over. We hope that future studies will empirically validate this framework and provide a better understanding of drivers' perceptual attention and behaviors.

This paper highlights the critical need and relevant background for a new framework to explain driver's behaviors when interacting with hazards. In particular, we believe this framework will be of value to the community by emphasizing the necessity to account for individual differences in hazard perception skills.

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Appendix A

Table A1. Existing frameworks explaining hazard processing.

Framework	Target Phenomenon	Model Components	Model Hypothesis
Model of processes underlying driving behavior in response to potential hazards [19]	Cognitive and perceptual processes associated with risk-taking behavior	1. Hazard perception: detection and quantify the potential dangerousness of hazard (based on risk perception). 2. Behavior: execute action (i.e., take the risk).	Young novice drivers have poor hazard perception because they overestimate their driving skills and underestimate their risk
Model of responding to risk [20]	Risk and its relationship to accidents	1. Hazard detection: awareness of a hazard. If not detected, crash risk increases. 2. Threat appraisal: decide whether a response is necessary. 3. Action selection: select a response based on driver's skills. A crash may occur if the driver does not possess the necessary skills. 4. Implementation: execute selected action.	Drivers' who have been involved in crashes perform worse when encountering a hazard

Table A1. *Cont.*

Framework	Target Phenomenon	Model Components	Model Hypothesis
Recognition-primed decision-making model for hazard behavior [22]	Cognitive processes involved in information-processing of learner drivers which cause behavior	1. Situational cues 2. Perception 3. Situation recognition: search long-term memory for similar cues and determine possible responses based on driving experience. 4. Serial option evaluation: select and test responses mentally until satisfied. 5. Behavior	Driving instructors' attitudes about cognitive skills that learner drivers need to develop
Model of hazard cognition [21]	Information processing of hazard scenarios	1. Detection of hazard: bottom-up processing whereby salient hazards are best detected. 2. Localization: determine location via visual or auditory information. 3. Identification: determine what the hazard is and what it means for the driver. 4. Assessment of relevance: pattern recognition, activation of schemata and scripts, perception and assessment of distances and speeds, all of which is based on the driver's experience. 5. Evaluation: weigh possible actions and ability to handle situation. 6. Hazard anticipation: predict the future state of the hazard.	Unknown
Hazard avoidance framework [23]	Hazard avoidance as explained by visual distance (four zones)	1. Vigilance zone: farthest visual distance; because a hazard is not materializing, the driver must maintain vigilance at this zone. 2. Strategic zone: next farthest distance; hazard anticipation cues are visible. 3. Tactical zone: next closest distance; area where hazard occurs and the driver may need to take action. 4. Operational zone: closest distance to driver; hazards materializing in this zone are most difficult to avoid.	Explain deficiencies of hazard avoidance skills for novice drivers

Table A2. Performance metrics to evaluate hazard perception–response framework and factors affecting performance.

Performance Metrics			
Stage	**Accuracy**	**Reaction Time**	**Factors Affecting Performance**
Hazard detection	Whether an eye movement was made (yes/no)	Saccade latency from hazard onset [8] [1]	Hazard saliency, hazard location, visual attention, driving experience, age
Hazard awareness	Determine whether a hazard exists in a given scenario and if so, to identify the hazard [1,7]	Fixation duration [55]; latency from first fixation to self-report detection [15]	Visual attention, driving experience, knowledge of traffic laws
Response selection	Report why the scenario is hazardous and what maneuver the driver would perform [7]	NA	Visual attention, response bias, knowledge of traffic laws
Response	Whether a crash occurred (yes/no)	Latency from hazard detection to response initiation [56]	Visual attention, motor movement, driving skills

[1] Although researchers typically evaluate fixation latencies (e.g., [11]), results vary based on complexity of the driving environment [43,57] and hazard distance from focal attention. Instead, saccade latency from hazard onset is a more accurate measure [8].

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