

Communication Interface Design for Autonomous Vehicle-Pedestrian Interaction: Evaluation Based on Pedestrian Crossing Decision Model

Authors: Jiang Qianni, Zhuang Xiangling, Ma Guojie, Zhuang Xiangling

Date: 2021-05-24T00:00:00+00:00

Abstract

Autonomous vehicles entering mixed-traffic roads shared by vehicles and pedestrians must ensure safety and efficiency in interactions with crossing pedestrians. To address this issue, high-level autonomous vehicles often install display devices on the vehicle exterior, namely external human-machine interfaces (eHMIs), to communicate information with pedestrians. In specific design implementations, existing research has primarily employed visual communication forms such as text, graphics, and projections to convey information including vehicle status (whether in autonomous driving mode), intentions, and crossing suggestions for pedestrians, and has evaluated the impact of interface usage on metrics such as pedestrian crossing intention, speed, and accuracy in contexts including real-road experiments, virtual scenarios, and laboratory experiments. However, pedestrian-centered external interface design must systematically support the information processing needs at various stages prior to pedestrian crossing decision-making. Therefore, by integrating pedestrian crossing decision-making processes and situation awareness theory, we propose a dynamic crossing decision model in pedestrian-autonomous vehicle interactions to evaluate the communication effectiveness of various interfaces from a pedestrian cognitive processing perspective. The evaluation results reveal that eHMIs should facilitate pedestrian perception, comprehension, and prediction of vehicle information. In the perception stage, multiple interface types and multi-presentation carriers should be combined to enhance information recognizability. In the comprehension stage, text explanations, reasonable selection of communication perspectives, signal standardization, and training are required to improve comprehensibility. In the prediction stage, implicit vehicle motion information should be integrated to help pedestrians quickly and accurately acquire vehicle future action intentions. More importantly, future research should focus on information communication design in multi-pedestrian, multi-vehicle mixed-traffic scenarios

and its impact on pedestrians. Theoretically, future research also needs to examine how external interfaces influence the formation of situation awareness and mental models through bottom-up pathways.

Full Text

Evaluation of External HMI in Autonomous Vehicles Based on Pedestrian Road Crossing Decision-Making Model

JIANG Qianni, ZHUANG Xiangling, MA Guojie

(Shaanxi Key Laboratory of Behavior and Cognitive Neuroscience, School of Psychology, Shaanxi Normal University, Xi'an 710062, China)

Abstract: For autonomous vehicles to operate on public roads shared with pedestrians, ensuring safe and efficient interaction with crossing pedestrians is essential. To address this challenge, high-level autonomous vehicles are typically equipped with external display devices—external human-machine interfaces (eHMIs)—to communicate with pedestrians. Current research primarily employs visual communication forms such as text, graphics, and projections to convey information about vehicle status (whether in autonomous mode), intentions, and crossing recommendations. These interfaces have been evaluated in real-road experiments, virtual scenarios, and laboratory settings for their impact on pedestrian crossing intention, speed, and accuracy. However, a pedestrian-centered external interface design must systematically support pedestrians' information processing needs at each stage of crossing decision-making. Therefore, we propose a dynamic crossing decision model for pedestrian-autonomous vehicle interaction by integrating the pedestrian crossing decision process with situation awareness theory, offering a cognitive processing perspective to evaluate the effectiveness of various interface designs.

The evaluation results suggest that eHMIs should facilitate pedestrians' perception, comprehension, and projection of vehicle information. At the perception stage, multiple interface types and presentation carriers should be combined to enhance information recognizability. At the comprehension stage, text explanations, appropriate communication perspectives, signal standardization, and training are needed to improve understandability. At the projection stage, eHMIs should integrate implicit vehicle motion information to help pedestrians quickly and accurately grasp the vehicle's future action intentions. More importantly, future research should focus on information communication design and its impact on pedestrians in multi-pedestrian, multi-vehicle mixed traffic situations. Theoretically, future studies also need to examine how external interfaces influence situation awareness and mental model formation through bottom-up processing pathways.

Keywords: autonomous vehicles, external human-machine interface, eHMI, pedestrian crossing decision model, pedestrian safety

1 Introduction

Autonomous vehicles are intelligent cars driven by computer systems equipped with automated systems for perception and decision-making. The perception system uses multiple sensors to assess vehicle status and understand surrounding traffic conditions, while the decision-making system safely and comfortably transports passengers to their destinations based on information from the perception system and traffic rules (Badue et al., 2019). Although researchers expect autonomous vehicles to effectively reduce traffic accidents caused by human error and improve road safety (Visser et al., 2016), potential safety risks to other road users must be considered before their introduction into current transportation systems. This paper focuses on how interface design for communication between autonomous vehicles (especially Level 3 and above) and pedestrians can meet pedestrians' crossing information processing needs.

From the pedestrian's perspective, before making correct crossing decisions, they must first form correct situation awareness of the traffic scene—that is, accurately perceive, comprehend, and predict vehicle behavior (Palmeiro et al., 2018). In traditional human-vehicle interaction, pedestrians rely on both bottom-up communication signals and top-down expectations to form judgments. However, both types of judgment cues may change when the interaction partner becomes an autonomous vehicle.

On the one hand, in the traditional bottom-up vehicle information processing pathway, pedestrians can determine whether they have been noticed by a vehicle through various signals from human drivers (waving, eye contact, flashing lights, smiling, etc.) and use this information to judge whether crossing is safe (Sucha et al., 2017). With autonomous vehicles, driving behavior is controlled by computer systems, allowing drivers to divert their attention from the driving task and only take over in special situations. Consequently, the reliability of cues from drivers decreases.

On the other hand, in the top-down vehicle information processing pathway, pedestrians' expectations of vehicles in traditional human-vehicle interaction are influenced by knowledge, experience, and informal traffic rules (Björklund & Åberg, 2005). For example, if a crossing pedestrian observes a driver looking at them, they expect the driver has seen them and will stop to wait until they finish crossing before accelerating. When the interaction partner becomes an autonomous vehicle, pedestrians may feel insecure, wondering whether the vehicle has noticed them, or may adhere to traditional interaction experiences that could lead to incorrect crossing decisions. Moreover, vehicle automation is a gradual process. During the transition from Level 0 (driver fully controls the vehicle in all situations) to Level 5 (autonomous vehicle operates independently without human intervention in any situation), automation levels continuously increase (SAE, 2016). Currently, fully autonomous vehicles are still in the road testing phase. Before they completely replace conventional vehicles, pedestrians will face a transitional traffic system where vehicles of different automation

levels coexist. In this transition period, pedestrians may not accurately identify the automation level of the vehicle they are interacting with and thus cannot switch psychological models for different vehicle types in a timely manner, affecting the accuracy of their vehicle behavior judgments. When road users predict autonomous vehicle behavior based on past experiences with conventional cars or unverified, unrealistic expectations of autonomous vehicles, they may develop incorrect expectations that lead to traffic accidents (Hagenzieker et al., 2019; Vissers et al., 2016).

Therefore, the safety level of interaction between autonomous vehicles and road users has become an important indicator for evaluating their safety (Vissers et al., 2016). The prerequisite for ensuring safe interaction between autonomous vehicles and pedestrians is the formation of effective communication. From a vehicle design perspective, this means autonomous vehicles must provide additional interaction information to compensate for the missing interaction information previously provided by drivers in traditional contexts, helping pedestrians form correct situation awareness. This is crucial for both road safety and pedestrian acceptance of autonomous vehicles (Deb et al., 2017). This paper reviews existing research: Section 2 summarizes the communication information content needed in autonomous vehicle-pedestrian interaction; Section 3 systematically analyzes current methods for presenting communication information and organizes interface types, communication content, evaluation methods, and indicators used by researchers in table form. In addition to systematically reviewing previous studies, Section 4 integrates the situation awareness model (Endsley, 1995) and the existing pedestrian dynamic crossing decision model (Palmeiro et al., 2018) to propose a dynamic decision model for pedestrian-autonomous vehicle interaction. Based on this model, improvement suggestions for communication interface design are proposed from the perspective of pedestrian information processing. Overall, this paper provides a new perspective and direction for theory-based eHMI design and evaluation, and offers references for pedestrian information processing and safety promotion in new human-vehicle interaction contexts.

2 Information Content for Communication Between Autonomous Vehicles and Pedestrians

As mentioned above, autonomous vehicles introduce uncertainty into pedestrian-vehicle interaction cues that must be compensated for through other means. Currently, extensive research focuses on how to design autonomous vehicles to meet pedestrians' information processing needs (see next section). The premise of these studies is identifying what additional information pedestrians need beyond traditional vehicle and environmental information to make safe decisions more efficiently. Typically, when vehicle behavior meets expectations, pedestrians' interaction needs with autonomous vehicles differ little from those with conventional vehicles (Madigan et al., 2019; Rothenbücher et al., 2016). Pedestrians need to obtain vehicle motion information and driver feedback as references for

crossing decisions. In autonomous vehicle-pedestrian interaction, driver feedback information is missing or unreliable, so vehicles must provide additional interaction information to compensate for the absence of non-verbal cues. Furthermore, autonomous vehicles need to provide pedestrians with information about vehicle driving mode and future action intentions to enhance interaction safety and efficiency (Schieben et al., 2018; Woodman et al., 2019).

Based on the above summary of road users' interaction needs, the information content that autonomous vehicles need to convey includes vehicle physical information, vehicle awareness and intent, and pedestrian crossing advice.

(1) Vehicle Physical Information: This includes vehicle driving mode and motion information—for example, whether the vehicle is in autonomous mode and whether it is accelerating or decelerating. Providing such information helps pedestrians form correct expectations of autonomous vehicle behavior (Schieben et al., 2018). Vehicle driving mode information can reduce the negative impact of missing driver cues on human-autonomous vehicle interaction (Faas et al., 2020). Vehicle motion cues provide reference information to help pedestrians infer the vehicle's future motion state and make safe crossing decisions (Lundgren et al., 2017).

(2) Vehicle Awareness and Intent: Vehicle awareness is feedback information provided to pedestrians after the vehicle detects them, allowing pedestrians to confirm whether the vehicle has detected them. Based on this, the vehicle typically needs to intelligently determine its next action plan by considering road conditions and pedestrian dynamic information recognition. The vehicle intent to be communicated here is predictive information about future actions (e.g., whether it will yield) (Mahadevan et al., 2018). Simultaneously conveying information about vehicle awareness and intent has a more positive impact on interaction effectiveness than providing only vehicle motion cues (Faas et al., 2020).

(3) Pedestrian Crossing Advice: This conveys crossing guidance or recommendations to pedestrians (e.g., “Please cross”) to support their crossing decisions. This type of information transforms the information presentation perspective based on vehicle intent. For example, when a vehicle makes a “yielding” action plan, to clearly indicate to pedestrians that “crossing is permitted,” the communication content based on its own intent would be “about to stop,” while the pedestrian crossing advice would be “please cross.” Researchers believe that presenting pedestrian advice information is more suitable during interaction than vehicle status and intent information (Ackermann, Beggiato, Schubert, & Krems, 2019). However, when multiple road users exist in a traffic scene, it is necessary to avoid non-target pedestrians receiving information and making incorrect crossing decisions that could create danger.

3 Communication Methods Between Autonomous Vehicles and Pedestrians

Autonomous vehicles need to develop communication methods appropriate to the communication content to convey interaction information. Communication methods mainly include implicit and explicit forms. Implicit communication refers to conveying vehicle information only through accompanying cues in vehicle movement (such as speed changes, trajectory alterations), while explicit communication primarily uses specially designed auditory and visual signals to present communication information.

3.1 Implicit Communication Methods

In traditional human-vehicle interaction, vehicle-provided information—especially vehicle distance and speed—is a key factor for pedestrians to judge whether to cross (Dey et al., 2017; Li et al., 2018). After introducing autonomous vehicles, the vehicle's motion pattern remains an important cue to assist pedestrian decision-making in human-vehicle interaction (Fridman et al., 2017; Mahadevan et al., 2018; Moore et al., 2019). When autonomous vehicle motion meets road users' expectations, pure implicit communication can satisfy their interaction needs (Dey & Terken, 2017). Fuest et al. (2018) noted that implicit communication methods employed by vehicles primarily convey information to road users by changing motion states (such as speed, trajectory). For example, vehicles communicate their intention to yield through deceleration behavior. Following this approach, researchers have measured the impact of vehicle deceleration patterns on pedestrian decision time. They found that higher deceleration rates make it easier and faster for pedestrians to perceive the vehicle's deceleration, but rapid deceleration makes pedestrians feel uncomfortable. Therefore, drivers can begin decelerating smoothly from a greater distance at a lower deceleration rate, which positively influences pedestrian crossing decisions (Ackermann, Beggiato, Bluhm, et al., 2019; Schneemann & Gohl, 2016).

Although implicit communication methods provide sufficient interaction information in some cases, when vehicle behavior violates pedestrian expectations or when pedestrians need to quickly and accurately identify vehicle intentions, vehicles still need to employ explicit communication methods to supplement interaction information (Dey & Terken, 2017).

3.2 Explicit Communication Methods

Mahadevan et al. (2018) found in their study of pedestrian crossing decisions that explicit communication methods presenting vehicle awareness and intent to pedestrians produce more positive interaction effects than presenting only vehicle motion information. When autonomous vehicles are equipped with displays, they can convey vehicle intentions through explicit methods, effectively resolving conflicts caused by failed intent communication during human-vehicle

interaction (Matthews et al., 2017). Therefore, researchers have designed external human-machine interfaces (eHMIs) to present vehicle status and motion intent information, replacing missing driver cues and meeting pedestrian interaction needs. Additionally, interface use can assist pedestrians in forming correct expectations of autonomous vehicle behavior, thereby improving the accuracy and safety of human-vehicle interaction (Eisma et al., 2019). To ensure accurate information conveyance, researchers have proposed four basic principles for designing eHMIs: standardized information content, clear crossing advice for pedestrians, intuitive and easily understandable signal content, and similarity to current communication methods (Ackermann, Beggiato, Schubert, & Krems, 2019).

eHMIs can also explicitly display implicit vehicle motion information (such as vehicle acceleration/deceleration) through visual or auditory means (Eisma et al., 2019). Combining signals provided by eHMIs with vehicle motion not only improves the recognizability of implicit information at longer distances but also helps pedestrians quickly and accurately identify vehicle intentions when vehicle behavior does not match expectations (Lagstrom & Lundgren, 2015; Lee et al., 2019; Mahadevan et al., 2018). However, it is important to note that information presented through eHMIs must be consistent with and timely synchronized with the vehicle's own implicit information (speed, braking behavior, etc.) to ensure pedestrians' accurate understanding of communication information (Madigan et al., 2019; Schieben et al., 2018).

Based on these advantages and design principles of eHMIs, researchers have evaluated eHMI design and effectiveness under conditions of real road sections, virtual scenarios, or picture/video presentations. Evaluation objects mainly include interactive interfaces using visual and auditory methods. Table 1 summarizes the communication information content provided by these interfaces and the evaluation methods and indicators used.

Table 1 Summary of Current eHMIs (External Human-Machine Interfaces) Designed by Researchers

Current eHMIs & Sources	Communication Information Content	Evaluation Indicators a
Anthropomorphic Interface		
Simulated eyes (Chang et al., 2017; de Clercq et al., 2019; Mahadevan et al., 2018)	Vehicle awareness & intent	Recognizability, understandability, and other basic assessments
Text Interface		
Real-time speed (Clamann et al., 2017)	Vehicle physical information	

Current eHMIs & Sources	Communication Information Content	Evaluation Indicators a
“Waiting” (Eisma et al., 2019)	Vehicle awareness & intent	
“I see you” (Mahadevan et al., 2018)	Vehicle awareness & intent	
“Braking” (Deb et al., 2018)	Vehicle physical information	
“WILL STOP” / “WALK” (Bazilinskyy et al., 2019)	Pedestrian crossing advice	
“Walk” / “Don’ t Walk” (de Clercq et al., 2019; Kooijman et al., 2019)	Pedestrian crossing advice	
“Cross Now” (Matthews et al., 2017)	Pedestrian crossing advice	
“GO” / “OK” (Song et al., 2018; Otherson et al., 2018; Velasco et al., 2019) Chen et al., 2020	Pedestrian crossing advice	Recognizability, understandability, and other basic assessments
Light Interface ※		
Light strip flashing/flowing (Fridman et al., 2017; Zhang et al., 2017; Faas & Baumann, 2019; Faas et al., 2020)	Vehicle physical information	
Dynamic light strip system (Lee et al., 2019)	Vehicle awareness & intent	
Light strip warning system (Habibovic et al., 2018; Lagstrom et al., 2015)	Vehicle awareness & intent	
“Waiting” (Li et al., 2018)	Vehicle awareness & intent	

Current eHMIs & Sources	Communication Information Content	Evaluation Indicators a
(Eisma et al., 2019; Burns et al., 2019; Ackermann et al., 2019; Bazilinsky et al., 2019; Löcken et al., 2019)		
Verbal Auditory Interface		
I see you (Mahadevan et al., 2018)	Vehicle awareness & intent	
cross (Mahadevan et al., 2018)	Pedestrian crossing advice	
Safe to cross (Deb et al., 2018; Hudson et al., 2018)	Pedestrian crossing advice	
Non-verbal Auditory Interface		
Music, horn sounds (Deb et al., 2018)	Vehicle physical information	

*Note: 1. eHMIs marked with * are ambiguous signals where the information content designed by researchers differs from participants' understanding, or participants cannot comprehend the meaning expressed through such interfaces. 2. Only first authors are listed for all studies. a. Evaluation indicators refer to pedestrian assessments: crossing decisions include decision intention, speed, and accuracy.*

3.2.1 Visual Communication Methods 1. Substitutive Interfaces Simulating Driver Communication Cues

Pedestrian crossing decisions are influenced by both vehicle-related cues and driver cues (Lundgren et al., 2017). The absence of driver cues may reduce pedestrians' trust in vehicles (Mahadevan et al., 2018). Therefore, researchers have designed eHMIs that provide substitute information simulating human driver communication cues (Eisma et al., 2019). These eHMIs include anthropomorphic mechanical arms (Mahadevan et al., 2018), eye contact systems (eyes on a car: Chang et al., 2017), facial expressions (Deb et al., 2018), and intent communication systems (ICS: Matthews et al., 2017) that replace drivers in providing vehicle intent information to pedestrians. Compared with vehicles without eHMIs, vehicles providing substitutive cues can accelerate pedestrians' decision-making processes and increase their perceived safety (Chang et

al., 2017).

2. Text Interface

Text communication is suitable for presenting brief, clear information. Researchers commonly use text to present current vehicle status (e.g., real-time speed information: Clamann et al., 2017), intent (e.g., “Braking” : Deb et al., 2018; “WILL STOP” : Bazilinsky et al., 2019), or instructions to pedestrians (e.g., “WALK” : de Clercq et al., 2019; “Cross Now” : Matthews et al., 2017). Text information does not require deliberate learning, can more clearly convey vehicle yielding intent, is more persuasive, and makes pedestrians feel safer (Ackermann, Beggiato, Schubert, & Krems, 2019; de Clercq et al., 2019; Kooijman et al., 2019).

3. Graphical Interface

Icon-based interfaces use simple images to present interaction cues and can be divided into two types based on graphical characteristics: anthropomorphic/non-anthropomorphic graphics and static/dynamic graphics. Compared with non-anthropomorphic graphics, anthropomorphic graphics (e.g., silhouettes of walking postures or refusal gestures) can more clearly convey information about whether current crossing is safe (Fridman et al., 2017). Researchers have also found that static information is inferior to dynamic graphics in terms of recognizability and information transmission effectiveness (Othersen et al., 2018). Since the meanings of icon interface images are artificially assigned by researchers during design and pedestrians have not learned the meanings of such images before experiments, the understandability and clarity of such interfaces need to be improved through training (Ackermann, Beggiato, Schubert, & Krems, 2019; Fridman et al., 2017).

4. Light Interface

Light strips composed of single or multiple LEDs are the main form of light interfaces. Light interfaces present communication information through three methods: changing static light colors, dynamic light flashing frequencies, and light strip flow (Bazilinsky et al., 2019). For example, Habibovic et al. (2018) designed the Automated Vehicle Interaction Principle (AVIP), which uses four modes of light strip flashing to convey vehicle motion status and behavioral intent to pedestrians, increasing pedestrians’ perceived safety. When transmitting information about changes in vehicle status, dynamic cues are more recognizable and clearer than changes in light color. To improve the clarity of light information, researchers should standardize information content or introduce new light colors not yet defined in traffic to convey communication information (Faas & Baumann, 2019; Zhang et al., 2017).

5. Projection Interface

Projection interfaces project graphics (e.g., blue arrows: Burns et al., 2019), crosswalks (Bazilinsky et al., 2019), smart roads (Löcken et al., 2019), or text (e.g., “Waiting” : Eisma et al., 2019) onto the ground. In this form of communication that integrates the interface with the environment, information is intuitive, clearly visible, and unaffected by vehicle motion (Fridman et al., 2017;

Löcken et al., 2019). However, projection interfaces may increase pedestrian attentional dispersion, manifested as more dispersed gaze patterns (Eisma et al., 2019). Therefore, when selecting such interfaces, both infrastructure compatibility and impact on pedestrian attention must be considered.

3.2.2 Auditory Communication Methods Auditory communication methods use non-verbal sounds (e.g., music, horn sounds: Deb et al., 2018) and verbal information (e.g., “I see you” / “Cross” : Mahadevan et al., 2018; “Safe to cross” : Hudson et al., 2018) to convey communication information. Auditory information facilitates interaction between vehicles and visually impaired pedestrians and plays a greater role in low-visibility traffic scenarios (de Clercq et al., 2019). However, other sounds in noisy traffic environments may interfere with information reception, and non-directional information may also affect pedestrian crossing decisions. Additionally, auditory cues more easily attract pedestrian attention and are suitable for enhancing pedestrian awareness and providing warnings (Lagstrom & Lundgren, 2015). Therefore, in emergency situations, auditory interfaces can be used to provide clear instructions to pedestrians, while in normal situations they can serve as supplementary information combined with visual information.

4 Pedestrian Dynamic Crossing Decision Model in Human-Vehicle Interaction

Based on the above summary of interface types and their advantages and disadvantages, current research in the external human-machine interface field primarily focuses on interface design and presentation effect evaluation. To further compare the effects of interfaces used in different empirical studies, researchers have provided classification methods for multi-dimensional comparison of interface effects using unified standards (Dey et al., 2020) and standardized evaluation paradigms (Rouchitsas & Alm, 2019). However, in human-vehicle interaction, pedestrians are the targets of interface information communication, and interfaces should meet pedestrians’ interaction needs and promote the establishment of good situation awareness. Therefore, this paper centers on the pedestrian crossing decision-making process, focusing on pedestrians’ different requirements for interface-presented information at different cognitive processing stages. Simultaneously, based on the crossing decision model, interface design is evaluated and new design points are proposed.

4.1 Dynamic Crossing Decision Model for Pedestrian-Autonomous Vehicle Interaction Based on Situation Awareness

As mentioned earlier, pedestrians must first establish good situation awareness of the external environment before making crossing decisions—that is, establish an internal representation of the dynamic external environment, which forms the basis for decision-making and action in dynamic traffic situations. Palmeiro et al. (2018) proposed a dynamic crossing decision model

for pedestrian-autonomous vehicle interaction based on Endsley's (1995) situation awareness model, suggesting that situation awareness is influenced by vehicle cues, environmental cues, and personal factors. This model includes factors that may affect situation awareness formation but lacks research on specific cognitive processing mechanisms. Therefore, this paper integrates this model with Endsley's (1995) situation awareness model to clarify the functions of various influencing factors in the processing pathway. The specific model is shown in Figure 1 [Figure 1: see original paper].

Figure 1. Pedestrian dynamic crossing decision model in interaction with autonomous vehicles, based on the situation awareness model (Endsley, 1995) and the dynamic crossing decision model (Palmeiro et al., 2018)

The primary stage of situation awareness is the perception of environmental cues, where individuals' attention allocation is influenced by cue saliency. In the top-down processing pathway, goals and content stored in long-term memory guide individuals' attention, recognition, and selection of perceived information (Endsley, 1990). In the comprehension stage, information obtained from the environment and schemas and mental models stored in the brain provide rich data to promote information integration and understanding (Endsley, 2000). The projection stage is the highest level of situation awareness, a process of predicting future movement of objects based on interpretation of information obtained during perception and comprehension stages, evaluating action feasibility and risks, and preparing for behavioral decision-making (Endsley, 1995). At this stage, mental models and expectations formed based on experience affect prediction accuracy. Ultimately, pedestrians make crossing decisions and behaviors based on predictions of future dynamics of vehicles and road scenes.

From this process, we can see that pedestrians can still rely on vehicle motion cues to make crossing decisions when interacting with autonomous vehicles. However, well-designed eHMIs can provide additional cues to compensate for missing driver cues, thereby ensuring pedestrians establish comprehensive and correct situation awareness. Pedestrians have different requirements for information presented by eHMIs at different cognitive processing stages. At the information perception stage, communication information presented on eHMIs must have high recognizability, requiring increased information saliency while considering placement location and form. At the comprehension stage, communication information must be clear, intuitive, and easy for pedestrians to understand—researchers need to select graphics and text familiar to pedestrians or explain information meanings to improve understanding accuracy. At the pedestrian projection stage, eHMIs need to explicitly present vehicle intent and motion state change information to help pedestrians predict crossing risks and assist their crossing decisions. The following sections evaluate eHMIs from previous studies based on these pedestrian needs, examining how different eHMIs affect the formation and updating process of pedestrian situation awareness and identifying design requirements and ideas that future research should focus on.

4.2 Perception Stage

The first stage of individuals forming situation awareness is obtaining information from the environment, including attributes, states, and dynamic information of environmental objects (Endsley, 1990). In bottom-up processing, individuals' selection of perceived information is influenced by cue saliency, presentation form, location, and features (Theeuwes, 2010; Treue, 2003). In top-down processing, individuals' goals, working memory, and long-term memory also affect information selection (Endsley, 1995). Information collected during the perception stage forms the basis for comprehension and projection, with 76.3% of situation awareness errors caused by perception errors (Jones & Endsley, 1996). Therefore, to enhance information perception effects, we can improve interfaces based on these influencing factors to increase the recognizability of information presented by eHMIs. However, we must also avoid information overload caused by presenting too much information, which may lead to perception failure.

In design, priority can be given to combining multiple interface types to improve recognizability. The readability of text interfaces is affected by vehicle distance and motion—excessive distance or high speed reduces text visibility. Therefore, to ensure effective use of text interfaces, further research on interface size design is needed (Lee et al., 2019). Compared with text interfaces, information presented by projection interfaces remains clearly visible even when vehicles move quickly and is unaffected by vehicle movement, thus possessing higher recognizability (Ackermann, Beggiato, Schubert, & Krems, 2019). However, ground projection eHMIs cause more visual attentional dispersion, so infrastructure compatibility and impact on pedestrian visual allocation must be considered when selecting such interfaces. Graphical interfaces use dynamic cues to convey vehicle motion change information, which helps improve information recognizability (Othersen et al., 2018). Similarly, light-based interfaces are more easily recognized by pedestrians when providing dynamic cues (Lee et al., 2019). Additionally, light color, brightness, and saturation settings affect information saliency and visibility (Faas & Baumann, 2019). Therefore, to ensure information recognizability, the advantages of various interfaces can be integrated to design multi-presentation-form interfaces that provide dynamic cues for pedestrian perception.

Furthermore, communication information carriers should not be limited to vehicles. eHMIs are typically placed on certain vehicle parts (windshield, roof, doors, headlights) or around the vehicle body. For example, 360° lighting devices allow pedestrians to receive information from multiple angles, improving signal visibility at greater distances (Lee et al., 2019). However, when considering information carriers, researchers often overlook road infrastructure and pedestrians in traffic situations. Smart roads are a type of eHMI designed in combination with road infrastructure that can provide intuitive and clear information with high visibility and are less affected by vehicle motion (Löcken et al., 2019). The interaction effectiveness of smart roads suggests that when designing eHMIs, we should consider combining vehicles, road infrastructure, and

pedestrians to diversify eHMI carriers—for example, presenting information on vehicles, road infrastructure, or pedestrians’ mobile phones to help pedestrians better perceive information.

4.3 Comprehension Stage

In traffic situations, this stage is the process where pedestrians recognize and understand the meanings of information provided by eHMIs. Text interfaces have the advantage that language is a daily communication tool with clear meanings, so such interfaces receive the highest clarity ratings for information transmission (Ackermann, Beggiato, Schubert, & Krems, 2019).

When using non-text interfaces, projected crosswalk interfaces receive the highest clarity ratings. When presenting information is through unlearned graphics or lights, information meaning ambiguity is highest (Bazilinsky et al., 2019). This is because crosswalks have clear meanings assigned in traffic situations, whereas when interaction interfaces display graphics, pedestrians cannot interpret them based on prior experience. Besides graphics, non-standardized light colors also affect pedestrians’ integration and interpretation processes. For example, when using colors with standardized meanings in traffic to convey information conflicting with their standard meanings, pedestrians may develop incorrect understanding of communication content (Faas & Baumann, 2019). Therefore, to improve signal understandability, we should standardize signals and train pedestrians on the one hand; on the other hand, we can combine colors with standardized meanings in traffic with clear text—for example, displaying “WALK” information in green, which represents “go” in traffic (Fridman et al., 2017; Bazilinsky et al., 2019).

Furthermore, information clarity is affected by information presentation perspective. Bazilinsky et al. (2019) proposed two information presentation perspectives: pedestrian crossing advice (e.g., “WALK,” pedestrian-centered information) and vehicle motion information and future action intent (e.g., “decelerating,” vehicle-centered information). Their research shows that pedestrians more easily understand crossing advice information, suggesting that presenting pedestrian advice information seems more appropriate (Ackermann, Beggiato, Schubert, & Krems, 2019). Conversely, Zhang et al. (2017) found that providing pedestrians with vehicle motion information and future action intent information results in higher interface understandability and greater crossing safety. Lagstrom and Lundgren (2015) also believe that eHMIs should only provide vehicle-related information during interaction and should not guide pedestrian crossing behavior. This is because other road users exist in real traffic scenes, and directional information may be difficult to convey precisely to target pedestrians. Additionally, pedestrians need to reference other vehicles’ behavior on the road before crossing. Therefore, caution is needed when conveying guidance about crossing actions.

It should be noted that information presentation perspective and form should be

considered comprehensively. For text information and graphics with standardized meanings (e.g., crosswalks), accurate interpretation is possible regardless of whether they are vehicle-centered or pedestrian-centered. However, for light information, interpretation depends on pedestrians' perspective. For example, although green has the standardized meaning of "go," interpreting the signal from a self-centered perspective would understand it as "let me go," while from a vehicle-centered perspective it would be interpreted as "the vehicle will proceed normally." This ambiguous interpretation could cause interaction failure.

In Table 1, among communication information types, 12 interfaces provide pedestrian advice, 8 interfaces provide only vehicle physical information without guiding pedestrian behavior, and 13 interfaces provide vehicle awareness and intent information. This indicates that current researchers still focus on presenting vehicle-related information in their designs. In summary, when determining information presentation perspective, we must consider not only pedestrians' understanding and acceptance of information but also ensure that pedestrians do not encounter danger when making crossing decisions based on interaction information.

4.4 Projection Stage

In the human-vehicle interaction process, pedestrians' main task at this stage is to identify vehicle intent and predict its future actions based on vehicle motion cues and information provided by eHMIs (Grahn et al., 2020).

Expectation is road users' subjective estimation of the likelihood of certain vehicle behaviors in specific traffic situations based on past experience and current situational cues (Houtenbos et al., 2005), and serves as the basis for pedestrians to predict vehicles' future actions. Typically, pedestrians can form expectations of vehicle behavior based on learned formal or informal traffic rules and road design (Björklund & Åberg, 2005). Pedestrians can also reference current time-to-vehicle-arrival, speed changes (Cœugnet et al., 2019; Rasouli et al., 2017), and road right-of-way (Houtenbos et al., 2005) to form expectations of vehicle motion intent. Pedestrians assess crossing risk and safety based on expectation information and ultimately make crossing decisions according to assessment results. For example, vehicle deceleration patterns may affect pedestrian decision time and accuracy. When vehicles begin decelerating from a greater distance and approach pedestrians at lower speeds, pedestrians can more quickly identify the vehicle's deceleration intent and better predict whether it will yield (Schneemann & Gohl, 2016).

However, when pedestrians only reference vehicle trajectory change information to infer future vehicle actions, they need extended decision time to confirm whether vehicle actions match their inferences. Explicit information presented through eHMIs can clearly convey future vehicle action information and reduce reaction time (Lagstrom & Lundgren, 2015). Therefore, some researchers suggest that eHMIs should be designed to combine interfaces with implicit in-

formation. For example, using displays to present real-time vehicle speed helps pedestrians predict vehicle intent more quickly and accurately (Clamann et al., 2017). This interface maintains consistency and synchronization between implicit and explicit information, improves the recognizability of implicit information, and promotes information transmission accuracy and understandability. Future eHMI designs should consider dynamically presenting vehicle status information through interfaces.

5.1 Model-Based Interface Design Improvement Recommendations

When interacting with conventional vehicles, pedestrians can predict vehicle behavior based on vehicle motion information to help them make crossing decisions. However, when the interaction partner becomes an autonomous vehicle, traditional driver cues will be missing, and pedestrians' situation awareness regarding vehicle behavior needs updating. Therefore, researchers propose adding external human-machine interfaces to convey vehicle physical information, vehicle awareness and intent information, and pedestrian advice to help pedestrians interact safely and effectively with autonomous vehicles. To effectively convey the above information to road users, researchers have designed visual (text, graphics, projection, etc.) and auditory (verbal and non-verbal) signals, and tested the impact of interface use on pedestrian crossing intention, speed, and accuracy indicators in real road experiments, virtual scenarios, and laboratory experiments. Based on the dynamic crossing decision model for pedestrian-vehicle traffic, we propose that eHMI design should reference pedestrians' cognitive processing needs to promote perception, comprehension, and projection of vehicle information. At the perception stage, multiple interface types and presentation carriers should be combined to enhance information recognizability. At the comprehension stage, text explanations, appropriate communication perspectives, signal standardization, and training are needed to improve understandability. At the projection stage, implicit vehicle motion information should be integrated to help pedestrians quickly and accurately obtain vehicle future action intent.

Specifically, based on characteristics of pedestrian information perception, eHMI saliency should be enhanced, and interface recognizability should be improved through multi-channel communication methods. Currently, most researcher-designed interfaces convey communication information to road users through single channels. Few studies have involved multi-channel combined interfaces, with only Mahadevan et al. (2018) attempting to present information using multi-channel interaction methods combining visual signals, auditory signals, and physical signals. However, various interfaces have certain defects: for example, text interfaces have poor readability at long distances and on fast-moving vehicles; graphical and light interfaces require training for road users; projection interfaces risk causing pedestrian attentional dispersion; and auditory interfaces are subject to interference from noisy environments. Additionally, single channels can only convey simple, clear information and struggle to handle complex

traffic situations (Löcken et al., 2019). Therefore, future researchers should combine the advantages of various interfaces to design multi-channel communication methods that provide more complex and diverse communication information to address multiple traffic situations.

At the comprehension stage, to improve pedestrians' understanding of communication information meaning, researchers can select brief, readable text interfaces to present information content. If non-text interfaces are used to present information, researchers should standardize signals—for example, unifying the meanings represented by light colors like traffic signals—to reduce negative impacts of pedestrians' regional cultural differences and comprehension levels on information understandability. Additionally, colors with standardized meanings in traffic can be combined with clear text—for example, displaying “Please cross” information in green to assist pedestrian understanding.

Before pedestrians make crossing decisions, they need to predict crossing risk. The interface's role at this stage is to assist pedestrians in assessing risk more accurately and quickly to make decisions. Vehicle motion cues (vehicle speed, distance) are the main reference communication information for pedestrians when perceiving risk, but such information has limitations. First, pedestrians may not accurately interpret vehicle motion information—for example, they may recognize vehicle deceleration behavior but incorrectly estimate arrival time. Second, pedestrians need to spend additional time confirming vehicle behavior, reducing traffic efficiency. Intuitive and accurate presentation of communication information is an advantage of interfaces. Therefore, we propose that future interface designs should adopt a mode combining interfaces with implicit vehicle information to intuitively present the process of vehicle motion changes.

5.2 Additional Requirements for External Interaction Interfaces in Real Traffic

The complexity of traffic situations means that even if eHMIs meet the above design requirements, the impact of road structure and situational information on pedestrian crossing decisions must also be considered. Based on the previous summary, researchers mainly use real-road experiments, virtual scenario experiments, video/picture experiments, questionnaires, and focus groups to evaluate interface effectiveness. Although researchers have examined interface effectiveness through diverse experimental forms, experimental situations are strictly controlled. To exclude the influence of irrelevant variables, researchers have consistently chosen “one-to-one” human-vehicle interaction situations to evaluate interfaces—that is, only a single autonomous vehicle interacts with a single pedestrian on the road, and the vehicle often travels at constant speed.

Although the “one-to-one” experimental scenario design can better control the influence of extraneous variables to evaluate interface effectiveness, its practical applicability requires further investigation. First, actual scenes contain multiple visual stimuli, and improving eHMIs based solely on “one-to-one” interaction

situation results may not represent their feasibility in complex traffic scenarios. For example, in traffic situations with multiple vehicles, pedestrians may not be able to distinguish light interface information from other vehicle and road lighting signals. Second, if using eHMIs increases pedestrians' cognitive load, errors may occur during information interpretation. Finally, different road users exist in real traffic scenes. When multiple pedestrians are on the road, the directiveness of information provided by eHMIs may become problematic. For example, non-target pedestrians may develop comprehension deviations due to inconsistencies between the situation and interface-provided information, potentially leading to incorrect crossing decisions (Li et al., 2018). Therefore, future research needs to consider the application effectiveness of eHMIs in real traffic scenes and their consistency with experimental research, as well as whether their actual use negatively impacts pedestrians' cognitive load and safety.

5.3 Future Research Directions

In practical terms, we should explore the actual application effects of interfaces in complex traffic situations. Based on pedestrian-centered interface design concepts and the integrated pedestrian decision-making model, we have proposed design principles for autonomous vehicle interfaces to support pedestrian perception, comprehension, and projection of information. However, the practicality of interfaces needs verification through research. For example, to enhance interface saliency, we recommend using multi-channel communication methods to present information. However, how to integrate multiple types of information without negatively impacting pedestrians' cognitive load requires further research and exploration. Therefore, future studies should consider both interface presentation effects and feasibility.

In theoretical terms, we should clarify how various elements of eHMIs affect pedestrians' situation awareness and even higher-level mental models. Existing eHMI evaluations have mainly focused on decision-stage performance, sense of safety, and design concept evaluation outside crossing situations (see Table 1). However, how eHMIs affect the formation and updating process of pedestrian situation awareness in specific human-vehicle interaction situations has not been addressed. This paper attempts to integrate previous research and theories to develop a model to clarify its influence mechanisms, but the specific details require substantial empirical evidence support. Therefore, future research should focus on how eHMIs affect situation awareness and mental model formation from bottom-up processing pathways.

In summary, in future research, we not only look forward to further improving eHMIs to assist pedestrians in making safe crossing decisions but also need to verify how eHMIs affect each pathway of the integrated model established in this paper. The combination of the two can establish model-based evaluation of eHMI information presentation effects, clarify design scheme consequences, and deeply understand their mechanisms of action to flexibly address the complexity of real-world traffic situations.

Ackermann, C., Beggiato, M., Bluhm, L. -F., Löw, A., & Krems, J. F. (2019). Deceleration parameters and their applicability as informal communication signal between pedestrians and automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 757-768.

Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272-282.

Badue, C., Guidolini, R., Carneiro, R. V., Azevedo, P., Cardoso, V. B., Forechi, A., ...De Souza, A. F. (2019). Self-driving cars: A survey. *Expert Systems with Applications*, *165*(3).

Bazilinskyy, P., Dodou, D., & de Winter, J. (2019). Survey on eHMI concepts: The effect of text, color, and perspective. *Transportation Research Part F: Traffic Psychology and Behaviour*, *67*, 175-194.

Björklund, G. M., & Åberg, L. (2005). Driver behaviour in intersections: Formal and informal traffic rules. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(3), 239-253.

Burns, C. G., Oliveira, L., Thomas, P., Iyer, S., & Birrell, S. (2019, June). Pedestrian decision-making responses to external human-machine interface designs for autonomous vehicles. Paper presented at the meeting of 2019 IEEE Intelligent Vehicles Symposium, Paris, France.

Chang, C.-M., Toda, K., Sakamoto, D., & Igarashi, T. (2017). Eyes on a car: An interface design for communication between an autonomous car and a pedestrian. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 65-73). New York, NY, United States: Association for Computing Machinery.

Chen, W., Jiang, Q., Zhuang, X., & Ma, G. (2020). Comparison of pedestrians' gap acceptance behavior towards automated and human-driven vehicles. In D. Harris, W. -C. Li (Eds), *Engineering Psychology and Cognitive Ergonomics. Cognition and Design** (pp. 65-73). Cham, Switzerland: Springer.

Clamann, M., Aubert, M., & Cummings, M. L. (2017, January). Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. Paper presented at the Transportation Research Board 96th Annual Meeting, Washington DC, United States.

Cœugnet, S., Cahour, B., & Kraiem, S. (2019). Risk-taking, emotions and socio-cognitive dynamics of pedestrian street-crossing decision-making in the city. *Transportation Research Part F: Traffic Psychology and Behaviour*, *65*, 141-157.

de Clercq, K., Dietrich, A., Velasco, J. P. N., de Winter, J., & Happee, R. (2019). External human-machine interfaces on automated vehicles: Effects on pedestrian crossing decisions. *Human Factors*, *61*(8), 1353-1370.

Deb, S., Strawderman, L., Carruth, D. W., DuBien, J., Smith, B., & Garrison, T. M. (2017). Development and validation of a questionnaire to assess pedestrian receptivity toward fully autonomous vehicles. *Transportation Research Part C: Emerging Technologies*, *84*, 178–195.

Deb, S., Strawderman, L. J., & Carruth, D. W. (2018). Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *59*, 135–149.

Dey, D., Habibovic, A., Locken, A., Wintersberger, P., Pfleging, B., Riener, A., ...Terken, J. (2020). Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, *7*.

Dey, D., Martens, M., Eggen, B., & Terken, J. (2017). The impact of vehicle appearance and vehicle behavior on pedestrian interaction with autonomous vehicles. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct* (pp. 158–162). New York, NY, United States: Association for Computing Machinery.

Dey, D., & Terken, J. (2017). Pedestrian interaction with vehicles: Roles of explicit and implicit communication. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 109–113). New York, NY, United States: Association for Computing Machinery.

Eisma, Y. B., van Bergen, S., ter Brake, S. M., Hensen, M. T. T., Tempelaar, W. J., & de Winter, J. C. F. (2019). External human-machine interfaces: The effect of display location on crossing intentions and eye movements. *Information*, *11*(1), 13.

Endsley, M. R. (1990). *Situation awareness in dynamic human decision making: Theory and measurement* (Unpublished doctoral dissertation). University of Southern California, Los Angeles, CA.

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors*, *37*(1), 32–64.

Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley, & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 3–6). Mahwah, NJ, USA: Lawrence Erlbaum Associates.

Faas, S. M., & Baumann, M. (2019). Light-based external human machine interface: Color evaluation for self-driving vehicle and pedestrian interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *63*(1), 1232–1236.

Faas, S. M., Mathis, L.-A., & Baumann, M. (2020). External HMI for self-driving vehicles: Which information shall be displayed? *Transportation Research Part F: Traffic Psychology and Behaviour*, 68, 171–186.

Fridman, L., Mehler, B., Xia, L., Yang, Y., Facusse, L. Y., & Reimer, B. (2017, January). To walk or not to walk: Crowdsourced assessment of external vehicle-to-pedestrian displays. Paper presented at the meeting of Transportation Research Board Annual Meeting, Washington, DC.

Fuest, T., Sorokin, L., Bellem, H., & Bengler, K. (2018). Taxonomy of traffic situations for the interaction between automated vehicles and human road users. In *Advances in Intelligent Systems and Computing: Vol. 597. Advances in Human Aspects of Transportation* (pp. 708–719). Cham, Switzerland: Springer.

Grahn, H., Kujala, T., Silvennoinen, J., Leppanen, A., & Saariluoma, P. (2020). Expert drivers' prospective thinking-aloud to enhance automated driving technologies - Investigating uncertainty and anticipation in traffic. *Accident Analysis & Prevention*, 146, 105717.

Habibovic, A., Lundgren, V. M., Andersson, J., Klingegard, M., Lagstrom, T., Sirkka, A., ...Larsson, P. (2018). Communicating intent of automated vehicles to pedestrians. *Frontiers in Psychology*, 9, 1336.

Hagenzieker, M. P., van der Kint, S., Vissers, L., van Schagen, I. N. L. G., de Bruin, J., van Gent, P., & Commandeur, J. J. F. (2019). Interactions between cyclists and automated vehicles: Results of a photo experiment. *Journal of Transportation Safety & Security*, 12*(1), 94–115.

Hudson, C. R., Deb, S., Carruth, D. W., McGinley, J., & Frey, D. (2018). Pedestrian perception of autonomous vehicles with external interacting features. In *Advances in Intelligent Systems and Computing: Vol. 781. Advances in Human Factors and Systems Interaction* (pp. 33–39). Cham, Switzerland: Springer.

Houtenbos, M., Hagenzieker, M., Wieringa, P., & Hale, A. (2005). The role of expectations in interaction behaviour between car drivers. In G. Underwood (Ed.), *Traffic and Transport Psychology: Theory and Application* (pp. 303–314). Kidlington, Oxford: Elsevier.

Jones, D. G., & Endsley, M. R. (1996). Sources of situation awareness errors in aviation. *Aviation Space and Environmental Medicine*, 67(6), 507–512.

Kooijman, L., Happee, R., & de Winter, J. (2019). How do eHMIs affect pedestrians' crossing behavior? A study using a head-mounted display combined with a motion suit. *Information (Switzerland)*, 10, 386.

Lagstrom, T., & Lundgren, V. (2015). *AVIP-Autonomous vehicles' interactions with pedestrians. An investigation of pedestrian-driver communication and development of a vehicle external interface.* (Unpublished doctoral dissertation). Chalmers University Technology, Sweden.

Lee, Y. M., Madigan, R., Garcia, J., Tomlinson, A., Solernou, A., Romano,

R., ...Uttley, J. (2019). Understanding the messages conveyed by automated vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 134-143). New York, NY, United States: Association for Computing Machinery.

Li, Y., Dikmen, M., Hussein, T. G., Wang, Y., & Burns, C. (2018). To cross or not to cross: Urgency-based external warning displays on autonomous vehicles to improve pedestrian crossing safety. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 188-197). New York, NY, United States: Association for Computing Machinery.

Löcken, A., Golling, C., & Riener, A. (2019). How should automated vehicles interact with pedestrians? A comparative analysis of interaction concepts in virtual reality. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 262-274). New York, NY, United States: Association for Computing Machinery.

Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., . . . Saluäär, D. (2017). Will there be new communication needs when introducing automated vehicles to the urban context? In *Advances in Intelligent Systems and Computing: Vol. 484. Advances in Human Aspects of Transportation* (pp. 485-497). Cham, Switzerland: Springer.

Madigan, R., Nordhoff, S., Fox, C., Ezzati Amini, R., Louw, T., Wilbrink, M., ...Merat, N. (2019). Understanding interactions between automated road transport systems and other road users: A video analysis. *Transportation Research Part F: Traffic Psychology and Behaviour*, 66, 196-213.

Mahadevan, K., Somanath, S., & Sharlin, E. (2018). Communicating awareness and intent in autonomous vehicle-pedestrian interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (pp. 1-12). New York, NY, United States: Association for Computing Machinery.

Matthews, M., Chowdhary, G. V., & Kieson, E. (2017). Intent communication between autonomous vehicles and pedestrians. *ArXiv Preprint: 1708.07123*.

Moore, D., Currano, R., Strack, G. E., & Sirkin, D. (2019). The case for implicit external human-machine interfaces for autonomous vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 295-307). New York, NY, United States: Association for Computing Machinery.

Otherson, I., Conti-Kufner, A. S., Dietrich, A., Maruhn, P., & Bengler, K. (2018). Designing for automated vehicle and pedestrian communication: Perspectives on eHMI from older and younger persons. In D. de Waard, K. Brookhuis, D. Coelho, S. Fairclough, D. Manzey, A. Naumann, L. ...R. Wiczorek (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference* (pp. 135-148). HFES.

Palmeiro, A. R., Sander, V. D. K., Vissers, L., Farah, H., De Winter, J. C. F., & Hagenzieker, M. J. T. R. (2018). Interaction between pedestrians and automated vehicles: A Wizard of Oz experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, 58, 1005–1020.

Rouchitsas, A., & Alm, H. (2019). External human-machine interfaces for autonomous vehicle-to-pedestrian communication: A review of empirical work. *Frontiers in Psychology*, 10, 2757.

Rothenbücher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016, November). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. In *2016 25th IEEE International Symposium on Robot and Human Interactive Communication* (pp. 795–802). IEEE.

SAE International (2016). *Surface vehicle recommended practice J3016-taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. SAE International.

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2018). Designing the interaction of automated vehicles with other traffic participants: Design considerations based on human needs and expectations. *Cognition, Technology & Work*, 21(1), 69–85.

Schneemann, F., & Gohl, I. (2016). Analyzing driver-pedestrian interaction at crosswalks: A contribution to autonomous driving in urban environments. In *2016 IEEE Intelligent Vehicles Symposium (IV)* (pp. 38–43). IEEE.

Song, Y. E., Lehsing, C., Fuest, T., & Bengler, K. (2018). External HMIs and their effect on the interaction between pedestrians and automated vehicles. In *Advances in Intelligent Systems and Computing: Vol. 722. Intelligent Human Systems Integration* (pp. 13–18). Cham, Switzerland: Springer.

Sucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*, 102, 41–50.

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection: Reply to commentaries. *Acta Psychologica*, 135(2), 133–139.

Treue, S. (2003). Visual attention: the where, what, how and why of saliency. *Current Opinion in Neurobiology*, 13(4), 428–432.

Velasco, J. P. N., Farah, H., Van Arem, B., & Hagenzieker, M. P. (2019). Studying pedestrians' crossing behavior when interacting with automated vehicles using virtual reality. *Transportation Research Part F: Traffic Psychology and Behaviour*, 66, 1–14.

Vissers, L., van der Kint, S., van Schagen, I., & Hagenzieker, M. (2016). Safe interaction between cyclists, pedestrians and automated vehicles. What do we know and what do we need to know? In *SWOV Institute for Road Safety Research*.

Woodman, R., Lu, K., Higgins, M. D., Brewerton, S., Jennings, P. A., & Birrell, S. (2019). Gap acceptance study of pedestrians crossing between platooning autonomous vehicles in a virtual environment. *Transportation Research Part F: Traffic Psychology and Behaviour*, 67, 1-14.

Zhang, J., Vinkhuyzen, E., & Cefkin, M. (2017). Evaluation of an autonomous vehicle external communication system concept: A survey study. In *Advances in Intelligent Systems and Computing: Vol. 597. Advances in Human Aspects of Transportation* (pp. 650-661). Cham, Switzerland: Springer.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.