Teaching Cars How to Speak Human

The Role of Culture and Branding in Shaping Communication between Autonomous Vehicles and Human Road Users

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DOI
10.4233/uuid:9ef749cd-0189-4fa6-bf2c-39f46dfd0723

Publication date
2025

Document Version
Final published version

Citation (APA)
Wesseling, A.-M. J. B. (2025). *Teaching Cars How to Speak Human: The Role of Culture and Branding in Shaping Communication between Autonomous Vehicles and Human Road Users*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:9ef749cd-0189-4fa6-bf2c-39f46dfd0723

Teaching Cars How to Speak Human

The Role of Culture and Branding in Shaping Communication between Autonomous Vehicles and Human Road Users

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen;
Chair of the Board for Doctorates
to be defended publicly on
Monday 27 October 2025 at 10:00 o'clock

by

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"My journey took me somewhat further down the rabbit hole than I intended
and, though I dirtied my fluffy white tail, I have emerged enlightened."

Sherlock Holmes (2009)

This dissertation has been approved by the promotors.

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Printed by: Volkswagen AG
ISBN: 978-94-6518-160-8
An electronic version of this dissertation is available at https://repository.tudelft.nl/

The results, opinions and conclusions expressed in this publication are not necessarily those of Volkswagen Aktiengesellschaft.

Summary

Imagine standing at a crosswalk, watching a car approach, only to realize the driver is absorbed in reading a newspaper. While this scenario might seem improbable today, the rise of Autonomous Vehicles (AVs) could make it a reality in the near future. AVs, capable of navigating roads independently, promise numerous benefits, including reduced emissions, improved traffic flow, and enhanced mobility and safety. However, removing the driver also eliminates a crucial element of road interaction: non-verbal cues such as eye contact and gestures. Without these cues, human road users (HRUs)—including pedestrians, cyclists, and other drivers—may struggle to predict an AV's intentions, leading to uncertainty and potential safety risks.

The field of external Human-Machine Interfaces (eHMI) research examines this communication gap and develops communication systems that allow AVs to communicate with all road users, even in the absence of a human driver, in order to bridge the gap.

Research on eHMI has underexplored two crucial factors: culture and branding. Culture influences driving norms, traffic behaviors, and communication preferences, which can shape how AV signals should be designed for different regions. Branding, on the other hand, plays a significant role in the automotive industry, influencing consumer perception and enabling market differentiation. This thesis investigates how cultural differences impact eHMI design and explores how branding can be incorporated without compromising the core communication function of the eHMI. Specifically, it addresses the following research questions:

- How do cultural differences shape the expectations and preferences of HRUs for eHMI designs?
- How do cultural factors affect the performance and effectiveness of specific eHMI modalities and designs communicating with HRUs?
- How does branding impact the performance of and preferences for eHMI systems?

This first study explores Human Road Users' (HRUs) preferences for various eHMI concepts across three culturally distinct regions: China, Germany, and the United States. Seven eHMI technologies were evaluated—Display, LED, vehicle inclination ("Incline"), Directed Sound Beam

("Sound"), Smart Assistant in Wearables, Smart Infrastructure, and Augmented Reality—with the goal of identifying both universal and culture-specific design preferences. The findings of this online survey reveal that while culture significantly shapes preferences for eHMI concepts, some universal trends also emerge. Across cultures, Display, Smart Infrastructure, and Augmented Reality ranked highest in terms of trust and usability. However, cultural differences were particularly pronounced in preferences for less conventional technologies. Participants from Germany and the USA consistently favored Display-based eHMI, whereas Chinese participants showed stronger preferences for Smart Assistants and Augmented Reality. However, fully localized hardware solutions are impractical, especially in international contexts where AVs may cross borders. Instead, the study advocates for a modular eHMI design strategy—one that combines a universal hardware baseline with culturally adaptive software modules. The baseline should integrate universally accepted technologies like Display, Augmented Reality, and Smart Infrastructure, possibly supported by LEDs and sound to create a multi-modal experience. Moreover, the system should implement a universal preference for egocentric perspective in eHMI communication—where messages are framed from the HRU's point of view—which could enhance clarity and global interoperability, as indicated by the universal preferences for this perspective found in this study. Meanwhile, the cultural modules should focus on localized information delivery tailored to each region's specific expectations and communication norms, as the study's findings indicate that information content is particularly sensitive to cultural differences. Ultimately, the study highlights the importance of cultural sensitivity in designing effective eHMI systems and positions software-based localization as a scalable and flexible solution for future global deployment of AVs.

Where study 1 established that cultural differences significantly shape preferences for eHMI, study 2 and 3 attempt to shift from identifying what differs between cultures (preferences and expectations) to exploring how information should be designed for cultural communication. This is referred to as "message coding"; the way information is packaged and delivered through a specific communication method or technology. In the context of eHMIs, it refers to how things like lights, sounds, or visual displays are used to encode messages that people on the road—like pedestrians or drivers—can quickly understand.

The second study focuses on how different message coding strategies of selected technology modalities—LEDs, sound, and displays—influence the effectiveness of eHMIs in China and Germany. The Virtual Reality (VR) study highlights the significant influence of culture on subjective responses, emphasizing the need to tailor eHMIs to cultural contexts. The role of the communication partner (e.g., pedestrian vs. car driver) also influences the effectiveness of coding strategies. The results show that culturally adaptive eHMIs are crucial for optimizing the user experience. In Germany, symbol-based displays proved to be most effective, while both symbol-based and anthropomorphic displays were suitable for China. Symbol-based visual cues are therefore recommended as a solid foundation for universal eHMI designs. The study also advocates for a multi-modal approach, combining auditory and visual signals to enhance communication, particularly in urgent situations. The use of ascending sound coding improves decision-making efficiency in high-risk scenarios, while color-coding the symbol cues could contribute to better understanding, perceived safety, and acceptance of autonomous vehicles.

The third study takes a step further by directly comparing two distinct eHMI coding strategies in VR: learned representation-based designs and universal cognitive innate tendency-based designs. Specifically, the study investigated eHMI systems that either rely on familiar, context-specific traffic symbols and behaviors (learned representations) or on cognitive innate tendencies that might be more universally applicable across cultures. The findings reveal that learned representation-based designs—such as traffic signs and road markings—are more intuitive and widely accepted across both cultures, showing promise for a universal eHMI coding strategy. These designs not only improve user understanding and AV acceptance but also do not affect decision-making and gaze time. Interestingly, the study also highlights the need for role-specific adaptations—pedestrians showed a stronger preference for traffic sign-based representations, while drivers preferred road marking-based cues. These differences indicate that a one-size-fits-all approach may not suffice, and that tailoring the eHMI design to the specific role of the HRU—pedestrian or driver—can enhance communication clarity and overall effectiveness, aiding eHMI scalability.

The fourth study shifts focus to branding freedom within eHMI systems, exploring how branding influences the effectiveness of eHMI in providing clear, intuitive, and culturally relevant cues. The findings of this online survey suggest that branding affects eHMI effectiveness and symbol recognition, with the recommendation to avoid branding for universal application when aiming to optimize subjective experiences. Cultural differences, such as China's higher openness to branding compared to Germany's resistance, indicate the potential for culture-specific branding approaches. Light branding could be applied in both contexts, but caution is necessary. However, decision time and traffic flow remained unaffected by branding, leading to some car manufacturers arguing in favor of the possibility for striking a balance between the value of implemented branding and a suboptimal subjective experience.

When integrating these findings, the modular eHMI system should operate across three types of traffic scenarios: non-ambiguous, ambiguous, and urgent/dangerous. In non-ambiguous situations, the system remains inactive, relying on the vehicle's standard cues to avoid information overload. In ambiguous scenarios, the system activates color-coded, learned representation-based symbols tailored to the type of HRU (i.e., road markings for drivers, traffic sign symbols for pedestrians). In urgent situations, the system adds auditory cues to intensify communication, ensuring rapid comprehension. Branding is recommended to not be implemented. However, with the value of branding in the automotive industry in mind, car manufactures may lobby for integrating light branding in non-critical situations, while deactivating the branding layer in high-stakes scenarios to prioritize safety. When developing this system, it is crucial to consider cultural preferences, ensuring that branding and communication cues align with local expectations. Additionally, the behavior of the AV should respect cultural factors, such as acceptable follow distances and traffic behaviors, offering effective interactions that align with cultural expectations.

In conclusion, this research demonstrates that while some aspects of eHMI design—such as technology modalities and visual coding strategies—can be standardized, others, like information content and branding, require cultural sensitivity and flexible adaptation. By proposing a modular, multi-modal eHMI system that integrates universal communication elements with culturally tailored software modules, this thesis offers a scalable framework for globally deployable and locally relevant AV communication—bridging the gap between human expectations and machine behavior in diverse traffic environments.

Samenvatting

Stel je voor dat je bij een oversteekplaats staat en een auto ziet naderen, om er vervolgens achter te komen dat de bestuurder verdiept is in het lezen van een krant. Hoewel dit scenario vandaag de dag onwaarschijnlijk lijkt, zou de opkomst van autonome voertuigen (AV's) het in de nabije toekomst realiteit kunnen maken. AV's, die in staat zijn om zelfstandig over de weg te navigeren, beloven tal van voordelen, zoals lagere uitstoot, verbeterde doorstroming van het verkeer en verhoogde mobiliteit en veiligheid. Het weghalen van de bestuurder neemt echter ook een cruciaal element van verkeersinteractie weg: non-verbale signalen zoals oogcontact en handgebaren. Zonder deze signalen kunnen menselijke weggebruikers (HRU's)—waaronder voetgangers, fietsers en andere bestuurders—moeite hebben om de intenties van een AV in te schatten, wat kan leiden tot onzekerheid en mogelijk gevaarlijke situaties. Het onderzoeksveld van externe Human-Machine Interfaces (eHMI's) richt zich op deze communicatiekloof en ontwikkelt systemen die AV's in staat stellen om met alle weggebruikers te communiceren, zelfs zonder menselijke bestuurder.

Binnen het eHMI-onderzoek zijn twee cruciale factoren nog onderbelicht gebleven: cultuur en branding. Cultuur beïnvloedt verkeersnormen, rijgedrag en communicatiestijlen, wat bepalend kan zijn voor hoe signalen van AV's in verschillende regio's moeten worden ontworpen. Branding speelt tegelijkertijd een grote rol in de auto-industrie, door consumentperceptie te beïnvloeden en merken te onderscheiden. Deze scriptie onderzoekt hoe culturele verschillen invloed hebben op eHMI-ontwerp en hoe branding kan worden geïntegreerd zonder de kernfunctie van communicatie aan te tasten. Concreet richt het onderzoek zich op de volgende vragen:

- Hoe beïnvloeden culturele verschillen de verwachtingen en voorkeuren van HRU's ten aanzien van eHMI-ontwerpen?
- Hoe beïnvloeden culturele factoren de prestaties en effectiviteit van specifieke eHMI-modaliteiten en -ontwerpen in de communicatie met HRU's?, en
- Hoe beïnvloedt branding de prestaties van en voorkeuren voor eHMI-systemen?

De eerste studie verkent de voorkeuren van menselijke weggebruikers voor verschillende eHMI-concepten in drie cultureel uiteenlopende regio's: China, Duitsland en de Verenigde Staten.

Zeven eHMI-technologieën werden geëvalueerd—Display, LED, voertuighelling (“Incline”), Gerichte Geluidsstraal (“Sound”), Slimme Assistent in wearables, Slimme Infrastructuur en Augmented Reality—met als doel zowel universele als cultuurgebonden voorkeuren te identificeren. De resultaten van deze online questionnaires tonen aan dat cultuur een significante invloed heeft op voorkeuren, maar dat er ook universele trends bestaan. Display, Smart Infrastructure en Augmented Reality kregen in alle culturen de hoogste scores op het gebied van vertrouwen en bruikbaarheid. Toch kwamen de grootste culturele verschillen naar voren bij minder conventionele technologieën: Duitse en Amerikaanse deelnemers gaven steevast de voorkeur aan displays, terwijl Chinese deelnemers meer vertrouwen toonden in slimme assistenten en augmented reality. Volledig gelokaliseerde hardwareoplossingen zijn echter niet praktisch, zeker niet in internationale contexten waar AV’s landsgrenzen kunnen overschrijden. Daarom pleit de studie voor een modulaire eHMI-aanpak, waarin universele hardware wordt gecombineerd met cultureel aanpasbare softwaremodules. De hardwarebasis moet breed geaccepteerde technologieën bevatten zoals displays, augmented reality en slimme infrastructuur, eventueel ondersteund door LED en geluid om een multimodale ervaring te creëren. Daarnaast moet het systeem wereldwijd een egocentrisch perspectief hanteren—waarbij de boodschap wordt afgestemd op het perspectief van de HRU—om helderheid en interoperabiliteit te vergroten. De culturele modules richten zich op het leveren van informatie die aansluit op de verwachtingen en communicatievoorkeuren per regio, aangezien de inhoud van de boodschap sterk cultuurgevoelig blijkt. Uiteindelijk onderstreept deze studie het belang van culturele sensitiviteit in eHMI-ontwerp en positioneert softwarematige lokalisatie als een schaalbare, flexibele oplossing voor wereldwijde implementatie van AV’s.

Waar de eerste studie vaststelde dat culturele verschillen een belangrijke rol spelen in voorkeuren voor eHMI, verkennen studie 2 en 3 hoe informatie cultureel afgestemd moet worden—dit wordt aangeduid als “message coding”: de manier waarop informatie wordt verpakt en overgebracht via een specifieke communicatiemethode of technologie. In de context van eHMI’s gaat het om hoe lichten, geluiden of visuele displays worden gebruikt om boodschappen over te brengen die weggebruikers snel kunnen interpreteren.

De tweede studie richt zich op hoe verschillende vormen van message coding binnen bepaalde technologieën—LEDs, geluid en displays—de effectiviteit van eHMI’s beïnvloeden in China en Duitsland. De VR-studie benadrukt de invloed van cultuur op subjectieve beleving en het belang van culturele afstemming. Ook de rol van de communicatiepartner (bijv. voetganger versus bestuurder) blijkt van invloed op de effectiviteit van de boodschap. In Duitsland bleken symbolen op displays het meest effectief, terwijl in China zowel symbolische als antropomorfe displays geschikt waren. Symbolen worden dan ook aanbevolen als fundament voor universele eHMI-ontwerpen. De studie pleit daarnaast voor een multimodale aanpak waarbij visuele en auditieve signalen worden gecombineerd, zeker in noodsituaties. Oplopende geluidsignalen verhogen de besluitvormingsefficiëntie in risicovolle situaties, terwijl kleurcodering de begrijpelijkheid, veiligheidsbeleving en acceptatie van AV’s kan versterken.

De derde studie vergelijkt twee verschillende benaderingen van message coding in VR: ontwerpen op basis van aangeleerde representaties versus ontwerpen op basis van universele cognitieve tendensen. De resultaten tonen aan dat aangeleerde representaties—zoals verkeersborden en wegmarkeringen—intuïtiever en breder geaccepteerd zijn in beide culturen, en daarom veelbelovend zijn voor een universele benadering. Deze ontwerpen verbeteren de interpretatie van signalen en de acceptatie van AV’s, zonder negatieve invloed op besluitvorming of blikrichting. Wel toont de studie aan dat aanpassing aan de rol van de HRU belangrijk is: voetgangers gaven de voorkeur aan verkeersborden, terwijl bestuurders beter reageerden op wegmarkeringen. Dit wijst op de noodzaak voor rol-specifiek ontwerp voor optimale effectiviteit en schaalbaarheid.

De vierde studie onderzoekt de invloed van branding in eHMI-systemen. De bevindingen van de online questionnaire tonen aan dat branding invloed heeft op de herkenbaarheid van symbolen en de subjectieve ervaring. Universele toepassing van branding wordt afgeraden, maar culturele verschillen—zoals de grotere openheid voor branding in China en de terughoudendheid in Duitsland—laten zien dat een cultuur-specifieke aanpak mogelijk is. Lichte vormen van branding zijn in beide contexten denkbaar, maar voorzichtigheid is geboden. Hoewel branding geen invloed had op besluitvorming of verkeersdoorstroming, pleiten sommige fabrikanten voor een compromis tussen merkherkenning en gebruikservaring.

Bij het integreren van deze bevindingen moet het modulaire eHMI-systeem functioneren in drie soorten verkeersscenario’s: niet-ambigue, ambigue en urgent/gevaarlijk. In niet-ambigue situaties blijft het systeem inactief en vertrouwt het op standaard voertuigsignalen om informatie-overload te voorkomen. In ambigue situaties worden kleurgecodeerde, op aangeleerde representaties gebaseerde symbolen geactiveerd, afgestemd op het type HRU (bijv. wegmarkeringen voor bestuurders, verkeersborden voor voetgangers). In urgente situaties worden auditieve signalen toegevoegd om snelle interpretatie te bevorderen. Branding wordt afgeraden in universele toepassingen, maar autofabrikanten kunnen aandringen op lichte branding in niet-kritieke contexten, zolang deze wordt gedeactiveerd in risicovolle situaties. Cruciaal is dat het systeem culturele voorkeuren respecteert—zowel in de communicatiesignalen als in het gedrag van het voertuig, zoals volgafstand en verkeersgedrag.

Tot slot laat dit onderzoek zien dat sommige elementen van eHMI-ontwerp—zoals technologie en visuele codering—kunnen worden gestandaardiseerd, terwijl andere—zoals informatie-inhoud en branding—vragen om culturele flexibiliteit. Door een modulair, multimodaal eHMI-systeem te ontwerpen dat universele communicatie combineert met cultureel afgestemde softwaremodules, biedt deze scriptie een schaalbaar raamwerk voor wereldwijd inzetbare en lokaal relevante AV-communicatie—waarmee de kloof tussen menselijke verwachtingen en machinegedrag in diverse verkeersomgevingen wordt overbrugd.

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5. Exploring Branding Freedom

List of Abbreviations

AV	Autonomous Vehicle
eHMI	External Human-Machine Interface
ExCom	External Communication system
HCI	Human-Computer Interaction
HMI	Human-Machine Interaction
HRU	Human Road User
OEM	Original Equipment Manufacturer
VRU	Vulnerable Road User

1.
Introduction

Traffic is an overwhelming place to be—a constant, chaotic rush of movement and noise. Cars surge forward, slow down, switch lanes, sometimes without warning. Horns intermittently blare from different directions. Cyclists weave between vehicles while pedestrians dart across streets, further adding to the bustle. Amidst this chaos, subtle cues—like a quick wave from a driver, eye contact with a pedestrian, or a vehicle's blinker—help us navigate. These small, human gestures foster collaboration, allowing us to manage the unpredictability of traffic together.

Yet, despite these cues, navigating traffic is a constant mental calculation. Should I cross now? Will that car slow down? Can I make the light, or should I stop? Every decision carries heavy potential consequences. Even when we are vigilant, factors beyond our control complicate the process.

Now, imagine the introduction of Autonomous Vehicles (AVs) into this already chaotic environment. These AVs can drive themselves. Suddenly, instead of the familiar, attentive driver, we might be shocked to find no driver at all, or perhaps a "driver" engrossed in a newspaper. We are left feeling insecure and hesitant, unsure about what to do. Without an attentive driver to offer reassuring waves, make eye contact or provide us with other cues, that vital layer of communication vanishes.

We are left questioning how AVs will communicate within a system that is heavily reliant on human interaction? Can AVs replicate these cues using technology, or will they develop entirely new forms of communication? In this chapter, we explore how AVs will integrate into traffic and examine the current research into effective communication systems that make AVs understandable and predictable to human road users.

1.1.

The Transformative Potential of AVs

The introduction of Autonomous Vehicles (AVs) promises to revolutionize personal mobility, offering numerous benefits that extend beyond convenience. By reducing human error—which contributes to 94% of traffic accidents—AVs have the potential to drastically reduce the estimated 1.19 million fatalities and up to 50 million non-fatal injuries occurring globally each year *(NHTSA, 2017; World Health Organization, 2023)*. In addition to improving safety, AVs can enhance traffic flow, increase highway capacity, and reduce congestion, leading to shorter travel times and a reduction in fuel consumption by up to 4% *(Chang et al., 2017; Fagnant & Kockelman, 2015; Narayanan et al., 2020; Wadud et al., 2016)*. Environmental benefits are also significant, potentially reducing CO2 emissions by up to 8.2% and NOx emissions by up to 8.9% with just a 25% adoption rate of advanced AVs, thus improving air quality and promoting healthier living environments *(Shapiro & Yoder, 2023)*. Additionally, AVs can enable greater mobility for the elderly, disabled, or those without personal vehicles, fostering social inclusion and economic opportunities. Other social benefits include increased convenience for drivers and more productive use of time during travel *(Cairns et al., 2014; Fagnant & Kockelman, 2015; Litman, 2023)*.

> ***“If you recognize that self-driving cars are going to prevent car accidents, AI will be responsible for reducing one of the leading causes of death in the world.”***
>
> *Quote from Mark Zuckerberg (Carson, 2016)*

AVs exist at different levels of automation, ranging from Level 0 (no automation) to Level 5 (full autonomy). At Level 0, human drivers are fully responsible for controlling the vehicle. Level 1 introduces basic driver assistance features, such as adaptive cruise control or lane-keeping assistance, but the driver must remain fully engaged. At Level 2, partial automation allows the vehicle to control both steering and acceleration, but the driver must be ready to take over at any time. Level 3 offers conditional automation, with the vehicle capable of handling all driving tasks in certain conditions, such as highway driving, though the driver must still be present to take control when needed. Level 4 involves high automation, where the vehicle can operate autonomously within certain environments, such as geofenced areas, without human intervention. Finally, Level 5 represents full autonomy, where the vehicle can operate without any human input under all conditions. These levels are defined by the Society of Automotive Engineers in the SAE J3016 standard, the global benchmark for AV automation levels *(SAE International, 2018)*. The scope of this thesis is limited to Level 4 and Level 5, in accordance with the SAE J3016 standard.

The integration of AVs into our traffic systems will enable a transformative shift toward safer, more efficient, and more accessible mobility. However, the widespread adoption of AVs faces significant challenges, particularly due to their inability to effectively communicate with human road users (HRUs).

1.2.

A Communication Challenge

Effective communication between road users is critical in traffic situations, particularly in those that fall outside the scope of formal traffic regulations. Traffic rules, signals, and road markings provide general guidelines but are not sufficient to address every possible scenario. Examples of ambiguous scenarios are (1) a pedestrian waiting to cross an intersection without a signal may be unsure whether to proceed, and a driver may be equally uncertain whether to stop, or (2) at a four-way stop with no clear priority signage, multiple drivers may approach at the same time, requiring informal communication to determine who goes first. Consequently, traffic situations often arise that are ambiguous and require informal communication between HRUs to clarify intentions and resolve uncertainty *(Maurer et al., 2016)*. Specifically, human-centric cues, such as eye contact, posture, and gestures, are relied on to communicate intentions and coordinate actions in these ambiguous situations *(Dey & Terken, 2017; Šucha et al., 2017)*. Unfortunately, the sensors, systems, and computers that make vehicles autonomous, and allow for the driver to be excluded from the driving task, disrupt the informal communication methods on which HRUs heavily rely.

Before AVs, HRUs could communicate directly with drivers using human-centric cues, such as eye-contact, behavior, pedestrian trajectory, posture and gestures. These cues primarily focus on communicating intentions in movement to obtain a mutual understanding and awareness through which actions can be coordinated *(Risto et al., 2017)*. Now, with the driver removed from the driving task, these human-centric cues are lost *(Mahadevan et al., 2018a)*. With this communication strategy lost, informal vehicle-centric cues are the only remaining interaction source *(Matthews et al., 2018)*. These vehicle-centric cues revolve around communicating through the movement of a vehicle, which is the central method for communicating the driver’s actions and intentions to pedestrians *(Müller et al., 2016)*. However, these cues may no longer be reliable for HRUs because AVs are operated by sensors and a central computer, resulting in anomalous driving behavior. In other words, the way an AV behaves in traffic is different from a traditional vehicle that has a human driver. As a result, these vehicle-centric cues deviate from a traditional vehicle, leading to misinterpretation by HRUs *(Dey et al., 2017; Tapiro et al., 2019; Wagner, 2016)*. Consequently, informal communication methods may lose their functionality entirely *(Färber, 2016)*.

This communication gap is particularly problematic in more ambiguous traffic situations such as pedestrian crossing scenarios. In these scenarios, 84% of HRUs attempt to make eye-contact *(Schmidt & Färber, 2009)*. When unsuccessfully attempting to initiate eye-contact with the non-existing or inattentive driver, mistrust and uncertainty follow *(Vissers et al., 2016)*. This is especially crucial when considering that behavior of an encountered vehicle that does not align with expectations—such as the anomalous driving behavior of AVs—causes HRUs to shift their gaze from the vehicle and its trajectory to the windshield and the driver *(Dey et al., 2019)*. This in turn exacerbates the issue. Simply put, AVs lack an attentive driver, creating a dilemma for HRUs as these AVs become more common on the road. This raises uncertainty for HRUs, as they cannot easily determine who is in control of the vehicles they encounter:

"Is the approaching vehicle, a human-driven car? An automated car with an inattentive driver? Or a fully autonomous car with no driver at all?"

This uncertainty influences HRU behavior, such as a pedestrian's trajectory and posture, making it more challenging for AVs to interpret their actions. The situation is further complicated by the inherently unpredictable nature of pedestrian behavior, which hinders AVs' ability to consistently assess and predict movements *(Benenson et al., 2015; Ferguson et al., 2014; Schneider & Gavrila, 2013)*. In such scenarios, HRUs often rely on human-centric cues like gestures to clarify their intentions and facilitate collaboration. However, AVs also lack the ability to fully comprehend the nuances and subtleties of this informal communication, making an already uncertain situation even more volatile and confusing *(Jafary et al., 2018; Vissers et al., 2016)*.

Given the concerns related to the AVs' inability to partake in and understand informal communication, it is essential to develop effective solutions to bridge the communication gap between AVs and HRUs to ensure safety and efficiency. The urgency of these solutions is heightened by the low public acceptance of advanced AVs, which increases hesitance and discomfort when encountering AVs with unpredictable behavior *(Wang & Zhao, 2019)*. These factors could significantly slow down the integration of AVs into our traffic system, delaying the realization of their potential benefits *(Carmona et al., 2021)*. Moreover, given that AVs are expected to share traffic space with

traditional vehicles and other HRUs for decades to come, the significance of this goal is heightened even further *(Litman, 2023)*. Therefore, research aims to develop novel communication solutions to facilitate the successful integration of AVs into our traffic system.

1.3. Bridging the Gap: Foundations in eHMI

The field focused on developing such innovative communication solutions for Autonomous Vehicles (AVs) is known as external Human-Machine Interfaces (eHMI) *(Matthews et al., 2018; Rasouli et al., 2017)*. These systems aim to expand the communication toolkit currently available to AVs—such as horns, rear lights, brake lights, reverse lights, headlights, high beams, and indicators.

At its core, eHMI seeks to enable AVs to communicate effectively with surrounding Human Road Users (HRUs), compensating for the loss of human-centric cues and the inconsistencies in vehicle-centric cues. By facilitating clear communication, eHMI can help reduce the ambiguity of various traffic situations, thereby lessening the reliance on informal communication and the need for AVs to interpret its subtle nuances.

The goal of this field is both vital and complex: enabling safe interaction between AVs and HRUs by bridging the gap between the ambiguity of informal communication and the constraints of traffic regulations, ensuring a safe coexistence in traffic. The rapid growth of literature and the diverse research directions within this field underscore the complexity of the challenge AVs face *(Dey, Habibovic, Löcken, et al., 2020)*.

1.3.1. Pioneering Studies in eHMI: Established Understandings

The field of eHMI research is built upon a foundation of seminal studies that have significantly shaped our understanding of this complex domain. These foundational works have provided essential insights into the design principles and effectiveness of eHMIs, established evaluation metrics, identified key traffic scenarios for their application, and explored the critical content of eHMI messages. In this section, we will examine these pioneering studies, highlighting their key findings that have informed and guided the research presented in this dissertation.

Metrics of eHMI Effectiveness

Evaluating the effectiveness of eHMI solutions is crucial for understanding their impact on traffic safety and efficiency. Extensive research has identified various measures that assess how well these interfaces facilitate communication between AVs and HRUs. The research field agrees on several key metrics that evaluate eHMI effectiveness and promote the successful integration of AVs into our traffic systems. These metrics, both subjective and objective, provide a comprehensive framework for evaluating the effectiveness of eHMI solutions, ensuring a multifaceted understanding of their performance and impact on traffic safety and efficiency.

The core metrics for evaluating external Human-Machine Interfaces (eHMIs) focus on enhancing the interaction experience between human road users (HRUs) and autonomous vehicles (AVs), ultimately fostering greater acceptance and trust in the technology. A key metric is *intuitive comprehension*, which refers to how easily and quickly HRUs can understand the eHMI's messages. An intuitive system facilitates quick and accurate interpretation of the AV's intentions through simplicity, facilitating HRU's understanding of the AV's behavior and enhancing decision-making in traffic scenarios *(Oidekivi et al., 2021)*. *Intuitive comprehension* closely aligns with usability factors, including subjective efficiency, ease of learning, memorability, and expected performance in various scenarios, which also contribute to the overall acceptance and effective use of AVs *(Ackermann et al., 2019; Bindschädel et al., 2022a; Deb et al., 2016; Habibovic et al., 2018; Hoff & Bashir, 2015; J. D. Lee & See, 2004; Louw et al., 2021; Mahadevan et al., 2018; Nastjuk et al., 2020; Parasuraman & Riley, 2016; Sheridan & Parasuraman, 2016)*. Effective and clear explicit eHMI systems that address missing driver cues, also improve *trust and acceptance of AVs* *(Deb et al., 2016; Mahadevan et al., 2018)*. Additionally, *perceived safety* and *understanding of AVs* is critical, as these factors foster trust and enhance *comfort* during interactions *(Ackermann et al., 2019; Habibovic et al., 2018)*.

Effective eHMIs also aid in the perception, comprehension, and projection of environmental elements, improving situational awareness and sequentially decision-making processes in traffic. Situational awareness refers to the mental reflection of surrounding elements, which demands significant cognitive workload. Non-optimized workload can cause distractions, insufficient processing time, and inaccurate perceptions *(Endsley, 2016; Baldwin & Coyne, 2005; Wickens, 2002; Silva, 2014)*. Hence, another vital metric is *decision-making efficiency.* eHMIs should enable quicker decision-making for HRUs by reducing cognitive workload, promoting better traffic flow *(Endsley, 2016).* Evaluating the decision-making efficiency is possible through measuring decision time and total gaze time on the encountered AV and its eHMI *(Mahadevan et al., 2018).* Additionally, humans are able

to optimize mental workload by guiding their attention based on expectations *(Endsley, 2016)*. Hence, expectations are important to consider. Understanding HRUs' expectations, which are derived from learned behavior and (cultural) context, is essential for designing eHMIs that align with familiar cues from previous traffic experiences *(Deb et al., 2020; Holländer, Wintersberger, et al., 2019; Rozkwitalska, 2013).*

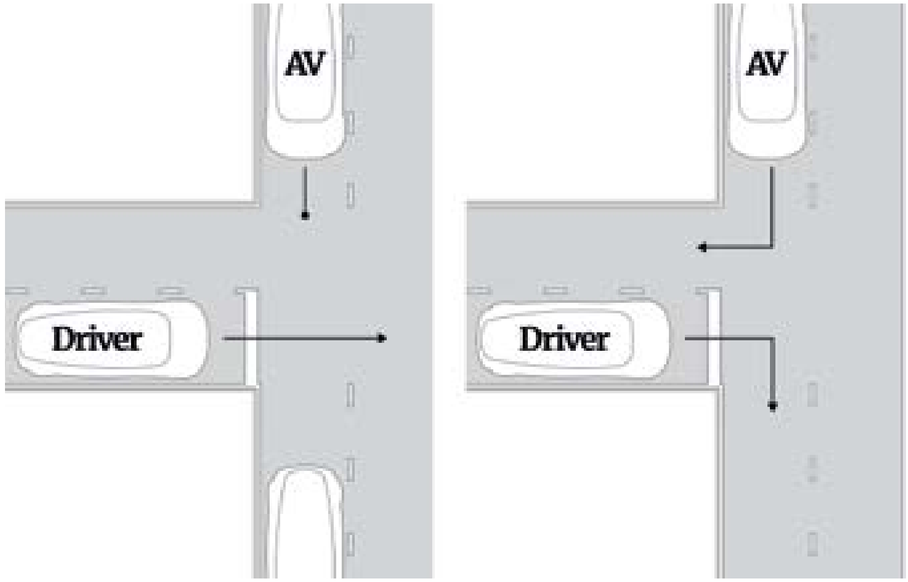
In summary, the evaluation of eHMI effectiveness is essential for ensuring the successful integration of AVs into our traffic systems. By examining the core metrics—such as intuitive comprehension, understanding of AVs, perceived safety, trust and acceptance (subjective), and decision-making efficiency (both subjective and objective)—researchers can gain valuable insights into how these communication solutions impact both HRUs and AVs. As the field of autonomous vehicles continues to evolve, these metrics will remain pivotal in guiding the development of eHMI systems that enhance safety, trust, and efficiency, ultimately facilitating smoother interactions between AVs and all road users.

Crucial Traffic Scenarios

The communication needs when encountering AVs are highly dependent on the specific traffic scenario encountered, as well as the desired outcome of that scenario *(Madigan et al., 2023)*. The type of information that must be conveyed varies significantly across different situations, making it essential to understand which scenarios require enhanced communication. Based on the extensive research that has been conducted, certain traffic situations have emerged as particularly crucial, such as pedestrian crossing scenarios and scenarios where road users share equal priority.

Crossing situations where pedestrians interact with automated vehicles are among the most critical traffic scenarios where eHMIs could provide substantial support *(Clamann et al., 2017; Coeugnet-Chevrier, 2019; Färber, 2016; Lagström & Malmstem Lundgren, 2015; Mahadevan et al., 2018)*. These scenarios often involve ambiguity, as pedestrians and AVs must clearly communicate their intentions to ensure safe and efficient crossings. In addition to crossing situations, traffic scenarios where road users theoretically share equal priority, such as navigating parking lots, also require enhanced communication. Furthermore, situations that involve cooperative driving, where collaborative behavior between AVs and human-driven vehicles could improve overall traffic flow or if there is no clear right of way, are key areas for potential eHMI application *(Dietrich et al., 2018; Madigan et al., 2023)*. For instance, at an intersection where the AV is driving in the priority lane and another vehicle is approaching from an intersecting road, the communication between the AV and the driver of the other vehicle becomes crucial to ensure smooth navigation. The expected cooperative behavior will vary depending on the AV's navigation goal, adding another layer of complexity to the communication challenge. These traffic scenarios have been visualized *(see Figure 1)*.

| **Figure 1** *Traffic Scenarios that require Cooperative Driving Behavior.*



Note: On the left, due to the stalled traffic ahead, the AV would normally join the queue. Yet, for the manual driver, it would be helpful that the AV were to stop before the road to allow the driver to cross the street, improving traffic flow. Normally, we would gesture people to go ahead. On the right, as the AV is going to turn left, human drivers might turn on their indicator early to show that the driver coming from the right can already commence their maneuver that allows them to turn onto the priority road early.

Despite significant progress in understanding the role of eHMIs, the existing literature lacks a comprehensive overview of all traffic scenarios where these systems could be beneficial. While pedestrian crossing scenarios have been extensively studied, there remains a gap in understanding the specific communication needs and information requirements for other traffic situations. More importantly, little research has explored and systematically evaluated different eHMI concepts across various traffic scenarios and intended communication partners. Addressing these gaps presents a valuable opportunity for future research to develop more adaptable and effective eHMI solutions that can enhance interactions between AVs and human road users in a wider range of contexts.

1.3.2.

Contested Concepts in eHMI: Diverging Perspectives

While the field of eHMI research has made significant strides in understanding how AVs can communicate with HRUs, it remains highly fragmented, with many opposing views on key aspects of eHMI design. Diverging perspectives exist on what message content should be conveyed, the most effective perspective of communication (i.e., whether messages should be egocentric or allocentric), and which technological modalities best support clear and intuitive interaction. These differences highlight the complexity of designing eHMI systems that are universally effective across diverse traffic scenarios and user groups.

Message Content: What Should eHMIs Communicate?

The aim of informal communication in traffic is to enable road users to exchange the information they need to interpret situations, communicate their intentions and awareness, negotiate, decide, and coordinate their actions effectively *(Dey & Terken, 2017; Šucha et al., 2017)*. In the context of Autonomous Vehicles (AVs), research has identified three primary areas of information that need to be communicated through eHMIs: intent, awareness, and status (or mode). The communication of intent pertains to information about the AV's trajectory and its planned or executed maneuvers. Awareness communication involves the AV's understanding of surrounding elements and its adherence to relevant traffic regulations. Status or mode communication refers to the AV's current behavior, speed, and the activation or deactivation of its autonomous driving mode.

The prevailing consensus in the eHMI research field suggests that while the specific information needs may evolve with the introduction of AVs into the traffic system, communicating these three aspects—intent, awareness, and status—could significantly enhance road users' comfort, perceived safety, and trust in AVs. This enhanced communication is expected to improve human understanding of AVs' behavior, which, in turn, may increase user acceptance *(Ackermann et al., 2019; Habibovic et al., 2018)*. However, while there is general agreement on the importance of these categories, the research often reveals differing views on what specific information should be communicated within each category.

For example, in pedestrian crossing scenarios, Lagström & Malmstem Lundgren (2015) argue that status-related information, such as whether the AV's autonomous driving mode is activated and its (de)acceleration, is crucial. Clamann, Aubert, & Cummings (2017) suggest that only information about the vehicle's (de)acceleration is necessary. In contrast, Färber (2016) demonstrate that communicating the AV's awareness of the pedestrian is sufficient. Mahadevan, Somanath, & Sharlin (2018) and Matthews, Chowdhary, & Kieson (2018) offer a more integrated approach, proposing that the communication of both awareness and intent would be most helpful in aiding crossing decisions. These varying perspectives highlight the lack of consensus on the specific information needs for different traffic scenarios. Furthermore, from a design perspective, the challenge lies in how these information needs can be effectively conveyed through an eHMI, considering the technological constraints and the human-centric nature of communication. Until more unified insights emerge, it remains unclear which specific information should be prioritized for communication in varying traffic contexts. This ongoing debate presents an important avenue for future research and development in the field of eHMIs.

Message Perspective: Egocentric vs. Allocentric Communication

In addition to the identification of information needs and relevant traffic scenarios, the literature surrounding eHMIs has also delved into the perspective from which the information is communicated. Specifically, while intent, awareness, and status (or mode) are universally recognized as critical elements for communication, these can be conveyed from two distinct perspectives: the "egocentric" and the "allocentric" perspectives. In the egocentric perspective, the AV communicates its own actions, focusing on what the vehicle is doing or planning to do. Conversely, in the allocentric perspective, the AV provides information regarding the actions of other road users, offering advice on their potential behavior.

The current body of research on eHMIs has explored road users' expectations and preferences for these different communication perspectives. However, much like the debates surrounding information needs, there is no consensus on which perspective is most effective or preferred. For instance, several studies have found that pedestrians tend to favor the allocentric perspective, possibly because traditional traffic communication often relies on such signals, which can leave less room for ambiguity in interpreting the vehicle's intentions *(Ackermann et al., 2019; Bazilinskyy et al., 2019; Deb et al., 2019; Faas et al., 2020)*. This perspective aligns with familiar, human-centered cues such as eye contact or gestures, which focus on signaling to others. However, opposing findings suggest that conventional signals, which tend to prioritize an egocentric perspective, are more expected and preferred by certain road users *(Deb et al., 2020; Merat et al., 2018)*. These studies suggest that road users are conditioned to interpret signals that focus on the AV's intentions or actions, such as indicating whether the vehicle is stopping or turning.

These differing perspectives not only highlight the variability in road user expectations but also have important implications for the design of eHMI systems. The ongoing lack of consensus in the literature regarding the preferred perspective emphasizes the need for further research to explore the implications of these perspectives across different traffic situations and user groups. This will be crucial for developing eHMIs that foster effective communication, trust, and safety in mixed traffic environments.

Modality Type: What Technology and Design?

Modality Type refers to the specific mode of communication through which an eHMI (external Human-Machine Interface) conveys information to road users. This modality dictates how messages are presented and can encompass visual, auditory, haptic, or a combination of these sensory channels. The choice of modality plays a crucial role in how effectively information is perceived, understood, and acted upon by human road users (HRUs) in various traffic situations. Additionally, the design of an eHMI modality is often sequentially influenced by the technology used to implement it. For example, LED lights serve as a visual modality, speakers for auditory signals, and vibration motors for haptic feedback. These technological choices shape how information is delivered, the communication range, and the potential to improve user interaction, trust, and safety. Research in the field of eHMIs spans a wide range of topics, often focusing on different aspects of communication between AVs and HRUs.

One area of investigation is the development of human-like AV driving behaviors to provide non-disruptive and intuitively understood information *(Bae et al., 2020; Moore, Currano, et al., 2019)*. However, replicating human driving behavior with high accuracy remains challenging due to the variability and subtlety of human decision-making, which is difficult to translate into algorithmic rules. Some studies suggest that the visibility of vehicle-centric cues is beneficial for improving communication from multiple angles *(Fuest et al., 2018; Risto et al., 2017)*. Despite these efforts, experiments using simulators and Wizard-of-Oz studies consistently show that relying solely on vehicle-centric cues can lead to confusion and conflicting interactions with HRUs, reinforcing the need for supplementary communication methods *(Clercq et al., 2019; Merat et al., 2018; Song et al., 2018)*.

Alternatively, research proposes to exaggerate the vehicle's anomalous cues, such as hard braking or increased vehicle pitch during deceleration, to provide clearer information to HRUs. This approach has proven effective in specific traffic scenarios, like pedestrian crossings, where these cues help bridge the communication gap *(Dietrich et al., 2020; Cramer et al., 2019)*. However, relying solely on vehicle-centric cues still does not provide a comprehensive solution, underscoring the need for more robust and intuitive eHMI systems that can offer additional cues and enhance interaction. For instance, Li et al. (2025) highlight the critical role of kinematic cues—such as lateral offsets—in improving drivers' interpretation of AV intentions. Their study notes that although eHMIs can increase perceived safety and trust, they may introduce also uncertainty when vehicle movements already clearly indicate intent, emphasizing the nuanced interaction between kinematic and interface cues in ambiguous traffic situations.

The literature suggests that incorporating additional cues can help address the absence of traditional driver cues and improve the interaction experience with AVs *(Mahadevan et al., 2018)*. Positive interaction experiences, in turn, can foster improved trust and acceptance of AVs *(Deb et al., 2016; Hoff & Bashir, 2015; Parasuraman & Riley, 2016; Sheridan & Parasuraman, 2016)*. Recent studies have shown a positive correlation between the substitution of traditional communication cues and improved HRU-AV interaction efficiency, reduced uncertainty and discomfort for HRUs, and increased trust and acceptance of AVs *(Clercq et al., 2019; Merat et al., 2018; Song et al., 2018)*. A significant portion of the literature focuses on the development of technology media for eHMI, with many articles proposing solutions to improve AV-to-human communication by introducing additional visual cues. One such proposal is the use of an LED-bar *(see Figures 2-4)*, which communicates abstract information through changes in color, movement, and light intensity. This technology has been praised for its potential to enhance perceived safety, contribute to positive interaction experiences, and may even be the most preferred communication medium, according to some studies *(Habibovic et al., 2018; Hensch et al., 2020; Mahadevan et al., 2018)*. However, other studies highlight concerns about trust, perceived usefulness, and the intuitiveness of LED-based communication *(Hensch et al., 2020)*, though these challenges can potentially be mitigated with short training due to the shallow learning curve *(Lagström & Malmstem Lundgren, 2015)*.

In addition to LED-based systems, displays have gained attention as another modality that can communicate specific information such as text, icons, or traffic signs *(see Figure 5)*. These displays have shown promise in enhancing pedestrian decision-making when crossing streets *(Chang et al., 2017; Clercq et al., 2019; Kitayama et al., 2017)* and improving perceived comfort and trust in AVs *(Holländer, Colley, et al., 2019)*. The wide range of communication possibilities, such as pictures, icons, animations, and text, offers flexibility in eHMI design. However, this flexibility also introduces risks, particularly regarding the clarity and reliability of the message, which are dependent on the display's positioning and accompanying visual cues *(Eisma et al., 2020; Troel-Madec et al., 2019)*.

| ***Figure 2*** *Volkswagen ID. ROOMZZ Showcar (Volkswagen AG, 2019a)*

| ***Figure 3*** *Volkswagen Golf R (Volkswagen AG, 2020)*

| ***Figure 4*** *Volkswagen ID.3 (Volkswagen AG, 2019b)*

| ***Figure 5*** *Prototype Tiguan with implemented display (Volkswagen AG, 2018).*

Another modality gaining traction is the projection of information onto the road, using Augmented Reality or light-based technology to display symbols, text, animations, and traffic signs *(see Figure 6)*. Projections offer the potential for intuitive, three-dimensional, personalized information, which can support decision-making and enhance situational awareness by revealing objects typically hidden from view *(Plavšic et al., 2009; Tong & Jia, 2019)*. However, projections can be demanding for HRUs, requiring them to divide their attention between the vehicle and the projected information, potentially increasing cognitive load *(Eisma et al., 2020)*. Furthermore, such eHMIs face challenges with visibility and salience, particularly in bright weather conditions, raising concerns about the reliability in certain environments. Head-locked AR, which moves with the user's gaze, ensures constant visibility, and conformal AR, which anchors information to physical objects, enhances realism and clarity in complex environments *(Peereboom et al., 2024)*. While recent studies show that AR can improve pedestrian safety when clearly visible, context-aware, and using familiar designs such as traffic symbols or road markings *(Tabone et al., 2023; 2024; Aleva et al., 2024)*, its real-world deployment remains limited. Especially since overreliance on familiar signals may also introduce risk when these cues conflict with vehicle behavior *(Lee et al., 2025)*. and AR's application is still mostly confined to experimental settings due to technological constraints, and are likely to be introduced in professional transportation contexts first *(Tabone et al., 2021; 2023)*.

In addition to visual modalities, auditory systems have been explored for eHMIs. Directed sound beams, which use multiple speakers to direct sound to specific locations, offer personalized acoustic information and could fill the gap left by quieter electric engines *(Fortino et al., 2016)*. Sound-based systems can also communicate warnings or acknowledgments, helping to establish trust and engagement in AVs *(Florentine et al., 2016)*. However, responses to sound can vary widely based on

| ***Figure 6*** *Osram's Rear Combination Light shows how lighting may evolve (Components Online, 2020).*

personal preferences or physical hearing limitations, indicating the need for further research into sound-based eHMIs *(Poveda-Martínez et al., 2017)*.

Despite the wealth of research on various technological modalities, there remains a lack of studies that comprehensively compare multiple eHMI concepts across different technologies and approaches *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017; Rasouli & Tsotsos, 2020)*. Many existing studies have small sample sizes, limiting the ability to generalize findings *(Rasouli & Tsotsos, 2020)*. As a result, there is no consensus on the optimal eHMI modality, and different findings regarding the presentation of information (e.g., text-based vs. animated messages) suggest that further exploration is necessary to identify user preferences and establish design guidelines for effective eHMIs *(Bazilinskyy et al., 2019; Cramer et al., 2019)*.

To move towards a consensus in the field of eHMI, it is crucial to conduct more comprehensive studies that directly compare various modalities, technologies, and communication strategies across diverse traffic scenarios. This would provide a clearer understanding of user preferences, the effectiveness of different communication cues, and the design elements that enhance trust, safety, and interaction efficiency. Additionally, larger-scale studies with more diverse sample sizes are needed to better generalize findings and ensure that eHMI systems cater to a wide range of road users. As the field continues to evolve, there is an increasing need for a universal standard that can guide the design of eHMI systems and inform policymakers *(Jafary et al., 2018)*.

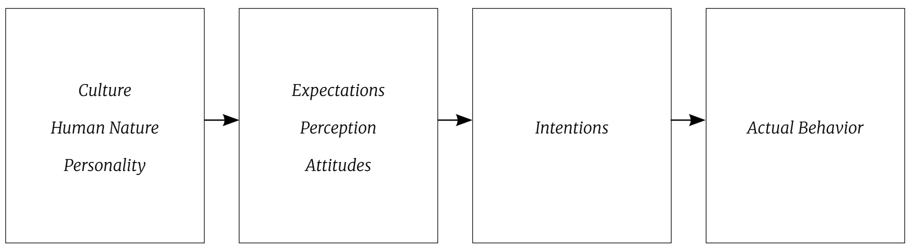
1.4.

Uncharted Territories: Frontiers in eHMI

The Cultural Dimension: An Underexplored Factor in eHMI Design

How information is portrayed and communicated is shaped by a culture's collective beliefs, thought patterns, emotions, and behaviors, including its symbols, language nuances, and unique cultural assumptions *(Ford & Kotzé, 2005; Leonard et al., 2009)*. These cultural factors also influence how information is interpreted, including cognitive styles, scanning patterns, pattern recognition, and color perception *(Alexander et al., 2017; Rasouli & Tsotsos, 2020; Zhang & Zhang, 2019).* For instance, reading patterns vary across cultures, with some cultures reading from left to right, while others read from right to left. Cultural differences are also evident in traffic regulations, adherence to rules, and behavior on the road *(Currano et al., 2018; Moeckli & Lee, 2007)*. Furthermore, cultural diversity impacts how individuals approach traffic situations and communicate with other road users *(Leonard et al., 2009)*. These differences are further amplified by the varying behavioral patterns, intentions, and communication nuances exhibited by human drivers and pedestrians across cultures *(Fruhen et al., 2019; Habibovic et al., 2013)*. Additionally, cultural influences extend to user expectations, with different cultures having varying expectations about how technology should behave and conform *(Auinger et al., 2011)*. This relationship between behavior and cultural factors is illustrated in the simplified model of behavior by Rozkwitalska (2013) *(see Figure 7)*.

| ***Figure 7*** *Simplified model of behavior (Rozkwitalska, 2013)*



Given the extensive impact of culture on traffic behavior and communication between human road users (HRUs), it is unsurprising that research highlights the critical importance of cultural considerations in eHMI design *(Lanzer et al., 2020; Weber et al., 2019; Wesseling et al., 2020).* Furthermore, the cultural dynamics between communication partners cannot be overlooked. Misunderstandings arising from cultural differences can lead to confusion and accidents, underscoring the need for culturally sensitive eHMIs. This becomes even more significant when considering how effective communication in traffic is essential for fostering cooperation among HRUs and ensuring smooth traffic flow *(Dietrich et al., 2018; Papadoulis et al., 2019; Rasouli & Tsotsos, 2020).* However, research is needed to pinpoint which aspects of eHMIs should be designed with specific cultural considerations and which aspects can remain universal. In cases where no cultural adaptations are necessary, eHMIs could offer universal access, much like standard traffic signs, which can be understood regardless of the country. As a result, the question arises: which aspects of eHMI can be standardized, and to what extent? More importantly, where should culture-specific design start, and where should universal design end?

Branding in eHMIs

Branding plays a fundamental role in shaping consumer behavior and driving market differentiation. Across industries, strong brands do more than just identify a product—they act as symbols of personal identity, lifestyle aspirations, and emotional resonance *(Keller, 2020)*. Brand equity, defined as the value derived from brand awareness, associations, perceived quality, and loyalty *(Aaker, 1991)*, enables consumers to form connections that extend beyond functional attributes. These associations not only facilitate self-expression but also reduce perceived risk, simplify decision-making, and increase expected utility *(Erdem et al., 2006)*. With heightened market competition, branding has grown more important than ever *(Franzen & Moriarty, 2015)*, emerging as a key source of sustainable competitive advantage *(Homburg, Schwemmle, & Kuehnl, 2015)*.

> ***"A car is the product of a feeling, or rather, a series of feelings"***
>
> *Quote from Nuccio Bertone (AHF, 2025)*

Design and language are two essential vectors of branding that contribute to consumer perception and preference. Design elements—ranging from aesthetics and functionality to symbolism—have been shown to influence sensory, emotional, and cognitive responses, boosting purchase intention, willingness to pay, and brand sentiment *(Abbas et al., 2024)*. Similarly, language-based elements like brand messaging and advertising improve repurchase intention and perceived experience quality *(Bapat, 2020)*. These complementary roles strengthen consumer relationships through emotional engagement and value congruence *(Safeer et al., 2021)*.

The automotive industry, specifically, is structured around deeply rooted emotional values such as heritage, status, and adventure—values embedded within brand identities that aim to offer customers a unique, distinctive proposition *(van Grondelle et al., 2023a)*. Automotive branding extends far beyond the badge; it is reflected in every aspect of the vehicle's design and experience. The iconic automotive emblem and the grille in which it is typically placed symbolize not only aesthetics but also a brand's history, reputation, and character *(Wang, 2023; van Grondelle, 2016)*. From these symbols, brand narratives unfold through the exterior form, interior architecture, and driving experience. It is therefore no surprise that, in the automotive industry, branding has long been a strategic pillar for product differentiation and consumer loyalty *(Abbott, 2006)*. Particularly in high-end segments, emotional ties, symbolic associations, and design appeal shape brand attachment and market positioning. Aesthetic refinement, visual consistency, and meaningful symbolism allow vehicles to express a brand's values, character, and heritage *(Kumar et al., 2015; Karjalainen, 2003)*. This symbolic function of design goes beyond mere visual appeal—it fosters emotional attachment and communicates a strategic brand identity.

Branding in vehicle design requires balancing consistency with innovation. There exists a delicate equilibrium between recognizable brand markers and novel elements that reflect a brand's evolution *(Burnap et al., 2016)*. Too much innovation risks confusing consumers or diluting brand identity; too little may fail to meet shifting customer expectations. This balance is particularly important as autonomous driving reduces traditional brand differentiators such as driving dynamics and handling. In this context, user experience becomes a central means of conveying brand identity *(van Grondelle et al., 2023a)*.

Core design features that express brand identity include proportions, signature lighting, dashboard layout, body silhouette, and even indicator blink patterns. These elements serve as visual attention anchors—intentionally designed and often empirically validated through eye-tracking and semantic association studies *(Seshadri et al., 2016)*. To measure the branding impact of design, researchers have used statistical modeling and consumer survey techniques to link specific attributes to emotional response and brand performance *(Burnap et al., 2015; Karjalainen, 2003)*.

> ***"When it comes to criteria for fine design, the proportions top the list. It is always somewhat of a mathematical game."***
>
> *Quote from Giorgetto Giugiaro (Marcus, 2024)*

As automated vehicles proliferate, new opportunities emerge for brand differentiation—particularly through eHMIs. eHMIs are visual or auditory systems designed to communicate the vehicle's intentions to other road users, such as pedestrians and cyclists. In addition to their functional role, they represent a new interface through which brands can extend their identity to the vehicle's exterior.

Even today, external vehicle communication already carries strong elements of branding. Headlight and blinker designs have evolved into distinctive visual signatures—often referred to as "light signatures"—that help identify brands even from a distance. Volkswagen's and Audi's sequential blinkers or BMW's dual-round headlights, for example, have become iconic styling elements that also serve a functional signaling purpose. Similarly, the stance and styling of a vehicle—whether it appears robust and sturdy or sleek and agile—convey subtle messages about its intended character and performance, reinforcing brand values such as reliability, sportiness, or luxury. The recent adoption of full-width LED light bars across the front of vehicles adds another layer of brand expression, providing both a futuristic look and a new opportunity for brands to differentiate through shape, motion, and lighting patterns. These elements show how form and function are already being merged in vehicle exteriors, laying a natural foundation for the branding potential of future eHMIs.

All in all, branding within the eHMI domain holds promise but must be approached with caution. While some degree of design freedom is necessary to support brand differentiation, the primary function of eHMIs is clear communication—they must unambiguously convey intent to a wide and culturally diverse audience. Overly stylized or ambiguous cues, while visually unique, may impair comprehension and compromise safety.

That said, a fully unbranded eHMI may create other issues. It risks disrupting the cohesive design language of the vehicle and could feel out of place within a branded environment. For human road users (HRUs), the vehicle's exterior—including the eHMI—plays an important role in projecting the brand's street presence *(Fiorentino et al., 2023; van Grondelle, 2023b)*. A mismatch between the vehicle's branding and the eHMI's style could impair trust, recognition, and emotional engagement. Moreover, the global rollout of automated vehicles brings additional complexity, as cultural expectations vary significantly across regions. What appears as intuitive or neutral in one country might be misinterpreted in another *(Shmueli & Degani, 2023)*. Designing eHMIs that are both branded and culturally appropriate is thus an emerging challenge.

In other words, as eHMIs become an increasingly prominent interface between vehicle and environment, the question arises: how much branding freedom should be allowed? And can that freedom coexist with the need for universally interpretable communication? These questions are at the heart of the research presented in this thesis. When exploring design freedom for eHMI, the primary function of the system—to clearly and safely communicate vehicle intent—must take precedence. While branding offers potential benefits in terms of emotional engagement and brand recognition, it should never detract from the core communicative purpose. This highlights the need for further research on how branding elements can be applied without compromising clarity, with design solutions that are flexible enough to meet both functional and branding objectives. Establishing the boundaries between expressive freedom and functional necessity is therefore a key challenge addressed in this thesis.

1.5.

Research Objectives

The effectiveness of eHMI systems, including its modalities, can be significantly influenced by cultural factors and branding design. As eHMIs play a critical role in the deployment of AVs, understanding how culture and branding shape user expectations and system performance become paramount. This thesis aims to contribute to the research field of eHMI by shedding light on influential factors—specifically culture and branding—that have been previously un(der)explored. To achieve this, the thesis addresses the following three research questions:

RQ 1. How do cultural differences shape the expectations and preferences of HRUs for eHMIs?
RQ 2. How do cultural factors affect the performance and effectiveness of specific eHMI modalities and designs communicating with HRUs?
RQ 3. How does branding impact the performance of and preferences for eHMI systems?

By systematically addressing these research questions, this thesis aims to produce a set of design guidelines that highlight both universal and culture-specific strategies for eHMI design. The intended outcomes include the exploration of how culture and branding can be considered in the design of such systems, ultimately contributing to safer, more effective and user-friendly interactions between HRUs and AVs. Furthermore, the presented findings pave the way for future research to further explore the complexities of eHMI, balancing the need for universal appeal with the necessity for localized adaptations.

1.6.

Core Contributions

This thesis aims to contribute to both the academic field and practical development of eHMI systems. The core contributions derived from this research can be summarized as follows.

1.6.1.

Scientific Contributions

Exploring the Influence of Culture in eHMI Design

This research will contribute novel insights into how culture shapes the design and effectiveness of external Human-Machine Interfaces (eHMIs). Building on prior findings that eHMI solutions are not universally transferable across cultural contexts, this work will emphasize culture as a foundational design consideration. Future studies will aim to identify the specific ways in which cultural differences influence user expectations, perceptions, and interactions with eHMIs. By doing so, this research will support the development of more inclusive and holistic study designs that reflect the diversity of global road users.

Evaluation of Design Freedom for eHMI Branding

Another unique contribution of this research will be the exploration of branding opportunities in eHMI design. Using both subjective measures (e.g., perceived safety, acceptance, understanding) and objective metrics (e.g., gaze duration, decision-making time), this work will assess the extent to which branding elements can be integrated into eHMIs across different cultural settings. These findings will offer the first systematic insights into the potential of branding in eHMI systems, helping to broaden the scope of future research and opening new pathways for practical implementation in vehicle communication strategies.

Comparative Evaluation of eHMI Modalities and Design Variants

A further scientific contribution of this research will be its systematic comparison of different eHMI modalities (e.g., visual, auditory) and design variants (e.g., anthropomorphized vs. symbolic communication). While previous studies have often focused on individual eHMI modalities, designs or isolated scenarios, this thesis will adopt a structured and comparative approach to evaluate the relative effectiveness of various eHMIs across different cultural contexts. By combining both subjective user feedback and objective performance data, the research will identify strengths, limitations, and context-dependent preferences for each modality and their designs. This contribution aims to fill a critical gap in the literature by providing a comprehensive understanding of how different eHMI strategies perform under varying conditions, offering valuable guidance for future design decisions and standardization efforts in the field.

1.6.2.

Practical Contributions

Cultural and Universal eHMI Guidelines

This research will generate actionable guidelines that map the influence of cultural variables on human road users' (HRUs) expectations, preferences, perceptions, comprehension, and behavior in response to eHMIs. By analyzing data from multiple cultural contexts—specifically China and Germany—it will identify both culture-specific and universal trends. These insights will support the creation of tailored eHMI solutions that enhance communication effectiveness while also proposing universal design elements applicable across cultures. The resulting guidelines will serve as a vital resource for designers, policymakers, and industry practitioners aiming to create intuitive, efficient, and safe interactions between AVs and HRUs.

Collectively, these anticipated contributions will help address gaps in current eHMI research by integrating cultural and branding considerations into both academic and practical frameworks. They will also serve as a foundation for future investigations and applications, with the goal of improving road safety, minimizing traffic misunderstandings, and supporting the broader adoption of autonomous vehicles.

Development of a Culturally and Brand-Aware eHMI System

Building on the findings, and the cultural and universal design guidelines, this research will propose a concept for an eHMI system that embodies these principles in practice. The proposed system will integrate culture-sensitive communication elements and branding considerations to create a more adaptive, intuitive, and user-centered eHMI system. By grounding the design in empirical evidence and cross-cultural insights, the system aims to serve as a prototype for future implementations.

1.7.

Thesis Outline

The road ahead for eHMI systems, and AVs with it, is as much about people as it is about technology. This thesis provides evidence that fosters a growing understanding that culture and branding cannot be sidelines when designing eHMIs. This thesis pioneers this previously uncharted territory, offering a series of studies that aim to explore how cultural differences and branding design influence the effectiveness of these systems. The previously described research questions comprise the structure of this thesis.

Chapter 2 describes a study that maps how and what components of eHMIs are influenced by culture. This facilitates the identification of aspects in eHMI research and design that require cultural consideration, while also highlighting areas where universal trends may allow for more universally applicable solutions. This chapter addresses *RQ1: "How do cultural differences shape the expectations and preferences of HRUs for eHMI designs?"*, and is based on:

Wesseling, AM.J.B., Mugge, R., van Grondelle, E., Othersen, I. (2020). Exploring Universal and Cultural Preferences for Different Concepts of Autonomous Vehicles' External Communication in China, USA and Germany. In: Rau, PL. (eds) Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments. HCII 2020. Lecture Notes in Computer Science, vol 12192. Springer, Cham. https://doi.org/10.1007/978-3-030-49788-0_49

Chapter 3 and 4 describe the completed research addressing *RQ2: "How do cultural factors affect the performance and effectiveness of specific eHMI components in communicating with HRUs?"* These studies investigate how cultural variations affect the performance of eHMI message coding, enhancing our understanding of their interactions in both single and cross-cultural contexts, ultimately forming eHMI design guidelines. These chapters are based on:

Wesseling, A.J.B., Mugge, R., van Grondelle, E.D. (2025). Identifying Cultural and Universal Guidelines for Message Coding of External Human-Machine Interfaces: A VR-based Approach. Manuscript ready for submission.

Wesseling, A.J.B., Mugge, R., van Grondelle, E.D. (2025). Exploring Learned vs. Innate Message Coding Strategies for External Human-Machine Interfaces: A Cross-Cultural VR Approach. Manuscript ready for submission.

Chapter 5 describes the exploration of the design freedom of branding in eHMIs. The described study investigates whether the inclusion of branding in eHMIs leads to negative effects in performance. This facilitates the mapping of the available design freedom of branding in eHMI systems, thereby addressing *RQ3: "How does branding impact the performance of eHMI systems?"*. This chapter is based on:

Wesseling, A.J.B., Mugge, R., van Grondelle, E.D. (2025). Branding Opportunities for eHMIs: A Cross-Cultural Analysis in Germany and China. Manuscript ready for submission.

The final part of this thesis, *Chapter 6*, brings together the key findings. It begins with a review of the core findings from each presented study (6.1), followed by the core contributions (6.2). The chapter then outlines the recommendations for practice (6.3) and science (6.4). Finally, the thesis ends with concluding remarks (6.5).

2.

The Influence of Culture on eHMI

Culture is everywhere, subtly shaping our interactions, expectations, and perceptions in ways we overlook. Yet, there are moments where cultural differences emerge in striking and unexpected ways. Such a moment of "culture shock" occurred when German kids requested that I imitate an elephant. My attempt with "Tetteretèt" was met with howling laughter and a "You're silly!". The correct response, as I soon learned, was (obviously) "Töröôh"(Thù-rreuuuu).

Just as the sound of an elephant varies dramatically between cultures, so too do the ways we navigate and communicate in traffic. For example, in Germany, drivers adhere to strict lane discipline, whereas in China, a more fluid approach to lanes prevails, with vehicles weaving in and out. Similarly, the interpretation of traffic signals varies—in some countries, flashing red lights signal a stop, while in others, they indicate caution. Even honking, a common practice in India to assert one's presence, is considered very rude in Japan, instead reserved exclusively for emergencies.

These cultural differences extend to the design of eHMIs (external Human-Machine Interfaces). If traffic communication varies across cultures, it raises the question: Do preferences and expectations for eHMIs differ across cultures? And, if they do, which specific components of eHMIs are influenced? Are there any commonalities that allow for universal design, or must we create entirely distinct eHMIs for each culture?

In this chapter, we investigate these questions and present findings that will guide the design of eHMI systems. Our goal is to identify both universal and culture-specific design principles to improve communication between AVs and human road users (HRUs), no matter their cultural background.

Based on: Wesseling, A.M.J.B., Mugge, R., van Grondelle, E., Othersen, I. (2020). Exploring Universal and Cultural Preferences for Different Concepts of Autonomous Vehicles' External Communication in China, USA and Germany. In: Rau, PL. (eds) Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments. HCII 2020. Lecture Notes in Computer Science, vol 12192. Springer, Cham. https://doi.org/10.1007/978-3-030-49788-0_49

2.1.

Introduction

How would you know whether you can safely cross the road if the driver of the approaching vehicle is reading a newspaper? Although such a scenario does not seem likely yet, the rise of AVs could make such a scenario increasingly feasible in the near future. Here, AVs refer to vehicles that are capable to safely and efficiently navigate to their destination with little to no input from the driver *(On-Road Automated Driving (ORAD) committee, 2018).* By taking over the active driving task from the driver, AVs could benefit society through reduced emissions, enhanced traffic flow, increased productivity, higher convenience, mobility access-for-all and radically improved traffic safety *(Alavi et al., 2017; Gao et al., 2016; Habibovic et al., 2019; Haghi et al., 2014).* However, next to taking over the active driving task, the AV should also take over all other responsibilities of the driver.

Communicating with other HRUs) is one of these responsibilities that should be taken over by the AV. The communication between HRUs allows humans to safely navigate and coexist in traffic as it enables us to interpret traffic scenarios, communicate our intentions, and negotiate, decide on and coordinate actions *(Ackermann et al., 2019; Fuest et al., 2018; Habibovic et al., 2019; Risto et al., 2017; Šucha, 2014)*.

For communication, HRUs (incl. drivers) rely on vehicle-centric cues (e.g., trajectory and velocity changes) and human-centric cues (e.g., eye-contact, posture and gestures) *(Habibovic et al., 2019; Šucha, 2014)*. In the case of AVs, the human-centric cues of the driver will be lost due to the removal of the driver *(Mahadevan et al., 2018a)*. Simply stated, AVs not having a driver presents a dilemma for HRUs, because HRUs do not know who controls any of the vehicles they see, “How can HRUs communicate and with whom?” With the vehicle-centric cues as the only interaction source left, bimodal communication becomes impossible *(Matthews et al., 2018)*. Furthermore, vehicle-centric cues may also no longer be reliable: AVs are not operated by human drivers resulting in anomalous driving behavior *(Dey et al., 2017; Tapiro et al., 2019; Wagner, 2016)*. This statement is supported by results of AV-testing in traffic, which indicate that minor accidents occur due to the AVs’ anomalous behavior together with the loss of bimodal interaction *(Rothenbucher et al., 2016)*. As such, a need develops for an external communication system that allows the AV to facilitate communication with surrounding HRUs within the current traffic system. Thinking of the diversity in communication styles between people in different cultures, designing an effective and intuitive system is a challenging task that warrants more research attention. The present study contributes by exploring universal and cultural preferences for different external communication concepts of AVs.

2.1.1.

External Human-Machine Interfaces

External Human-Machine Interfaces (eHMIs) constitutes the research area that has emerged from the need to develop an external communication system that enables AVs to communicate with all HRUs effectively and intuitively *(Matthews et al., 2018; Rasouli et al., 2017)*. Past research in the field of eHMI focuses on two topics: (1) communication of information and (2) developing eHMI concepts.

Communication of Information

Research on information needs for eHMIs points to three main areas: communication of intent, awareness and status (or mode). Communicating the intent of the AV refers to the trajectory and planned or executed maneuvers. Communicating awareness refers to the AV’s understanding of the surrounding objects and regulations. The information related to the reason for the AV’s behavior, current speed and whether the autonomous driving mode is activated or not, refers to communicating the status (or mode). By communicating the awareness, intent and status of the AV, the loss of bimodal interaction and the AV’s anomalous behavior could be overcome leading to enhanced comfort and perceived safety for HRUs *(Habibovic et al., 2018)*. In addition to enhanced comfort and perceived safety, communicating awareness and intent could also aid in crossing decisions *(Mahadevan et al., 2018a)*. While communication of intent, awareness and status (or mode) are all considered important, these can be communicated using different perspectives. For example, in an “*egocentric*” perspective, the AV communicates its own actions, whereas in an “*allocentric*” perspective the AV gives you advice concerning your actions. At present, research in eHMI has yet to explore HRUs’ expectations and preferences for different perspectives of communication of eHMIs. The present research aims to explore the perspective and information expectations of HRUs to provide recommendations for the development of future AVs.

Developing eHMI systems

Research on eHMIs focuses on two approaches: (1) emphasizing vehicle-cues and (2) simulating driver-cues through additional modalities. The raison d’être of the research in emphasizing vehicle-cues is based on current situations (e.g., during the night) where HRUs can successfully deduce intent and awareness from the vehicle’s natural inclination behavior and currently available systems, such as blinkers. In addition, the added benefit of vehicle-cues is that they are visible from multiple angles increasing visibility *(Fuest et al., 2018; Risto et al., 2017)*.

Different studies concluded that additional modalities could aid AVs in addressing the missing driver-cues and enhance the interaction experience *(Deb et al., 2016; Mahadevan et al., 2018a)*. Potential benefits of developing positive interaction experiences are improved trust and acceptance towards AVs *(Hoff & Bashir, 2015; Lee & See, 2004; Parasuraman & Riley, 2016; Sheridan, 2002)*. Concepts of eHMIs that have been researched focus on lighting technologies *(Florentine et al., 2016; Habibovic et al., 2018; Krahnstöver, 2017; Löcken et al., 2016)*, vehicle behavior *(Fuest et al., 2018; Risto et al., 2017)*, displays *(Fridman et al., 2017; Habibovic et al., 2019; Kitayama et al., 2017)*, acoustics *(Fortino et al., 2016; Poveda-Martínez et al., 2017)*, and wearables *(Meschtscherjakov et al., 2017)*. These studies have compared different concepts within their chosen approach and technology concept (e.g., display) to describe what specific communicating form and design will have the most positive effect on interactions with the AV. However, few studies exist that describe and compare multiple eHMI concepts across technologies and approaches to come to a more complete overview of user preferences towards eHMI concepts *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017).* Furthermore, the few studies that do exist have a limited sample size *(Rasouli & Tsotsos, 2020)*.

Studies that compare preferences for eHMI concepts rely on the subjective responses that they trigger among HRUs. The subjective responses of HRUs previously used in studies indicate several evaluation criteria: recognizability, unambiguousness, interaction comfort, intuitive comprehensibility and the feeling of increased safety *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017)*. These factors closely relate to factors used to describe usability and trust which are considered important factors for Human-Machine Interaction (HMI), user acceptance and the adoption of automated systems and their correct use *(Bevan, 1995; Hjetland, 2015; Khan et al., 2016; Körber et al., 2018)*. Lastly, the subjective responses for usability and trust that eHMI systems trigger could be dependent of what kind of traffic scenario is encountered. As such, traffic scenario is an additional aspect to be considered while comparing eHMI systems. In short, trust and usability are important factors for testing the potential of eHMI systems and different scenarios are to be considered.

2.1.2. Culture

A currently unexplored research direction in eHMI is the implication of cultural differences on the design of eHMI by AVs. Here, the term culture refers to patterns in how people think, feel and act, which influences how they communicate amongst each other and with technology *(Ford & Kotzé, 2005, p. 714)*. Cultural differences are crucial to consider in the development of Human-Computer Interaction (HCI) and HMI because behavior and performance are strongly influenced by culture *(Heimgärtner et al., 2017; Khan & Williams, 2014)*. Cultural adaptability in HCI and HMI could thus prove valuable. Research in culture and cultural adaptability could aid in generating trust that is required for the successful integration of AVs in our traffic system. To consider culture in the development of eHMI, two approaches are proposed in the literature. The first approach is to conceptualize HMI for specific cultures, which is known as localization *(Ford & Kotzé, 2005)*. With localization, different HMIs are designed for different markets to satisfy the different expectations and opportunities. The second approach is to create unity across different vehicle types, brands and cultures by designing HMI following universal principles to improve understandability and avoid confusion across cultures *(Habibovic et al., 2018)*. This approach is called internationalization and aims to facilitate universal access. However, the question then arises: *"What aspects of eHMI could be unified, and to what extent?"* Or, more specifically, *"where should localization begin and internationalization end?"*

2.1.3. Aim of the Study

This study aims to gain insight in HRUs' preferences for different eHMI concepts in three target cultures (i.e. China, Germany and the United States of America). The preferences for the following concepts for eHMI systems are researched: Display, LED, emphasized inclination caused by vehicle behavior ("Incline"), Directed Sound Beam ("Sound"), Smart Assistant in Wearables, Smart infrastructure, and Augmented Reality. These concepts for AVs' eHMI on HRUs were compared based on the subjective responses describing usability and trust. In addition, the present research aims to explore the perspective and information expectations of HRUs. Through these insights, this study aims to offer to insights in internationalization and localization opportunities for eHMI systems. The overall aim of this study can be summarized by the following research question:

"Which HRU preferences regarding information needs and concepts for eHMI can be identified across and within the cultures of China, Germany and the United States of America?"

2.2.
Method

The explorative study was conducted using a 3x7-mixed factors design with the independent variables of culture and technology concept. Participants represented either the culture China, USA or Germany *(between-subjects factor)*. The within-subject factor of technology concept consisted of seven levels.

2.2.1.
Participant Selection

A total of 752 participants *(48.01% Female)* from a consumer panel participated in our study with a mean age of 42.31 years *(SD = 13.06 years; min = 18, max = 70)*. To ensure that the three target cultures were represented accurately, participants were filtered by applying several selection criteria. Firstly, all participants in the sample were required to be residents of one of the target cultures (i.e. China, Germany and United States). Secondly, for participants holding a nationality of and residency in one of the target cultures, an additional criterion of a minimum residency of 5 years was applied. Thirdly, participants with other nationalities were only included in the sample if they had resided in one of the target cultures all their lives. Fourth, through the outlier detection of cultural VSM 2013 dimensions scores of each participant, representativeness of the national cultural dimensions scores for each subsample was checked. Lastly, participants could not have a color perception and/or physical impairment as this would hinder the perception of the stimuli or may significantly alter behavior in traffic. Forty-two responses were excluded based on the selection criteria. The selected 710 participants *(47.18% Female)* had a mean age of 42.58 years *(SD = 13.02 years; min = 18, max = 70).*

2.2.2.
Stimuli Selection

The concepts tested in this research were selected based on their described potential in the literature. The first eHMI system selected was a display that was implemented in the front of the vehicle and showed dynamic icons *(Fridman et al., 2017; Habibovic et al., 2019; Kitayama et al., 2017; Othersen et al., 2018)*. In addition to the display, a concept with a LED bar placed in front of the windshield was selected. This LED bar aims to communicate through indicating the direction and trajectory intent of the AV with animation created by the individual LEDs *(Florentine et al., 2016; Habibovic et al., 2018; Löcken et al.,*

2016). Next to these concepts, an adjustable suspension system was included in the tested concepts. This suspensions system *(later referred to as Incline)* emphasizes the vehicle's natural inclination behavior to increase vehicle cues *(Cramer et al., 2019; Dey et al., 2017; Fuest et al., 2018; Risto et al., 2017)*. Another selected concept relied on acoustics. This concept is referred to as directed sound beam and consists of multiple speakers that direct sound to a desired spatial location, making it possible to deliver spatial, personalized acoustic information *(Fortino et al., 2016; Poveda-Martínez et al., 2017)*. Literature also investigated an eHMI concept relying on wearables, which refers to electronic devices offering haptic, acoustic and/or visual feedback. In this case, the wearable used as a communication system is a smartphone that offers personalized information to the HRUs through a pop-up notification *(Meschtscherjakov et al., 2015)*. To increase versatility and abide by traffic regulations when being an occupant in the vehicle, wearables have been operationalized as a smart assistant in a smartphone and in-vehicle HMI. Next, light projections on the street facilitated by the technology of multi-lens arrays (MLAs) were added to the line-up of tested concepts *(Future Talk - Evolution of Light, 2019)*. These light projections indicate the intent of AVs through animations and icons projected on the street. It must be noted however, that the projected light has been converted to smart infrastructure as projected light is not yet feasible in full daylight. Similar to light projections, smart infrastructure allows for additional information and adjustable road markings. However, rather than projecting light, the lights are to be embedded in the road. To ensure that the value of the adjusted concepts was not lost, the concepts were adapted without taking away the base concept through which the modality communicated for eHMI. Apart from slight alterations to two concepts, one concept was added: Augmented Reality (AR). This technology holds a high potential due to its intuitive presentation of condensed three-dimensional personalized information *(Plavšic et al., 2009)*.

In short, the presented study explores the potential of the following seven concepts for eHMI systems: Display, LED, emphasized inclination caused by vehicle behavior ("*Incline*"), Directed Sound Beam ("*Sound*"), Smart Assistant in Wearables, Smart infrastructure, and Augmented Reality to gain insight in HRUs' preferences for and information and perspective expectations of eHMI systems.

To explore the potential of eHMI systems, previous studies rely on HRUs' subjective responses to factors describing usability and trust. Based on these previous studies, the factors that together measure usability are subjective efficiency of use, subjective ease of learning, high memorability and expected performance *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017)*. The adaptation of the identified factor of trust generated through the improvement of human understanding is described by increased safety and demonstrable willingness to use an information system *(Fraedrich*

& Lenz, 2016). As such, the aspects have been tested relating to usability are whether the concept is clear and easy to understand, communicates in an intuitive manner and is easily recognizable. For trust, the aspect tested are whether the eHMI system makes HRUs feel safer in traffic and whether HRUs experience higher comfort during and after interaction. These subjective HRUs responses that can be derived and could prove useful indicators for the potential of eHMI systems revolve around usability and trust.

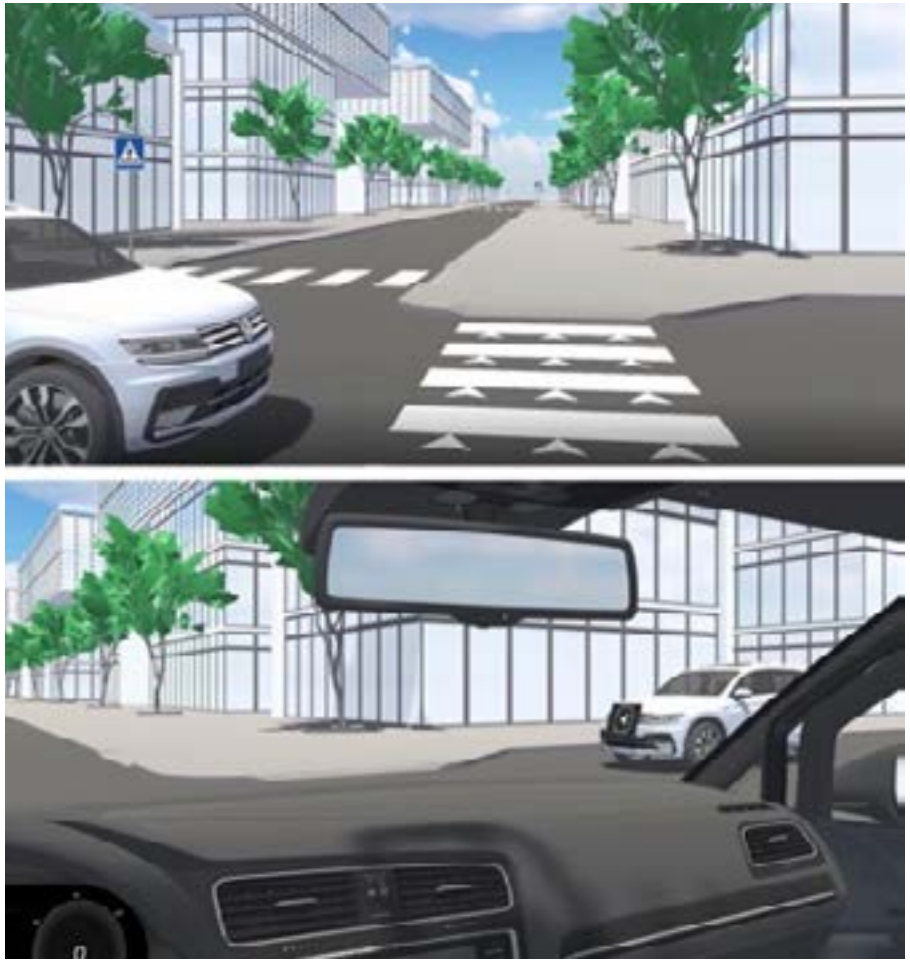
2.2.3.
Materials, Procedure and Measures

Participation was voluntary and the questionnaire lasted between 45 to 60 minutes. Each section of the questionnaire had a short introduction to inform the participant what they could expect. The first section consisted of questions related to demographics that were based on the VSM 2013 model (i.e. age, gender, nationality, current country of residence, educational background and employment) *(Hofstede & Minkov, 2013)*. Three questions were added to enable the selection of participants: years of residency in current country of residence, color perception impairments and physical impairments. The second section consisted of questions related to personal attitude towards different topics in their life to investigate culture as described by the VSM 2013 model *(Hofstede, 2011; Hofstede & Minkov, 2013)*. Through 24 items, each with a 5-point Likert scale, Hofstede's six cultural dimensions can be calculated, which together describe the characteristics of a national culture.

The different eHMI concepts were introduced via a video for each selected concept. Each video showed an AV attempting to communicate with its environment in two traffic scenarios: (1) a pedestrian crosswalk and (2) a cooperative driving scenario *(see Figure 8).* These were chosen as HRUs rely heavily on communication with drivers in these traffic scenarios *(Ackermann et al., 2019; Risto et al., 2017)*. All seven videos were presented in a randomized order and adapted to traffic signs and road markings of each culture.

Participants were instructed to turn on the sound before being allowed to continue with the questionnaire. After reading a short explanation about how each video would show an AV attempting to communicate with its environment, the participants were asked to consider for each video what message and how the vehicle wished to communicate. To ensure that participants understood each concept correctly, a short explanation of the concept was shown after each video.

| ***Figure 8*** *Scenarios with concepts: (Top to bottom): (1) Pedestrian crosswalk with approaching vehicle from left with AR; (2) Cooperative Behavior with approaching vehicle from right with Display.*



This explanation described how the technology functioned and the intended communication by the presented concept. Participants had to reflect on the perceived and intended communication. During this reflection, the participants had the option to watch the video again.

Participants were then asked to rate their preferences for each concept. Specifically, participants were to respond to the multi-measures of trust and usability and expected performance in (or suitability for) multiple scenarios to gain insight in expectations and preferences for eHMI. These aspects were all scored on a 7-point Likert scale (*1 = "Completely disagree" - 7 = "Completely agree"*).

Firstly, the expected performance was measured by asking how much participants agreed with whether the different concepts would perform well (or be suitable) in certain traffic scenarios (i.e. warning in a safety-critical situation; a non-safety-critical situation, and a scenario unrelated to driving). Secondly, the multi-item measure of trust was tested with two questions: *"I would feel safer in traffic"* and *"I would find this concept comfortable in interaction"*). Thirdly, several factors of usability were scored using the following questions: (1) *"This concept is clear and easy to understand"* (subjective efficiency of use); (2) *"This concept communicates in an intuitive manner"* (ease of learning); (3) *"This concept is easily recognizable"* (memorability), and (4) *"I think that this concept would work well in different kinds of traffic or weather"* (expected performance). This rating process was repeated for all videos. To ensure that the participant was able to recall the concept accurately, the video of the concept was available and could be replayed during the rating process.

The last section of the questionnaire revolved around the information expectations and general evaluation. To measure HRUs' information expectations regarding which information should be communicated by eHMI systems, several questions related to intent, awareness and status were asked. The questions were formulated as follows: *"Please evaluate which information you think should be communicated by the Autonomous Vehicle."*

Intent-related questions: *"The AV is going to start moving," "The AV is turning," "The AV is deaccelerating,""What the AVs trajectory is,""The AV is performing a "special maneuver" (e.g. parking)," and "The AV will change its direction".*

Questions related to awareness: *"The AV has detected you (the human road user),""The AV is giving right of way,"and "The AV is taking right of way".* Status-related questions: *"Why the AV is behaving the way it does (traffic jam ahead, parking),""The speed of the AV,"and "The AV is driving autonomously".*

These questions were scored on a 5-point scale that was derived from the Kano Model (i.e. *(5) "I like it that way,"(4) "It must be that way,"(3) "I am neutral,"(2) "I can live with it that way" or (1) "I dislike it that way"*) (Xu et al., 2009).

To gain insight in expectations related to the communication perspective, participants were asked: *"From what perspective should the AV communicate?"* The participant was able to choose between (1) *"The vehicle will communicate its own status or behavior"* (e.g., *"I brake, I see you"*) and (2) *"The vehicle will communicate its advice for other road users"* (e.g., *"You can cross")*.

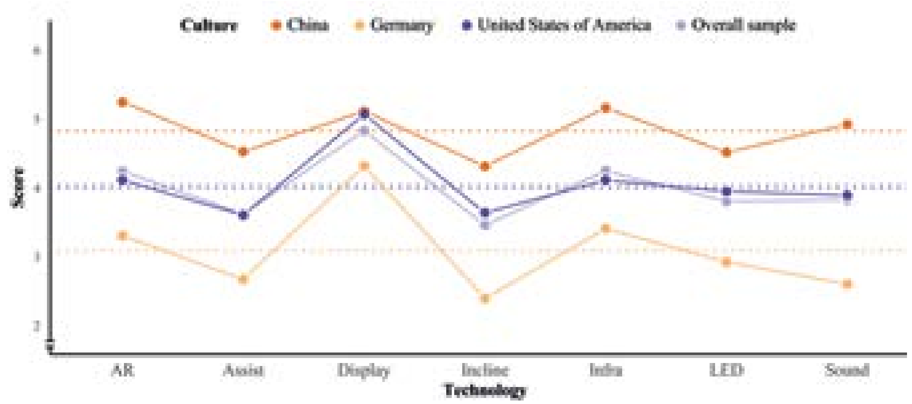
2.3.
Results and Discussion

Data analysis was performed with a significance level of α = .05 and using multi-level mixed models with the fixed effects of culture *(between-subject)* and technology concept *(within-subject)* and a hierarchal level *(participant)*. Through ANOVAs and Tukey HSD pairwise comparisons, the effects of culture and technology concepts were examined. A Chi square test was executed to investigate the preferences for perspective.

Communicating a Warning in Safety-Critical Scenarios

The main effect of culture was significant, $F(2, 287) = 77.55, p < .001$. The Chinese sample $(M = 4.82, SD = 1.94)$ scored significantly higher than the American sample $(M = 4.05, SD = 2.19, p < .001)$ and the German sample, $M = 3.09, SD = 2.02, p < .001$. The German and American sample scored significantly different $(p < .001)$ as well. The difference in cultural means is visualized with the colored dotted lines in Figure 9.

| ***Figure 9*** *Means of the subjective suitability of the concepts (lines) and mean across concepts (dotted lines) for overall sample and subsamples for communicating in safety-critical scenarios.*



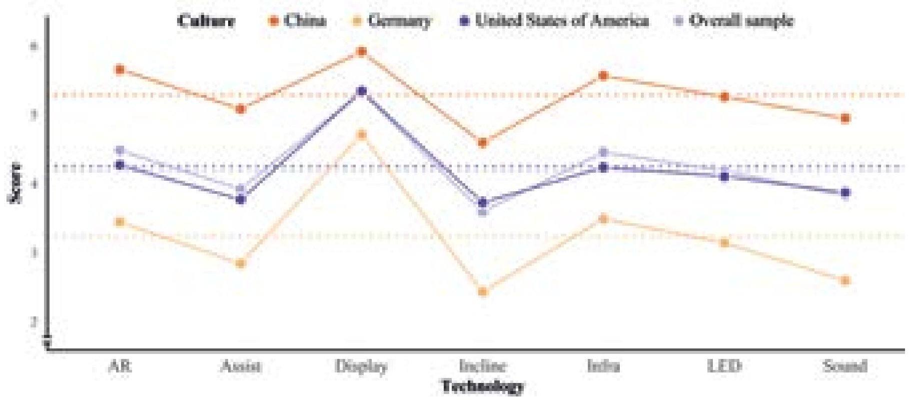
Technology shows a main effect on the subjective scores for safety-critical scenarios, $F(2, 945) = 84.98, p < .001$. In safety-critical scenarios, the perceived performance concept of Display was significantly rated the highest and significantly higher than all other technologies, $M = 4.83, SD = 1.80, p < 0.05$. Augmented Reality $(M = 4.24, SD = 2.13)$ and Smart Infrastructure $(M = 4.24, SD = 2.12)$ were rated second with no significant difference between them, $p = 1$. The technologies of Sound, LED, Assist and Incline had no significant differences $(p > .05)$ and were rated lowest.

A significant interaction effect $(F(12, 205) = 9.22, p < .001)$ between technology and culture was identified. The most striking result to emerge in relation to the interaction effect is the difference in score for Display. As shown in Figure 6, America and Germany rated Display significantly higher in comparison to the other technologies. China did not score Display higher and rather rated Display not significantly different than Smart Infrastructure, Augmented Reality and Sound, $p > .05$. These technologies together did have the highest score in China. To summarize, although a consistent universal preference for Display, Augmented Reality and Smart Infrastructure was identified, China did not indicate an equal preference for Display in comparison to other technologies as the United States and Germany. These differentiating preferences could indicate an opportunity for localization.

Communicating in Non-Safety Critical Scenarios

Culture shows a main effect on subjective scores for non-safety critical scenarios, $F(2, 468) = 128.66$, $p < .001$. Similar to the previous scores of the safety-critical scenario, China $(M = 5.28, SD = 1.70)$ scored higher than the United States $(M = 4.19, SD = 2.17, p < .001)$ and Germany, $M = 3.23, SD = 2.03$, $p < .001$. A difference between German and American scores was present as well, $p < .001$. The mean scores of each culture have been visualized with the colored dotted lines in Figure 10.

| ***Figure 10*** *Means of the subjective suitability of the concepts (lines) and mean across concepts (dotted lines) for overall sample and subsamples for non-safety critical scenarios.*



The main effect of technology is significant, $F(2, 1412) = 129.39$, $p < .001$. The perceived performance concept of Display was rated the highest, $M = 5.33$, $SD = 1.59$. The second highest score, due to no significant difference $(p = 1)$, was given to Augmented Reality $(M = 4.48, SD = 2.14)$ and Smart Infrastructure, $M = 4.45$, $SD = 2.14$. The technology of LED was preferred after these

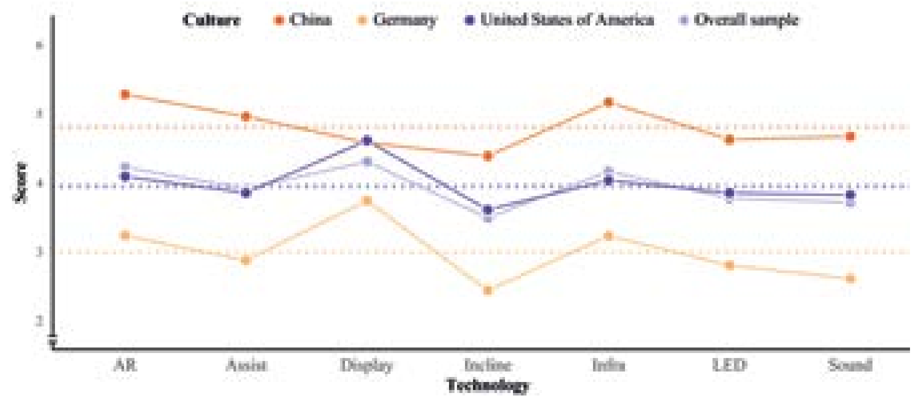
technologies with $M = 4.19$ $(SD = 2.14)$, followed by Smart Assistant $(M = 3.92, SD = 2.20)$ and Sound $(M = 3.82, SD = 2.19)$ with no significant difference identifiable between these technology concepts, $p > .5)$. Incline $(M = 3.59, SD = 2.16)$ scored significantly lowest, $p < .05$.

The interaction effect between technology and culture was significant, $F(12, 144) = 6.59$, $p < .001$. Interestingly, the interaction effect did not influence the overall trend in highest expected performance scores for non-safety critical scenarios. The preferred technology concepts in each culture remain Display, Augmented Reality, Smart Infrastructure and LED. All in all, results show a consisted trend in preferred technologies across cultures with Display as the most preferred technology, followed by Augmented Reality, Smart Infrastructure and LED for non-safety critical scenarios.

Communicating in Scenarios Unrelated to Driving

The main effect of culture is significant, $F(2, 288) = 81.92$, $p < .001$. Once more, China $(M = 4.81, SD = 1.86)$ scored higher than the United States $(M = 3.98, SD = 2.21, p < .001)$ and Germany $(M = 2.99, SD = 2.01, p < .001)$ with a significant difference between these cultures as well, $p < .001$. The colored dotted lines in Figure 11 show the different mean scores of each culture.

| ***Figure 11*** *Means of the subjective suitability of the concepts (lines) and mean across concepts (dotted lines) for overall sample and subsamples for scenarios unrelated to driving.*



Technology shows a significant main effect on the perceived performance of technology concepts in scenarios unrelated to driving, $F(2, 391) = 37.09$, $p < .001$. With no significant difference $(p \geq 0.10)$ found, the perceived performance of Display $(M = 4.30, SD = 1.95)$, Augmented Reality $(M = 4.22, SD = 2.21)$ and Smart Infrastructure $(M = 4.16, SD = 2.19)$ received the highest scores.

Similarly, Smart Assistant ($M = 4.22, SD = 2.21$), LED ($M = 4.22, SD = 2.21$) and Sound ($M = 4.22, SD = 2.21$) received no significant difference in scores and were rated highest after the previously named technologies. Incline ($M = 3.49, SD = 2.18$) scored the lowest for the perceived performance in non-safety critical scenarios. Most technology concept did not score significantly different from each other, which can be seen in Figure 11.

The interaction effect between technology and culture was significant, $F(12, 191) = 9.07, p < .001$. Strikingly, the score for Display by China in comparison to the previous scenarios was considerably lower and was rated here as one of the lowest technologies. In comparison, Display is rated significantly as the highest technology in both America ($M = 4.61, SD = 1.90, p < .05$) and Germany ($M = 3.74, SD = 1.96, p < .05$). It must be noted that all technologies apart from Display and Incline in both Germany and the United States do not score significantly different ($p > 0.05$) from each other. A similar observation can be made in China where Smart Assistant, Display, LED and Sound did not receive a significant difference in score, $p > 0.05$. This observation was made again in China's highest scored technologies: Augmented Reality, Smart Infrastructure and Smart Assistant, $p > 0.05$. All in all, the result of this analysis could indicate less strong preferences for technologies in scenarios unrelated to driving, except for Display and Incline. In other words, in scenarios unrelated to driving localization opportunities may prove valuable if only one technology is used in the eHMI system.

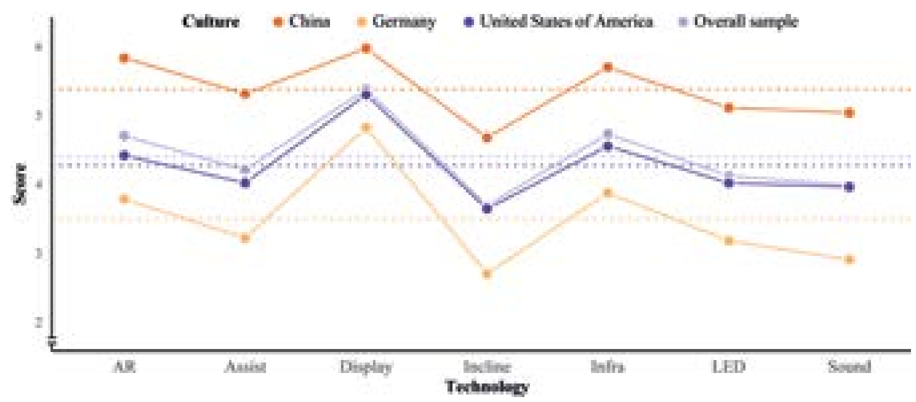
Usability of Technology Concepts

The multi-item measure of usability (*4 items*; $a \geq 0.87$) shows a significant main effect of culture, $F(2, 399) = 111.08, p < .001$. Similar to the previous scenarios, China ($M = 5.37, SD = 1.69$) scored higher than the United States ($M = 4.27, SD = 2.19, p < .001$) and Germany, $M = 3.50, SD = 2.10, p < .001$. Here, the cultures of Germany and the United States significantly differ in scores as well, $p < .001$. Figure 12 show the different means for each culture through the colored dotted lines.

A main effect of technology is present, $F(2, 5518) = 512.56, p < .001$). Display scored the highest in usability ($M = 5.37, SD = 1.63$), followed by Smart Infrastructure ($M = 4.73, SD = 2.06$) and Augmented Reality ($M = 4.70, SD = 2.10$) with no significant difference between them, $p = 0.5$. The following highest scores of Smart Assistant ($M = 4.20, SD = 2.15$) and LED ($M = 4.12, SD = 2.14$) also had no significant difference in score, $p = 0.1$. Incline ($M = 3.69, SD = 2.20$) scored the lowest.

The interaction effect between technology and culture was significant for subjective usability, $F(12, 400) = 18.60, p < .001$. Although Figure 12 shows slight differences in overall trends caused

| ***Figure 12*** *Means of the perceived usability of the concepts (lines) and mean across concepts (dotted lines) for overall sample and subsamples.*



by the interaction effect on Display, Smart Infrastructure and Sound, the order based on highest scores remains unchanged. Usability scores indicate that the technology of Display is rated the highest across and within all cultures. With no significant difference between Augmented Reality and Smart Infrastructure found in China ($p = 0.5$), Germany ($p = 0.5$) and the United States ($p = 1$), a trend of preferred technologies seems to be identifiable. This trend within usability closely resembles the scores of non-safety critical scenarios *(see Figure 10)*. All in all, with similar preference for technologies based on usability scores, universalization could be possible.

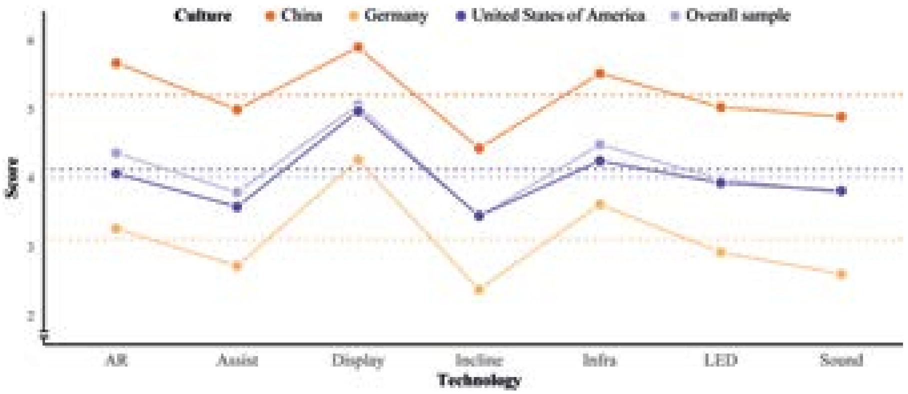
Trust in Technology Concepts

The variables of subjective safety and comfort are items in the multi-item measure of trust, 2 items; $a \geq .79$. Trust is influenced by the main effect of culture, $F(2, 39) = 111.03, p < .001$. In line with previous results, China ($M = 5.20, SD = 1.76$) scored higher than the United States ($M = 4.11, SD = 2.25, p < .001$) and Germany, $M = 4.00, SD = 2.10, p < .001$. Here, the cultures of Germany and the United States have a significant difference in scores as well, $p < .001$. See Figure 13 for the different means for each culture visualized by the colored dotted lines.

A main effect of technology influences trust scores, $F(2, 2516) = 248.31, p < .001$. Across cultures, Display scored the highest, $M = 5.06, SD = 1.82$. Smart Infrastructure ($M = 4.48, SD = 2.014$) and Augmented Reality ($M = 4.36, SD = 2.24$) had no significant difference between them ($p = 0.1$) and were rated highest after Display. The technology of LED ($M = 3.98, SD = 2.19$) was significantly lower than the previously named technologies, $p < .001$. After LED, the technologies of Smart Assistant

(M = 3.79, SD = 2.23) and Sound *(M = 3.78, SD = 2.23)* were rated with no significant difference between them, *p = 1*. The lowest score was given to the technology of Incline, *M = 3.43, SD = 2.21, p < .001*.

| ***Figure 13*** *Means of the trust of the concepts (lines) and mean across concepts (dotted lines) for overall sample and subsamples.*



Subjective trust scores show an interaction effect between technology and culture, *F(12, 165) = 8.12, p < .001*. Based on the technology results within culture, the technologies of Display, Smart Infrastructure and Augmented Reality were scored highest in usability. The interaction effect did not affect the trend of preference for these technologies. See Figure 13 for an overview of the subjective usability for each technology and culture.

Communication Perspective Expectations

There is no significant influence of culture on preferences concerning the perspective of communication by eHMI *(Chi square = 0.86, p > .5, df = 2)* indicating an opportunity for universalization. The preference for the “Egocentric” perspective was preferred significantly more than the “Allocentric” perspective *(Chi square = 3.86, p < .05, df = 1)* *(see Table 1)*. In short, the preference for communication perspective is not influenced by culture and the universal preferred perspective is “Egocentric” perspective.

Information Expectations

The information expectations relate to three main areas: communication of intent, awareness and status and were rated on a 5-point scale based on the KANO model. The preferences for information expectations indicate a main effect of culture, *F(2, 50) = 63.10, p < .001*. China *(M = 4.32, SD = 0.74)* scored higher than the United States *(M = 3.89, SD = 1.05, p < .001)* and Germany, *M = 3.55, SD = 1.12,*

| ***Table 1*** *Preferences for perspective across and within cultures.*

	CH (N=251)		GER (N=239)		USA (N = 220)		Overall (N = 710)	
	N	%	N	%	N	%	N	%
Egocentric	145	57.77	151	63.18	135	61.36	431	60.70
Allocentric	106	42.23	88	36.82	85	38.64	279	39.30

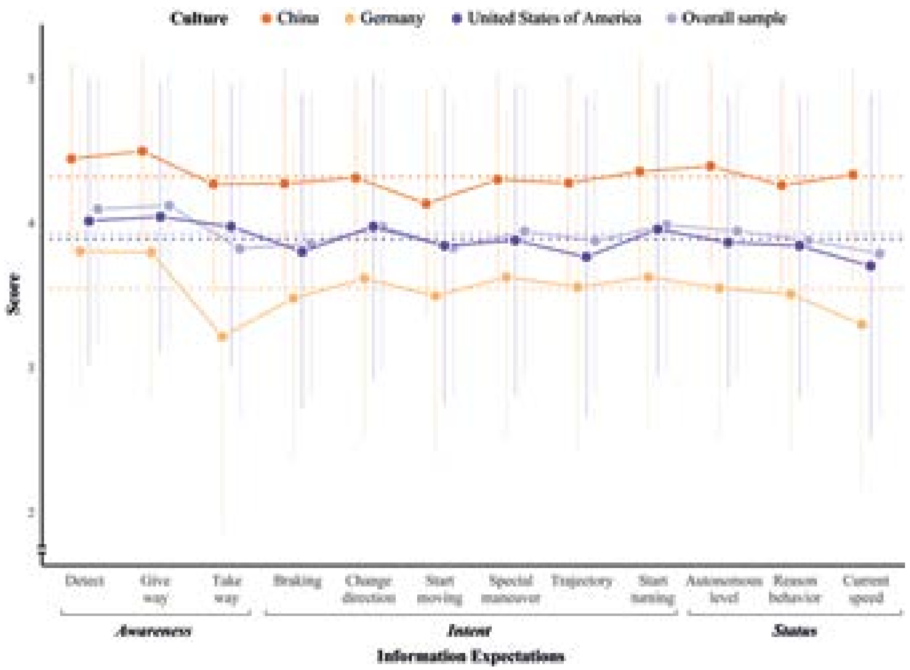
Note: Percentage (%) and Sample size (N)

p < .001. Germany and the United States have a significant difference in scores as well, *p < .001*. The results indicate that German participants tended to score all information aspects in the range of neutral and expected information (3-4). In contrast, China rated all scores between expected and liked (4-5), which could indicate a preference for a larger amount of information. This indication for preferences is supported by HCI guidelines *(Heimgärtner, 2007a)*.

A main effect of information was found, *F(11, 86) = 19.57, p < .001*. The information aspects of Give Way *(M = 4.12, SD = 0.92)* and Detection of HRU *(M = 4.09, SD = 0.92)*, both related to awareness, were indicated as most liked and expected information and did not significantly differ in scores, *p = .50*. The following score of communication the intention of Turning *(M = 3.98, SD = 1.01)* did not differ significantly from Detection of HRU, *p = .50*. In addition, the following scores for communicating an intention to Change direction *(M = 3.97, SD = 1.00)*, to execute a Special maneuver *(M = 3.94, SD = 1.03)* and to indicate intention through Trajectory *(M = 3.87, SD = 1.05)*, and the aspect of Autonomous level *(M = 3.94, SD = 1.01)* and Reason for behavior *(M = 3.88, SD = 1.01)* related to status (or mode) were not scored significantly different from each other, *p > .05*. Lastly, the lowest rated information aspects of intention to start Braking *(M = 3.86, SD = 1.05)* and to start Moving *(M = 3.83, SD = 1.03)*; of awareness to Take right of way *(M = 3.82, SD = 1.15)*, and of mode related to current Speed *(M = 3.79, SD = 1.11)* did show significantly different scores in comparison to each other and to Reason for behavior and Trajectory *(p = .10)* *(see Figure 14)*.

An interaction effect between information and culture is present, *F(22, 44) = 4.97, p < .001*. The interaction effects become apparent on multiple occasions, as can be seen in Figure 14, which show several deviations of trends in universal and cultural preferences. Firstly, where Germany and the United States liked *Current Speed* significantly less in comparison to other information aspects, China rated it amongst the highest. Secondly, the scores of the American sample also show a significantly lower preference for *Trajectory*. Thirdly, Germany indicated a significantly

| ***Figure 14*** *Mean and SD for information expectations concerning awareness, intent and status to be communicated by external for the overall sample and cultural subsamples.*



lower preference for *Take Way.* Fourthly, China scored *Start Moving* significantly lower than other information preferences. In addition, the preference for *Detect* and *Give Way* are rated much higher in Germany in comparison to the other information aspects. This difference in rating is not as extreme in China and even less so in the United States of America. These cultural trends differentiate considerably indicating highly differentiating preferences for information. This is the most striking result to emerge from the data related to information expectations and indicate an important finding in the understanding that universalization for eHMI may not provide optimized experiences across cultures. In other words, information expectations may require localization as approach in the design of eHMI systems to optimize interaction experiences.

2.4.
Conclusion

This study aimed to compare concepts for and investigate information expectations of eHMI across and within cultures. The aim of the study originated from the want for a large sample study where multiple eHMI concepts across technologies and approaches are compared as noted in previous research *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017; Rasouli & Tsotsos, 2020).* Moreover, by executing the study in different cultures, cultural differences in user preferences for these various eHMI concepts can be investigated which was yet to be explored for eHMI *(Heimgärtner et al., 2017; Khan & Williams, 2014)*. Based on the results, localization and universalization opportunities for eHMI were to be identified. The results in this paper provide evidence that culture influences information expectations and preferences for eHMI concepts.

Although culture significantly impacts technology concept preferences for eHMI, universal trends can be identified. Based on the results in usability, trust, safety critical scenario and non-safety critical scenario, the technologies of *Display, Smart Infrastructure* and *Augmented Reality* have the highest potential for eHMI systems. Although a consistent universal preference can be identified, scenarios unrelated to driving show that culture influences preference so that a difference in preferences can be identified. Where Germany and the United States prefer the technologies previously listed, China indicates a preference for *Augmented Reality, Smart Assistant* and *Smart Infrastructure*. Moreover, Germany and the United States showed a higher preference for *Display* in comparison to other technologies. This considerably higher preference in comparison to other technologies was not repeated in the Chinese culture. These differences in preferences could show that localization may prove valuable for eHMI.

The recommendation for a localization approach in technology concepts for eHMI would lead to Autonomous Vehicles with localized hardware to address cultural technology concept preferences for eHMI. Localized eHMI hardware would not only lead to increased manufacturing costs but also pose problems when, for example, crossing borders. In other words, hardware solutions are considered undesirable when designing eHMI.

When considering that localized hardware is undesirable, it may be needed to combine different technology concepts in order to come to a more holistic eHMI system that is preferred across cultures. The universal trends in technology concept preferences could indicate opportunities for such a holistic system. In addition, software solutions may provide opportunities for localization which would allow for eHMI systems to be optimized for each culture.

The combination of localized software and universal hardware can be captured through the design of eHMI as a modular concept. This modular concept could consist of a baseline concept and cultural modules. The baseline concept focuses on hardware and relies on the overall trends in preferences for technology concepts across cultures and other universal trends. The cultural modules are software-oriented and should aim to optimize satisfaction of user expectations and user experience through localization.

Based on the results of this study, the baseline concept should consider *Display* in combination with *Augmented Reality, Smart Infrastructure* and/or *LED.* It must be noted however that *Sound* may hold value to allow for a multi-modal concept for eHMI to stimulate additional senses to vision and support HRUs with vision defects. A universal trend which can be woven into the baseline concept is the universal preference for the "*Egocentric*" perspective as the perspective in which eHMI systems are to communicate. A universal perspective could improve the unambiguousness and universal understanding of eHMI when traveling to different cultures and may lower the threshold caused by regulations for the implementation of AVs in different cultures.

The baseline concept should be extended with software-based cultural modules that aim to optimize satisfaction of user expectations and user experience. This opportunity for localization aligns with the cultural preferences for information. More specifically, the influence of culture is most apparent in the differentiating preferences for information. Due to the cultural influence, universalization of communicated information by eHMI may not provide optimized experiences in all cultures. As a result, information expectations should be considered an important aspect in the development of the cultural modules to facilitate localization.

2.5. Limitations & Future Work

The findings of this study provide a positive indication for universalization of the different concepts for eHMI. This is desirable to be investigated in more detail in future work, since the different tested concepts may not have been designed optimally for each of the different cultures as the design of the concepts has been based on studies that have been executed in specific or single cultures. This extends to the environment in which the concepts where introduced. The virtual environment shown in the movies does not express the cultures precisely even though markings and signs have been adjusted. Future research should also consider the potential effects of culture on the design of eHMI more carefully, for example through the application of HCI-guidelines to adapt each concept for each culture. In addition, future research on eHMI can extend the explanations of which universal and culture-specific design guidelines can be identified that positively influence the usability and trust of eHMI within each culture.

Building on the Findings

The current study emphasized the importance of culture in eHMI design. Some aspects, such as information expectations, were found to vary greatly across cultures, while others—like technology modalities and communication perspective—showed cross-cultural trends. These trends suggest there are design opportunities for universalization of eHMIs.

Beyond their technological function, modalities offer varying degrees of freedom in information design to facilitate communication—for instance, LED strips can convey simple signals, sound enables tonal variations, while displays allow for more complex messaging, such as text, symbols, and facial expressions. This way this information is portrayed is called message coding. By exploring different message coding strategies across these modalities, the study aims to explore further which aspects of eHMI communication can be standardized and where cultural adaptations are necessary. With the perspective of OEMs in mind, the study, in the following chapter, concentrates on technology modalities suitable for implementation in AVs. The methodology shifted from online surveys to Virtual Reality, allowing for more immersive, culturally relevant testing of eHMI designs in realistic traffic scenarios as well as the inclusion of an objective measure.

3.

Cultural and Universal Guidelines for Message Coding

Context plays a crucial role in how we interpret information. In traffic, a red light means "stop," whereas for a remote it means "off"—their meanings shift. The same happens in other scenarios, from recognizing social signals during a conversation to interpreting symbols on our smartphones. In each case, our brains rely on context to assign meaning to the information we receive, ensuring that we respond appropriately.

How quickly we understand information depends on whether the manner in which the information is portrayed—the coding of the message—aligns with our expectations formed through repeated exposure, training and other experiences. However, these expectations can vary significantly between cultures. For example, in Europe, white is associated with brides, while red is the traditional color in China. Similarly, in traffic, the way we interpret signals depends on cultural context. For an eHMI to be effective, it must consider these varying cultural lenses.

In this chapter, we explore how cultural context influences the comprehension of eHMI messages. Which types of message coding can provide the clearest, most comprehensible communication? And lastly, does the effectiveness of different message coding differ between the investigated cultures?

This chapter presents a study that tackles these questions which are vital for creating eHMI systems that provide the most effective support to HRUs within and across different cultures.

3.1.
Introduction

How to communicate with someone if you do not share a common language? This question illustrates the challenge of communication between Autonomous Vehicles (AVs) and Human Road Users (HRUs). In conventional traffic, HRUs communicate through vehicle (i.e., dynamics) and/or human cues (e.g., gestures, indicators) *(Habibovic et al., 2019; Šucha, 2014)*. Effective communication is essential for cooperation among HRUs, facilitating smooth traffic flow *(Dietrich et al., 2018; Papadoulis et al., 2019; Rasouli & Tsotsos, 2020)*. However, when it comes to AVs, these cues are insufficient, leading to miscommunications and potential accidents *(Rothenbucher et al., 2016).* To bridge this gap, AVs rely on external Human-Machine Interfaces (eHMIs) to re-establish effective communication with HRUs *(Matthews et al., 2018; Rasouli et al., 2017).* Research in eHMI has explored many solutions, but there exists an essential yet often overlooked aspect of communication—the influence of culture.

3.1.1.
The Role of Culture

Communication, whether verbal or non-verbal, is deeply embedded in cultural norms and expectations. Culture shapes how humans perceive, understand, convey and respond to information, as interpretations are guided by a culture's beliefs, symbols, language nuances, and assumptions *(Leonard et al., 2009)*. Each culture has unique cognitive styles, ways of reading, scanning patterns, and assigned meanings to colors, leading to distinct processing and understanding of the same messages *(Alexander et al., 2017; Rasouli & Tsotsos, 2020; Zhang & Zhang, 2019).*

The impact of culture extends to the realm of traffic, where traffic regulations, rule adherence, and traffic behavior vary between cultures *(Currano et al., 2018; Moeckli & Lee, 2007)*. Cultural values and norms also influence road safety attitudes, risk perception and its outcomes (*Atchley et al., 2014).* The behavior and interactions between drivers, bicyclists and pedestrians vary as well, leading to distinct expectations of others' behavior, which are reinforced by prior experiences and learned societal norms *(Das & Dutta, 2019; Fruhen et al., 2019; Habibovic et al., 2013)*. As a result, traffic interactions are framed by the explicit rules and shaped by implicit cultural expectations, influencing how individuals communicate and behave in traffic *(Leonard et al., 2009)*. In other words, culture influences every aspect of traffic interactions, from the interpretation of signals to the responses in specific situations with different types of HRUs.

This cultural diversity is exemplified by the differing traffic cultures and signals observed in China and Germany. In China, traffic culture is characterized by fluidity and adaptability, where HRUs negotiate their space dynamically and may not always strictly adhere to traffic rules. In the bustling streets, honking is a mere indication of presence or a nudge to move someone along and is therefore a common and accepted part of driving behavior. Next to frequently used horns, the flexible interpretation of signals and road markings reflect a more pragmatic approach to navigating the densely populated and fast-paced urban areas. In contrast, Germany's traffic culture is marked by strict adherence to traffic rules, signals, and road markings, with most HRUs following well-defined rules and exhibiting high levels of order. As, honking is reserved for urgent warnings or imminent danger, frequent or unnecessary honking is considered rude and thus less common. This strict rule adherence leads to more structured interactions on the road, fostering a more regulation-driven cooperation among all HRUs.

Given these cultural variations in communication and traffic behavior, it is unsurprising that an eHMI that is effective in one cultural context does not necessarily work in another *(Lanzer et al., 2020; Weber et al., 2019).* This variety also raises important questions about how different HRU types (e.g., pedestrians and car drivers) interpret eHMI signals in different cultural contexts.

3.1.2.
External Human-Machine Interface (eHMI)

Research in eHMI emphasizes the importance of considering the type of communication partner and ensuring that message design aligns with cultural expectations *(Auinger et al., 2011; Rasouli & Tsotsos, 2020; Weber et al., 2019; Wesseling et al., 2020)*. Proposed eHMIs rely on a variety of modalities—such as (exaggerating) vehicle-centric cues *(Bae et al., 2020; Bindschädel et al., 2022a; Cramer et al., 2019; Dietrich et al., 2020; Fuest et al., 2018; Moore, Currano, et al., 2019; Moore, Strack, et al., 2019),* displays *(Chang et al., 2017; Hudson et al., 2019; Lim & Kim, 2022; Löcken et al., 2019; Yamin & Park, 2023), LEDs (Dey et al., 2020; Lagström & Malmstem Lundgren, 2015; Mirnig et al., 2021; Yamin & Park, 2023)* and sound *(Deb et al., 2016; Florentine et al., 2016)*—to communicate the AV's intent, awareness and status *(Ackermann et al., 2019; Färber, 2016; Habibovic et al., 2018; Matthews et al., 2018).* However, for eHMIs to be effective, their message must be easily perceivable, understandable and intuitive for diverse HRUs.

A key factor influencing the effectiveness of eHMIs is message coding, which defines how information is structured and conveyed through symbols, text, colors, animations, or a combination of these elements. The way messages are coded determines how quickly and accurately HRUs interpret them.

Prior research suggests that explicit eHMI solutions, particularly animated designs, enhance perceived safety, improve understanding and evoke more positive emotions in HRUs *(Oehl et al., 2022; Othersen et al., 2018).* Additionally, such explicit solutions help compensate the missing driver-cues, leading to better interaction experiences, improved trust, and greater acceptance and willingness to use AVs *(Deb et al., 2016; Hoff & Bashir, 2015; Louw et al., 2021; Mahadevan et al., 2018a; Nastjuk et al., 2020; Parasuraman & Riley, 2016; Sheridan & Parasuraman, 2016).* Color coding of visual eHMIs presents another opportunity. These colors can either be traffic light colors (albeit restricted by regulations) with their contextual meanings or, alternatively, cyan and white for presenting more neutral information without triggering negative associations and alertness in HRUs *(Bazilinskyy et al., 2021; Shmueli & Degani, 2023)*. Furthermore, display-based message coding can incorporate traffic symbols—such as traffic signs *(Bazilinskyy et al., 2019; Hudson et al., 2019; Lim & Kim, 2022; Löcken et al., 2019; Wesseling et al., 2020)*, anthropomorphized messages—such as eyes or a smiley to foster emotional connection *(Chang et al., 2017, 2022; Lim & Kim, 2022; Mahadevan et al., 2018a)*—or text-based messages *(Bazilinskyy et al., 2021; Lim & Kim, 2022; Yamin & Park, 2023)*.

While extensive research has explored these different modalities and message coding strategies, the effectiveness of these designs is likely not universal. Interpretations of colors, symbols, animations and text are also derived from the cognitive styles, cultural norms, and learned expectations, likely leading to varying levels of effectiveness of the eHMI coding strategies across different cultures *(Alexander et al., 2017; Ford & Kotzé, 2005; Leonard et al., 2009; Rasouli & Tsotsos, 2020; Zhang & Zhang, 2019).* This raises critical questions about whether standardized eHMI systems can accommodate the wide range of HRUs' expectations or if culturally adaptive eHMI solutions are necessary to ensure effective and intuitive communication between AVs and HRUs.

Given the cultural differences in behavior, communication and understanding, it is crucial to investigate how pedestrians and car drivers from different cultures interpret and respond to various eHMI message coding strategies

3.1.3. .
Aim of the Study

The study aims to systematically investigate the influence of culture on the effectiveness of eHMI message coding strategies. Conducted in two distinct traffic cultures (i.e., China and Germany), this cross-cultural research examines how pedestrians and car drivers interpret and respond to different eHMI coding strategies, focusing on intuitive communication, understanding, perceived safety, acceptance of AVs, and decision-making in traffic. The findings aim to inform the development of culturally adaptive and universal eHMI design strategies. Specifically, the findings help identify where universal design is feasible and where culturally specific solutions are necessary. Ultimately, these insights aim to guide the design of future eHMI solutions that effectively re-establish communication in diverse traffic environments.

3.2.
Material and Methods

The VR study utilized a 2x2x7 mixed design, examining the independent variables of culture *(between-subjects)*, communication partner *(manual car driver vs. pedestrian; within-subjects)*, and message coding *(six eHMI system conditions; within-subjects).* Participants hailed from China or Germany and experienced both communication partner levels and all message coding types.

3.2.1.
Participants

A total of 59 participants *(46% female, 54% male, 0% other, 0% 'I prefer not to answer')*, aged 21 to 58 years *(M = 39.37 years; SD = 10.01 years)*, were selected for the study. The selected participants of the Chinese group *(N = 30, 50% Female, 50% Male)* had a mean age of 36.67 years old *(min = 22; max = 55; SD = 8.46 years)* and the German group, comprised 29 participants, *(41% Female, 59% Male)* had a mean age of 42.17 years old *(min = 21; max = 58; SD = 10.84 years).*

The selection of participants was based on specific criteria, including being native to China or Germany as well as having at least 5 years of current residency. Lifelong residents of other nationalities were considered natives in the context of this study. Participants with color perception or physical impairments were excluded due to potential interference with VR-stimuli perception or behavior in traffic simulations. After applying these criteria, all potential participants from German and Chinese consumer panels were stratified and randomly selected as study participants to ensure balanced demographics.

3.2.2.
Equipment

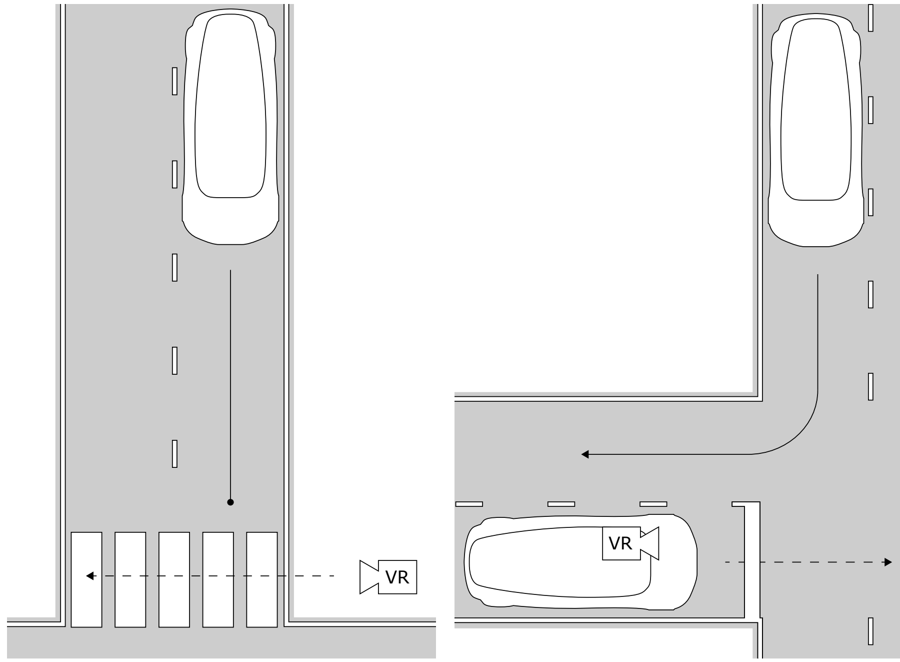
The VR-environments were generated by a VR-capable PC running Unity 3D *(Version 2019.4.0f1 LTS (Unity Technologies, 2019))* paired with the SteamVR Plugin *(Version 2.4.5, SDK 1.7.15 (Valve Corporation, n.d.))*, HTC Vive Base Stations and an HTC Vive Pro headset. VR was used in this study to ensure replicability, guarantee uniform acoustic noise, control traffic autonomy, and provide consistent weather conditions and initiation locations and times for the different scenarios *(Camara et al., 2020; Colley & Rukzio, 2020; Deb et al., 2018; Holländer et al., 2019; Nuñez Velasco et al., 2019; Pillai, 2017)*. Additionally, the contextual environments were adapted to align with the expected traffic cultures of Chinese and German participants to ensure behavior and comprehension of the communicated information was not affected by cultural unfamiliarity *(Eisele & Petzoldt, 2022)*.

3.2.3.
Stimuli

To include different communication partners, this study incorporated a manual car driver cooperation scenario and a pedestrian crossing, because prior research identified these scenarios as essential traffic situations in which eHMI could offer valuable support (*Clamann et al., 2017; Coeugnet-Chevrier, 2019; Dietrich et al., 2019; Färber, 2016; Lagström & Malmstem Lundgren, 2015; Mahadevan et al., 2018a*). Both scenarios were designed to reflect the habitual behavioral patterns of both traffic cultures, ensuring that participants were not confused and behaved naturally *(Weber et al., 2019)*. Both scenarios are depicted in Figure 15, showing the participant's perspective with a VR-camera icon.

In the pedestrian crosswalk, the participant was tasked with safely crossing the road at a crosswalk in front of a yielding autonomous vehicle coming from the right. A jerk-limited braking profile ($j = -2 / +2\ m/s^3$, $a_{max} = -2\ m/s^2$ *(Dietrich et al., 2020)*) was applied 1 second (s.) after the scenario began, bringing the vehicle from 50 km/h to a full stop in 7.94 s over 55.2 m, with an initial time-to-collision of 3.97 s if speed were maintained. In the cooperative driving, an AV approaching from the

| ***Figure 15*** *The scenarios: (l.t.r.) (1) Pedestrian crosswalk scenario, (2) Cooperative driving scenario.*



left intends to turn right, encountering the participant's car at an intersection where the participant aimed to go straight without having the right of way. In this scenario, participants sat in a fixed-position chair, adjustable in height for optimal visual clarity, while the participant's car remained stationary in VR to prevent motion sickness *(Vasser & Aru, 2020)*.

The study aims to explore message coding types within explicit dynamic eHMI systems, leveraging modalities that seem to hold universal potential *(Wesseling et al., 2020)*. As such, the study explores message coding strategies for the modalities of LED, display, and directed sound beam.

For LED technology, prior research designed the LEDs to be lit in sections that track the position of the pedestrian relative to the AV and indicate direction by sweeping motions towards the intended direction of the AV *(Dey et al., 2020; Lagström & Malmstem Lundgren, 2015; Mirnig et al., 2021; Yamin & Park, 2023)*. However, the use of color coding in message delivery remains a topic discussion within eHMIs. Prior research suggests that green is intuitive for indicating 'please cross' *(Bazilinskyy et al., 2020)*. Similarly, green is favored over red, when signaling yielding intent of AVs *(Dey et al., 2020)*. These colors have been relied on to investigate whether color-coding increases the efficacy of LED technology for message coding, by adding these colors to the shown LEDs for the pedestrian scenario. For the car driver scenario, orange is traditionally used as indicating intent to turn, which has therefore been applied to the eHMI to add color-coding. For alternative to color-coding, the no color-coded LED relied solely on white, as prior research found this color to be most effective for conveying neutral information *(Bazilinskyy et al., 2021; Shmueli & Degani, 2023)*.

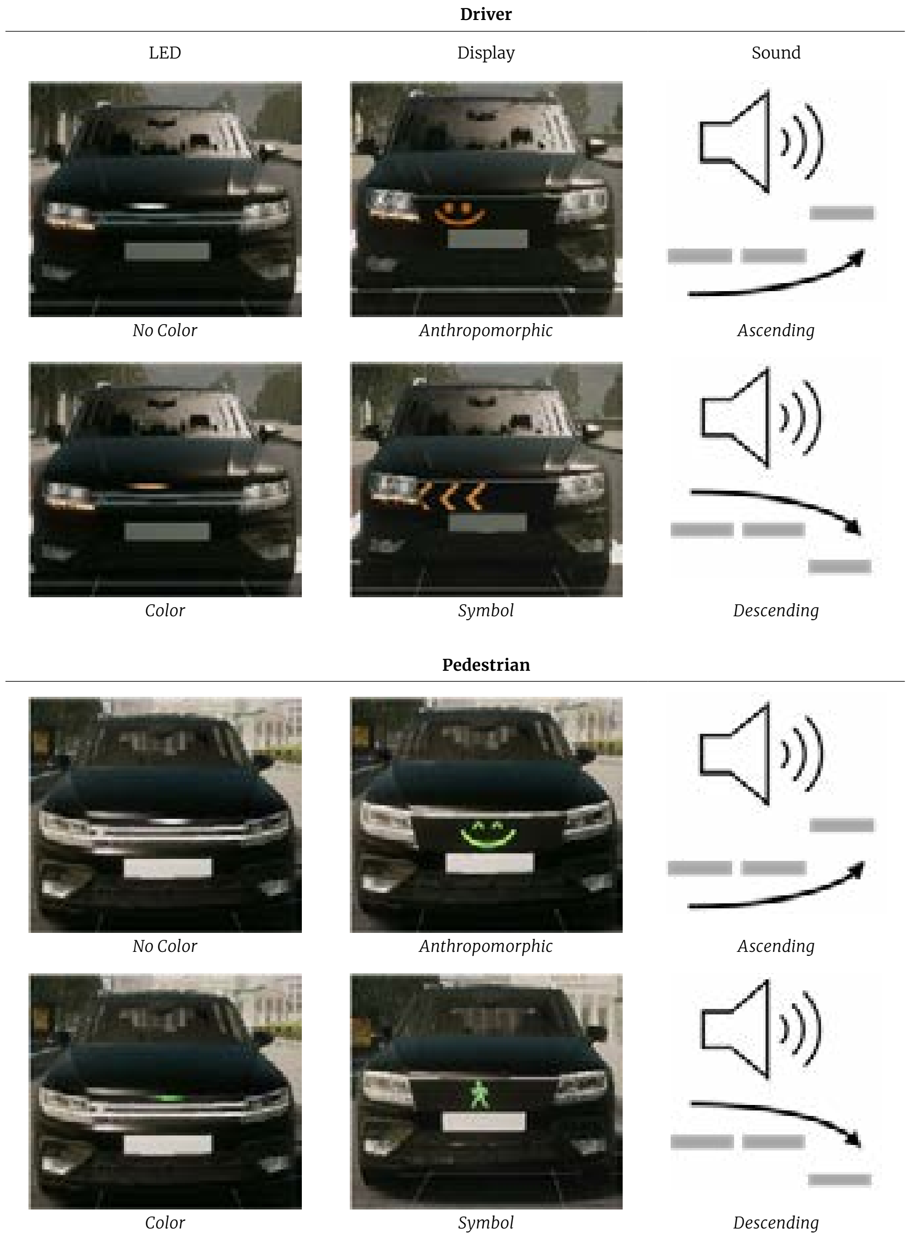
Display technology offers an additional level of message coding possibilities. Anthropomorphized coding, such as smiley faces, reduce perceived stress and foster increased confidence and attention in pedestrians *(Verma et al., 2019)*. This type of coding is thought to mimic human-like cues, allowing for neutral states and expanding the expressive potential of AVs *(Cefkin et al., 2019; Clercq et al., 2019; Mahadevan et al., 2019)*. Alternatively, symbol-based coding, which draws on familiar traffic signage, offers the ability to surpass language barriers, cross-cultural familiarity and legibility from greater distances *(Bazilinskyy et al., 2019; Hudson et al., 2019; Löcken et al., 2019; Wesseling et al., 2020)*. Textual coding, however, is omitted in this study due to its limitations, particularly in transcending language barriers and challenges posed to individuals with dyslexia and varying literacy levels *(Bazilinskyy et al., 2021)*. Therefore, the study focused on anthropomorphic (i.e., a white neutral face shifting to a orange/green smiley face) and symbol-based message coding (white road markings/pedestrian traffic sign animated into directional sweeping orange road markings/ walking green pedestrian traffic sign).

Directed Sound Beam technology enables spatial, personalized acoustic information, which could be particularly useful for distracted and vision-impaired pedestrians *(Deb et al., 2016)*. Similarly to textual-coding of displays, textual-coding of sound is excluded from this study. Instead, given the established role of auditory messages in automotive safety systems (e.g., front braking warning, safety belt alarms, parking sensors), this study focused on two distinct sound coding options—ascending and descending tones through two tones followed by a higher/lower tone *[*beep beep beep*]*. Cultural preferences in tonal characteristics of voiced speech, which are closely related to tonal preferences in music, exist *(Han et al., 2011)*. These cultural differences may contribute to the wide variability in HRU responses to auditory messages, warranting the need for deeper exploration *(Florentine et al., 2016; Poveda-Martínez et al., 2017)*.

The eHMI has been integrated in the bumper of the vehicle as pedestrians initially, after looking at the environment, focus on the bumper and hood of the vehicle first *(Bindschädel et al., 2022b)*. The implementation of eHMI cues in the roof has therefore been excluded as this placement contradicts

with pedestrians' inherent visual scanning patterns *(Guo et al., 2022)*. All types of message coding (*see Table 2*) were integrated into a car that is common in both traffic cultures.

| ***Table 2*** *Visualization of the message coding levels included for the different communication partners.*



3.3.

Measures & Procedure

Ethical approval for this study ensured compliance with guidelines for human participant research. Following these guidelines, the study began with an introduction, privacy policy, and voluntary consent declaration, which were provided previously to each participant along with the study invitation. After these administrative procedures, participants were asked to complete the initial survey where demographic data, including gender and age, were gathered. The participant was then introduced to a virtual world mirroring their traffic culture and allowed time to familiarize with the demo scenario. The familiarization process within VR was conducted without a time limit.

The participants then engaged in a randomized traffic scenario, receiving context, time to understand the required task and the opportunity to familiarize with the scenario. In the car driver scenario, the aim was to turn right onto the main street while not having priority, pressing the spacebar when ready to drive, indicating decision time. This objective measure aimed to gauge the effectiveness of the conveyed message and recorded the starting time of the scenario and the timestamp of a spacebar press. In the pedestrian scenario, the task was to cross the road safely. All participants started from a set position to ensure replicability and comparability.

Once familiar with the scenario and task, the participant completed all six message coding conditions and the baseline condition to establish baseline levels (i.e., without eHMI) in a randomized order. After each condition, the participant was asked to fill out a survey section related to subjective measures regarding the traffic experience. This survey section was therefore filled out seven times and consisted of four statements rated on a 7-point Likert scale *("Completely disagree" =1 and "Completely agree" = 7).* The study opted to rely on single items to limit the study length and included eHMI effectiveness measures. More specifically, measure focused on rating intuitive comprehension *("This concept communicates in an intuitive manner")*, understanding of AV's behavior *("This concept improves my understanding of the autonomous vehicle")*, perceived safety *("This concept would make me feel safer in traffic")* and user acceptance *("I would accept Autonomous Vehicles more quickly if they will implement this concept").*

This procedure was repeated for the other traffic scenario. The participant was asked to leave feedback about the proposed eHMIs in an open question. The duration of the study was between 45 and 60 minutes per participant.

3.3.1.

Statistical Analyses

Analyses were performed within R (version 4.1.3 *(R Core Team, 2021b)*). To conduct ANOVA estimations for factorial designs, analysis relied on afex package with effect sizes calculated with generalized eta-squared (η_G^2) utilizing Type III Sum of Squares and Greenhouse-Geisser corrections *(Singmann et al., 2021)*. For post-hoc testing, pairwise comparisons were performed with Tukey's Honestly Significant Difference to adjust for multiplicity using the graphics package *(R Core Team, 2021a)*.

3.4.

Results

3.4.1.

Subjective Measures

The three-way mixed ANOVAs were conducted for each subjective measure, using Culture *(between-subject)*, Message Coding *(within-subject)*, and Communication Partner *(within-subject)* as fixed effects, and participant number *(No.)* nested within message coding and communication partner as a random effect *(Error)*. All estimated marginal means *(EMM)*, standard errors *(SE)*, and upper and lower bound confidence intervals (95% CI) are described for each subjective measure at the end of this chapter (see Table 5 - 8).

Main Effect of Culture

A significant main effect of culture was observed for intuitive comprehension *(F(1, 55) = 56.82, p < .001, = .23)*, understanding of AV *(F(1, 55) = 58.85, p < .001, = .27)*, perceived safety *(F(1, 55) = 62.11, p < .001, = .28)* and acceptance of AVs, *F(1, 55) = 52.29, p < .001, = .25*. The Chinese sample scored significantly higher than the German sample *(see Table 3)*.

| *Table 3* *Descriptive Statistics of all subjective measures' ratings for the main effect of Culture.*

	China			Germany			
	EMM	*SE*	*95% CI*	*EMM*	*SE*	*95% CI*	*Sig.*
Intuitive Comprehension	5.66	0.15	5.36, 5.96	4.04	0.16	3.72, 4.35	< .001
AV Understanding	5.61	0.16	5.30, 5.93	3.88	0.16	3.55, 4.21	< .001
Perceived Safety	5.69	0.15	5.39, 5.99	3.98	0.16	3.67, 4.30	< .001
AV Acceptance	5.52	0.16	5.19, 5.85	3.80	0.17	3.45, 4.14	< .001

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, Sig. = Statistical Significance (p)

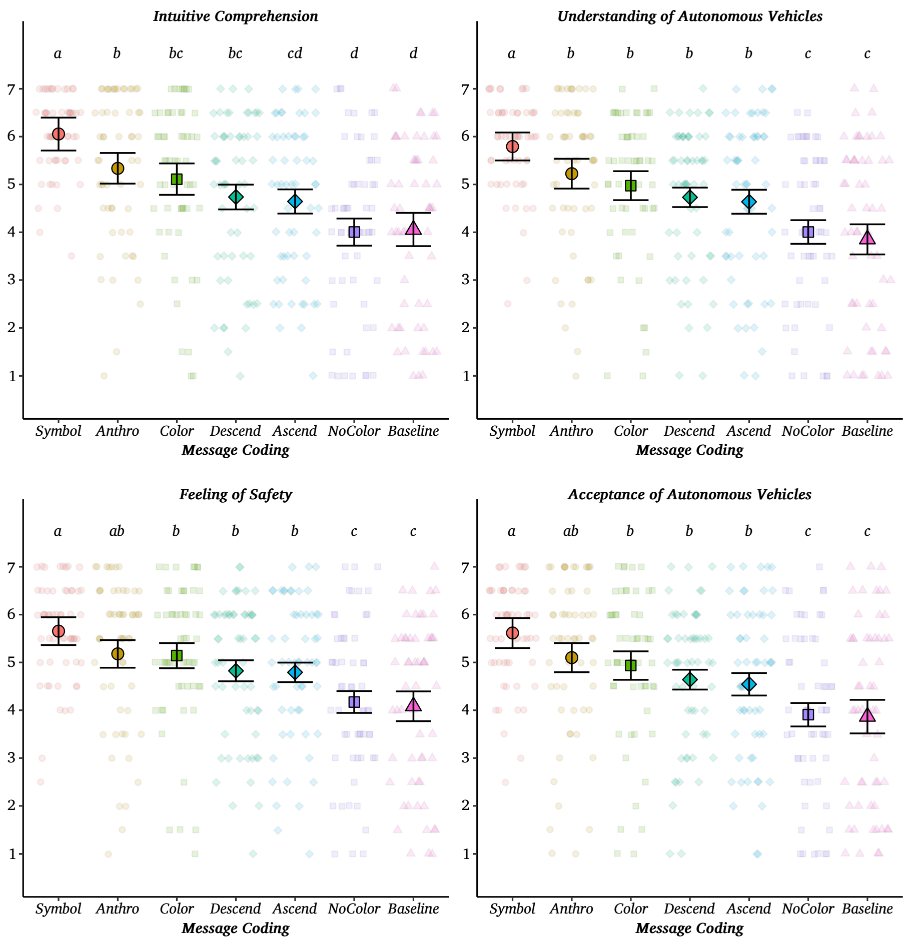
Main Effect of Message Coding

Analysis revealed a significant main effect of message coding for intuitive comprehension *($F(4.52, 248.52) = 25.43$, $p < .001$, $\eta_G^2 = .17$)*, understanding of AV *($F(4.51, 248.04) = 27.23$, $p < .001$, $\eta_G^2 = .16$)*, perceived safety *($F(4.42, 243.13) = 20.56$, $p < .001$, $\eta_G^2 = .12$)* and acceptance of AVs *($F(4.45, 244.77) = 22.74$, $p < .001$, $\eta_G^2 = .14$)*. These main effects have been visualized in Figure 16.

For both intuitive comprehension and understanding of AV, Symbol outperformed all other conditions, significant outperforming the second highest rated condition *(p = .007 and p = .05 respectively)*. For perceived safety, both Symbol and Anthropomorphic *(second-best, p = .12)* received the highest ratings. However, only the Symbol condition scored significantly higher than the Color LED condition *(third-best, p = .04)*. In terms of AV acceptance, while the Symbol condition was not rated significantly higher than the Anthropomorphic condition *(second-best, p = .10)*, it did receive significantly higher ratings than Color LED *(third-best, p = .01)*. These results suggest that the Symbol condition held the greatest potential for enhancing subjective experiences in traffic universally.

The provided message coding conditions aimed to improve participants' subjective experience. Post-hoc testing revealed that most conditions significantly improved participants' subjective experiences compared to the baseline *(see Figure 16)*. However, NoColor LED did not show significant improvements across all measures: intuitive comprehension *(p = 1.00)*, understanding of AV *(p = .968)*, perceived safety *(p = .998)*, and acceptance of AVs *(p = .999)*. Similarly, Ascending Sound also showed no significant improvement for intuitive comprehension *(p = .06)*.

| **Figure 16** *Main Effect of Message Coding for Intuitive Comprehension (UL), Understanding of Autonomous Vehicles (UR), Feeling of Safety (LL), and Acceptance of Autonomous Vehicles (LR).*



Note: The graphs are displaying Estimated Marginal Means with Standard Errors and post-hoc grouping letters based on Tukey's Honestly Significant Difference (HSD).

Main Effect of Communication Partner

No significant main effect was found for Communication Partner in intuitive comprehension *($F(1, 55) = 2.62$, $p = .111$, $\eta_G^2 < .01$)*, understanding of AV *($F(1, 55) = 0.12$, $p = .729$, $\eta_G^2 < .01$)*, perceived safety *($F(1, 55) = 0.18$, $p = .676$, $\eta_G^2 < .01$)*, and acceptance of AVs *($F(1, 55) = 0$, $p = .953$, $\eta_G^2 < .01$)*. The absence of an effect revealed that the role of the participant did not significantly impact the ratings.

Interaction Effect between Culture and Communication Partner

Similarly, the interaction effect between Culture and Communication Partner was not significant for all measures: intuitive comprehension *($F(1, 55) = 0.02$, $p = .889$, $\eta_G^2 < .01$)*, understanding of AV *($F(1, 55) = 2.19$, $p = .144$, $\eta_G^2 < .01$)*, perceived safety *($F(1, 55) = 0.02$, $p = .878$, $\eta_G^2 < .01$)* and acceptance of AVs *($F(1, 55) = 0.02$, $p = .876$, $\eta_G^2 < .01$)*. The findings indicate no cultural differences in how car drivers and pedestrians experienced the message coding between cultures.

Interaction Effect between Culture and Message Coding

The analysis revealed a significant interaction effect between Culture and Message Coding for each subjective measure, suggesting that cultural differences influenced how message coding levels were perceived. More specifically, significant effects were found for intuitive comprehension *($F(4.52, 248.52) = 8.86$, $p < .001$, $\eta_G^2 = .07$)*, understanding of AV *($F(4.51, 248.04) = 9.4$, $p < .001$, $\eta_G^2 = .06$)*, perceived safety *($F(4.42, 243.13) = 7.1$, $p < .001$, $\eta_G^2 = .046$)* and acceptance of AVs *($F(4.45, 244.77) = 8.94$, $p < .001$, $\eta_G^2 = .06$)*. These interaction effects have been visualized in Figures 17-20.

German participants exhibited more discernable differences in the ratings for Message Coding levels for all subjective measures, indicating heightened sensitivity compared to Chinese participants.

Symbol outperformed all other conditions in the German subsample with significant differences compared to the second-best condition (i.e., either Anthropomorphic or Color LED) for intuitive comprehension *($p < .001$)*, understanding of AV *($p < .001$)*, feeling of safety *($p < .001$)* and acceptance of AVs *($p = .01$)*. Additionally, the levels of Anthropomorphic and Color LED were rated higher than the baseline condition for intuitive comprehension *($p = .003$, $p = .001$ respectively)*. For understanding of AV, feeling of safety, and acceptance of AV, Color LED *(all $p < .001$)*, Anthropomorphic *($p < .001$, $p = .007$, $p = .002$)*, Descending *($p < .001$, $p = .009$, $p = .005$)* and Ascending Sound *($p < .001$, $p = .011$, $p = .025$)* were all rated higher than the baseline condition.

Contrastingly, in the Chinese subsample, limited significant differences were identified among the Message Coding conditions. The only significant differences observed were between the NoColor LED *(worst)* and Anthropomorphic *(best)* in intuitive comprehension *($p = .014$)* and acceptance of AV *($p = .028$)*, as well as between the NoColor LED *(worst)* and both the Anthropomorphic *(second-best, $p = .030$)* and Symbol *(best, $p = .003$)* level in understanding of AV.

Figure 17 *Interaction Effect between Culture and Message Coding for Intuitive Comprehension.*

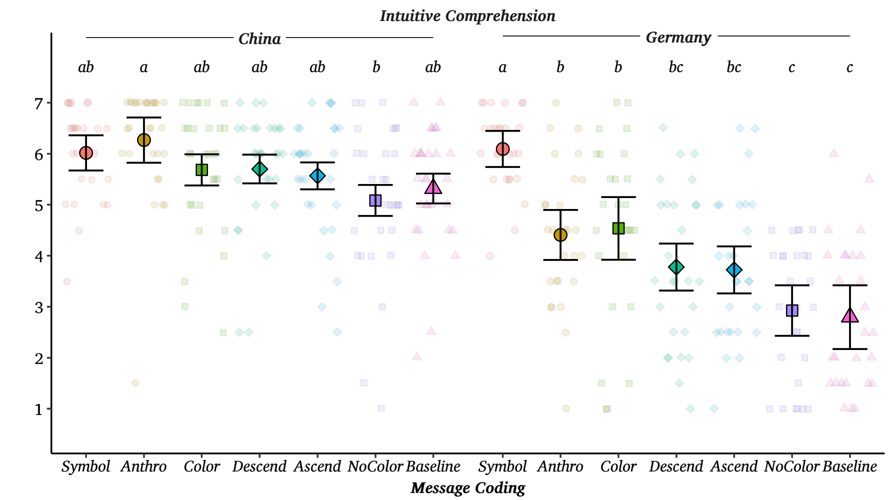
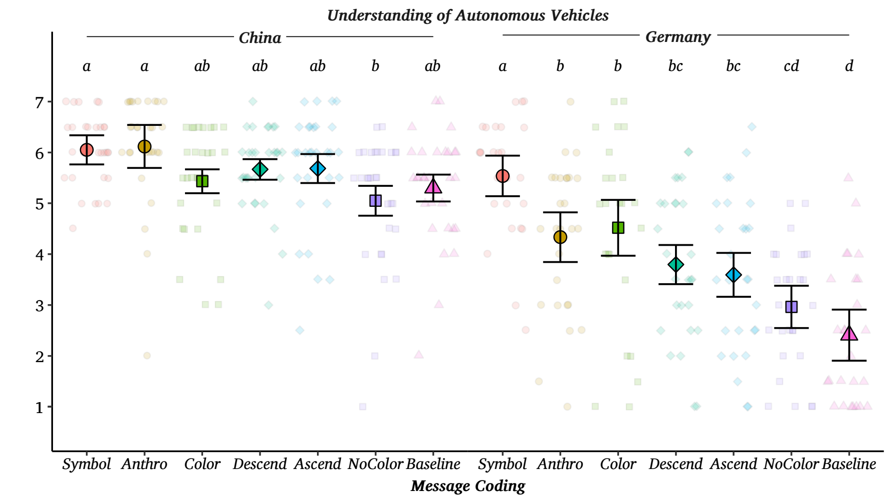
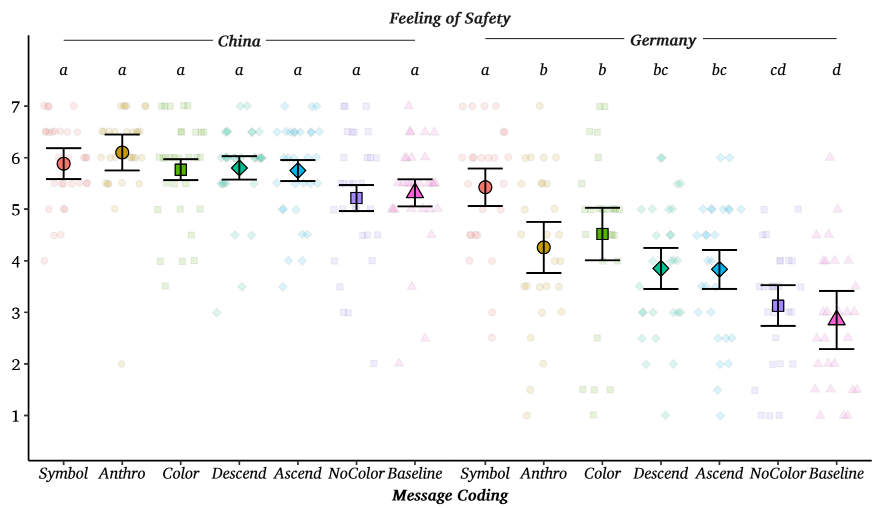


Figure 18 *Interaction Effect between Culture and Message Coding for Understanding of Autonomous Vehicles.*

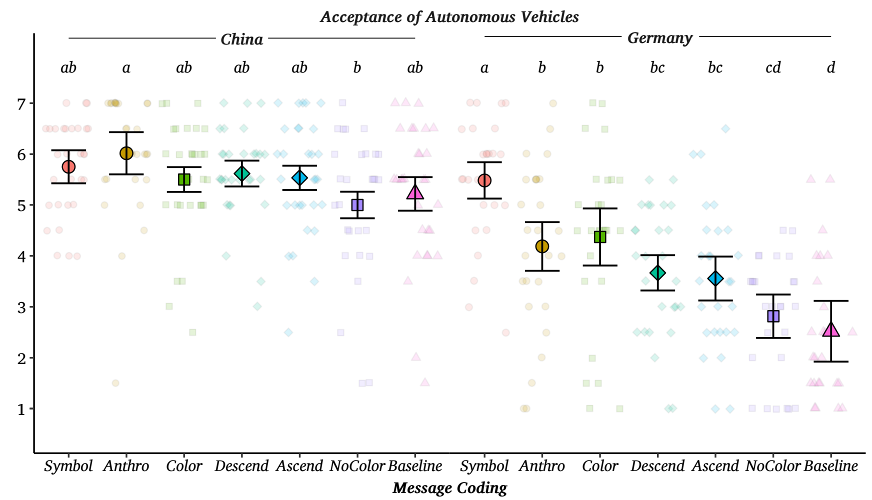


Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

| **Figure 19** *Interaction Effect between Culture and Message Coding for Feeling of Safety.*



| **Figure 20** *Interaction Effect between Culture and Message Coding for Acceptance of Autonomous Vehicles.*



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

These results indicated that, when considering cultural differences, German participants indicated a consistent positive impact on their subjective experience when interacting with Symbol, Anthropomorphic and Color LED eHMIs, whereas Chinese participants did not indicate a significant positive effect compared to the baseline.

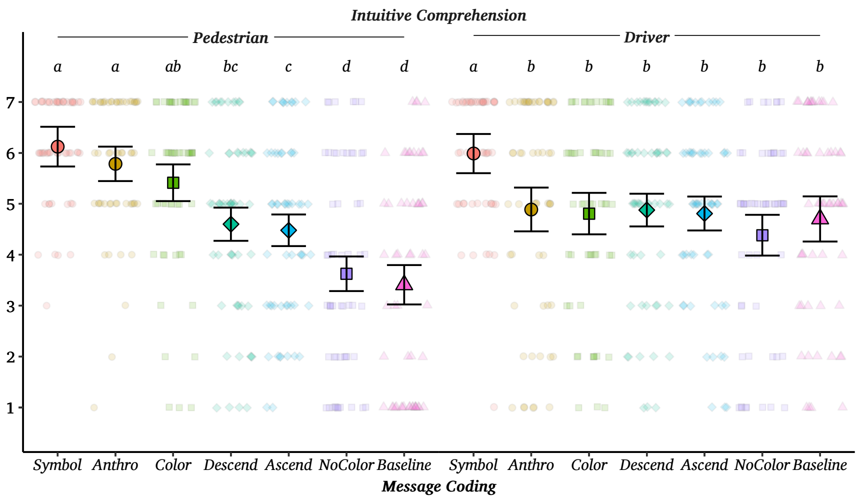
Interaction Effect between Communication Partner and Message Coding

A significant interaction effect between communication partner and message coding existed for all subjective measures: intuitive comprehension *($F(4.52, 248.52) = 8.86$, $p < .001$, $\eta_G^2 = .07$)*, understanding of AV *($F(4.51, 248.04) = 9.4$, $p < .001$, $\eta_G^2 = .06$)*, perceived safety *($F(4.42, 243.13) = 7.1$, $p < .001$, $\eta_G^2 = .05$)* and acceptance of AVs *($F(4.45, 244.77) = 8.94$, $p < .001$, $\eta_G^2 = .06$)*. The interaction effect has been depicted in Figures 21-24.

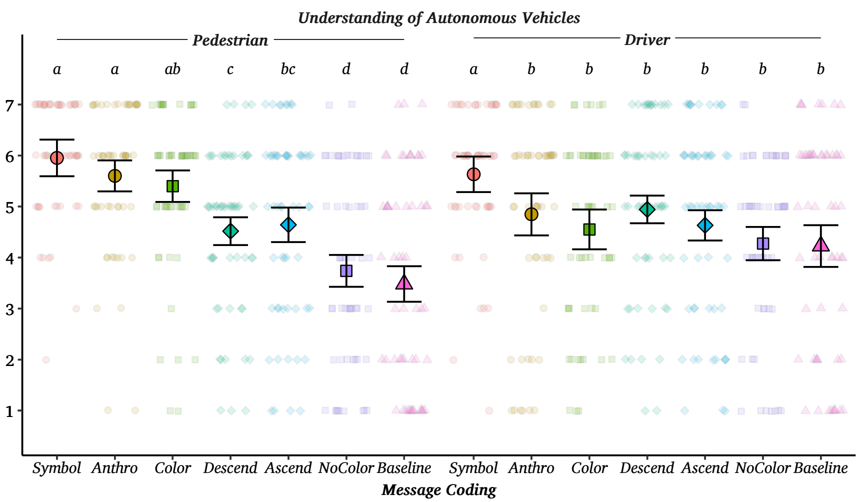
The findings revealed consistent preference for Symbol *(best)* by car drivers. Car drivers rated Symbol higher compared to the baseline for intuitive comprehension *(p = .002)*, and understanding of AV *(p < .001)*. Additionally, drivers experienced a significantly higher perceived safety when interacting with Symbol *(p = .005)*, Anthropomorphic *(p = .010)*, Color LED *(p = .011)*, Descending *(p = .011)* and Ascending Sound *(p = .012)* compared to the baseline condition. Lastly, drivers also indicate a positive impact on acceptance of AV, when comparing Symbol *(p = .013)* and Descending *(p = .013)* to the baseline condition.

For the pedestrian communication role, the ratings displayed a gradient with no significant difference between Symbol *(highest)* and Anthropomorphic (*second-highest*), Symbol and Color LED *(third-highest)*, and Anthropomorphic and Color LED for intuitive comprehension *(p = .974, p = .231, p = .917)*, understanding of AV *(p = .919, p = .366, p = .993)*, perceived safety *(p = .999, p = .981, p = 1.00)*, and acceptance of AV *(p = 1.00, p = .831, p = .987)*, respectively. For intuitive comprehension, no significant difference was found between Color LED and Descending *(fourth-best, p = .215)*. Additionally, Color LED and Ascending Sound (*fourth-best)* were not rated significantly different for understanding of AV (*p = .470*). For Descending and Ascending Sound, no significant differences existed between these conditions for intuitive comprehension *(p = 1.00)*, understanding of AV *(p = 1.00)*, perceived safety *(p = 1.00)*, and acceptance of AV *(p = 1.00)*. NoColor LED *(worst)* did not outperform Baseline for intuitive comprehension *(p = .996)*, understanding of AV *(p = .935)*, perceived safety *(p = 1.00)*, and acceptance of AV *(p = 1.00)*, with significant differences compared to both Descending and Ascending Sound *(p = .001, p = .002, p = .031, p = .014 respectively)*.

| ***Figure 21*** *Interaction Effect between Communication Partner and Message Coding for Intuitive Comprehension.*

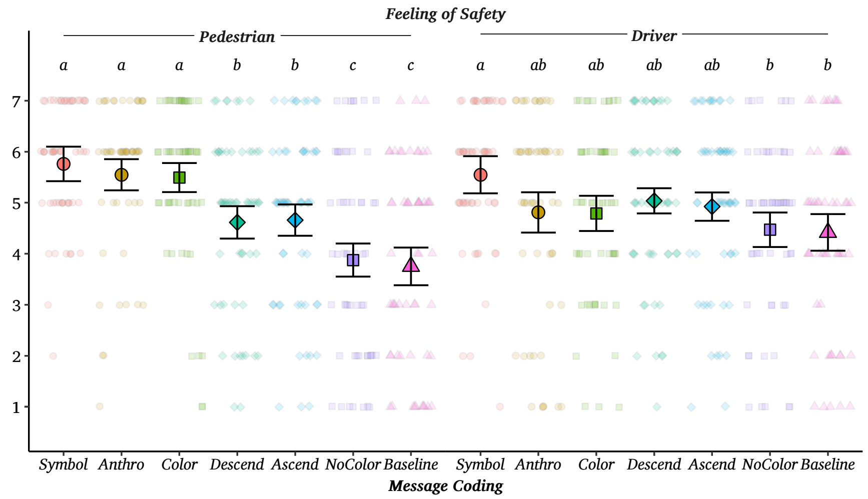


| ***Figure 22*** *Interaction Effect between Communication Partner and Message Coding for Understanding of Autonomous Vehicles.*

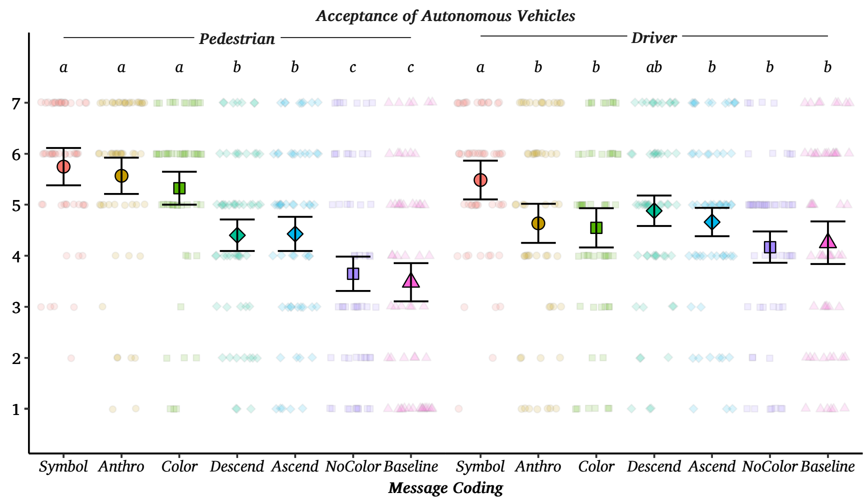


Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

| ***Figure 23*** *Interaction Effect between Communication Partner and Message Coding for Feeling of Safety.*



| ***Figure 24*** *Interaction Effect between Communication Partner and Message Coding for Acceptance of Autonomous Vehicles.*



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

These findings indicated that the effectiveness of message coding in influencing participants' subjective experiences varied depending on who the eHMI was communication with. In other words, different types of HRUs may interpret or respond to the coding condition in different ways, resulting in this variability in subjective experiences ratings.

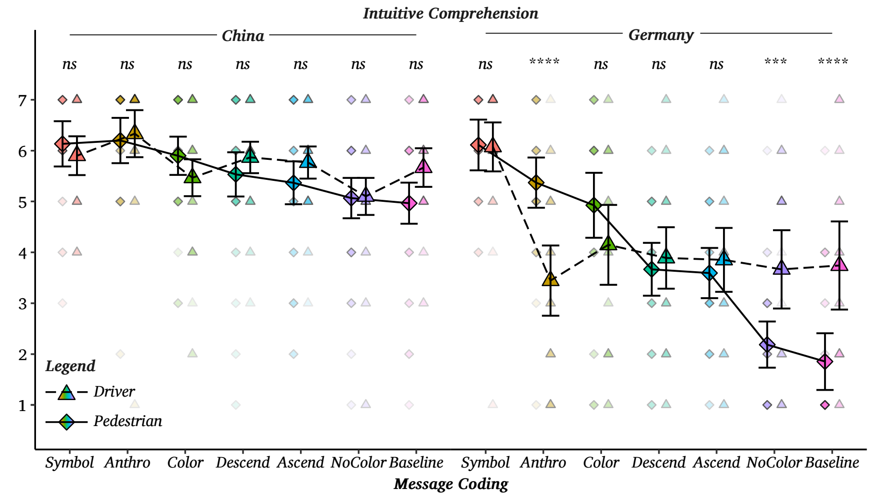
Three-way Interaction Effect

A three-way interaction effect between culture, communication partner, and message coding was observed for intuitive comprehension *($F(5.41, 297.56) = 8.08, p < .001, \eta_G^2 = .03$)*, understanding of AV *($F(5.09, 280.2) = 4.35, p < .001, \eta_G^2 = .02$)*, perceived safety *($F(5.4, 296.79) = 4.82, p < .001, \eta_G^2 = .02$)* and acceptance of AVs *($F(5.14, 282.71) = 4.77, p < .001, \eta_G^2 = .02$)*. This interaction effect suggested that cultural differences influenced how message coding is experienced, which is also influenced by the type of communication partner. Figures 25-28 depict the three-way interaction effects.

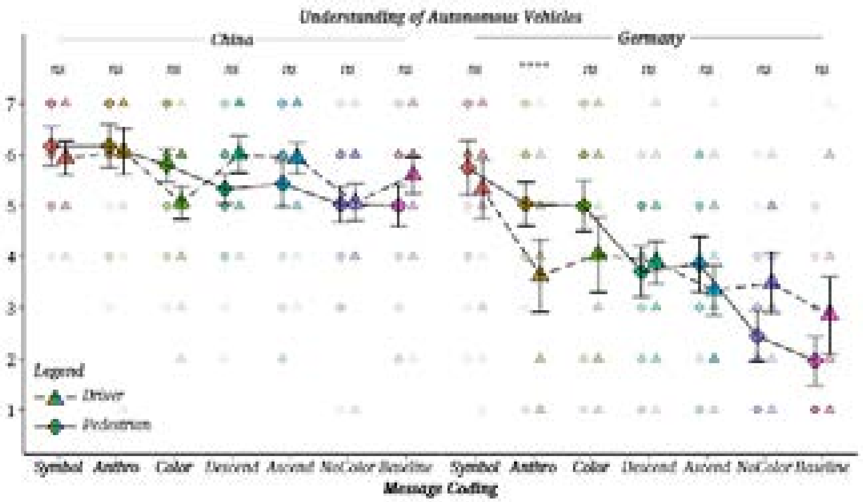
No significant differences could be determined within the Chinese subsample. The lack of significant differences indicates that Chinese participants did not show distinct preferences for the type of message coding in the car driver or pedestrian role.

In contrast, the German subsample indicated differences depending on their role as car drivers and pedestrians for the type of message coding. The most significant difference occurred for Anthropomorphic coding. Pedestrians rated Anthropomorphic significantly higher compared to car drivers across all subjective measures *(all $p \leq .001$)*, although this rating did not outperform the highest rated symbol-coding. Additional differences were found for the NoColor LED and Baseline conditions with car drivers noting higher ratings compared to pedestrians. These differences applied to intuitive comprehension *($p = .006$, $p < .001$, respectively)*, and for the Baseline condition in acceptance of AV *($p = .023$)*. This suggests that German participants had role-specific preferences, indicating that eHMI design may need to be adapted to the type of communication. In other words, these results indicated that universal eHMI designs may work in some cultures, while role-specific coding adaptations may be necessary in others.

| Figure 25 *Three-way Interaction Effect between Culture, Communication Partner and Message Coding for Intuitive Comprehension.*

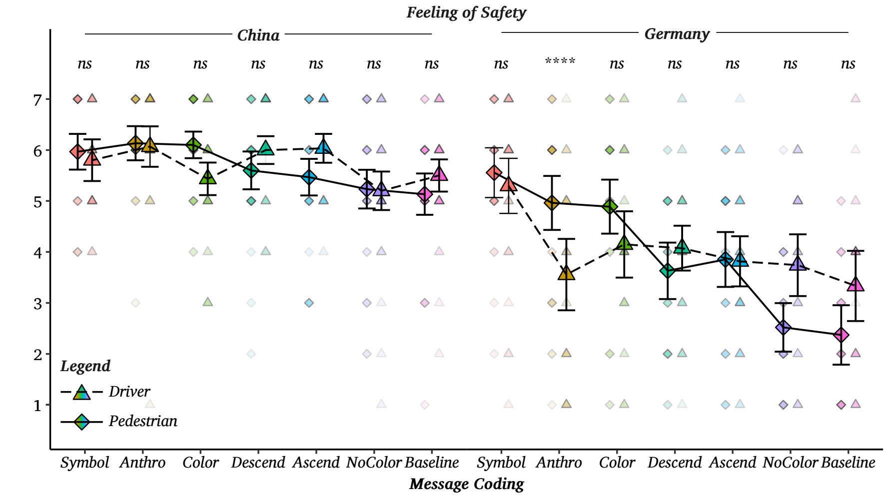


| Figure 26 *Three-Way Interaction Effect between Culture, Communication Partner and Message Coding for Understanding of Autonomous Vehicles.*

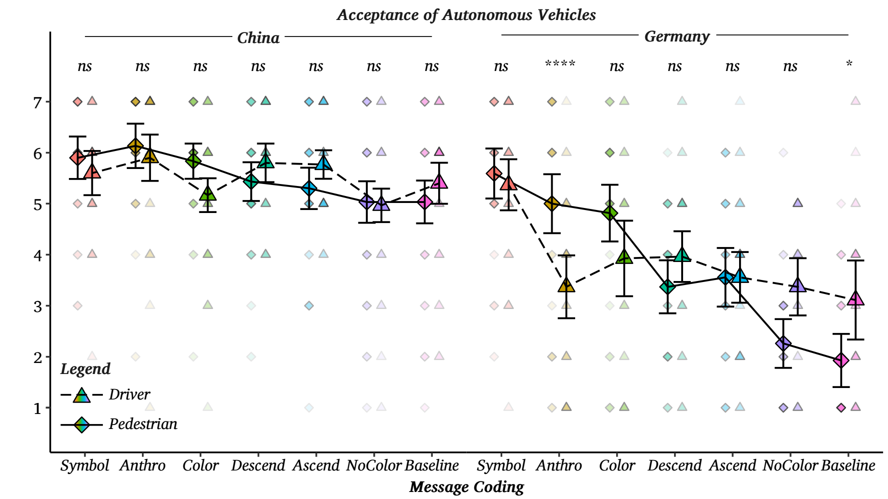


*Note: The graph is displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

| ***Figure 27*** *Three-way Interaction Effect between Culture, Communication Partner and Message Coding for Feeling of Safety.*



| ***Figure 28*** *Three-Way Interaction Effect between Culture, Communication Partner and Message Coding for Acceptance of Autonomous Vehicles.*



*Note: The graph is displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

3.4.2.

Decision Time

Decision time, measured exclusively in the car driver communication role, was analyzed using a two-way mixed ANOVA. The model included culture *(between-subject)*, message coding *(within-subject)*, and a random effect with participant numbers nested within message coding *(see Table 4 for descriptive statistics and comparisons across and within cultures)*.

A significant main effect of culture was observed *(F(1, 51) = 88.11, p < .001,* η_G^2 *= .51)*, indicating culture influences decision time in the car driver role. Specifically, the Chinese participants *(EMM = 10.02s, SE = 0.25, [9.51; 10.52])* exhibited slower decision times compared to German participants *(EMM = 6.70s, SE = 0.25, [6.2; 7.19])*, suggesting culture may impact decision speed in this context *(p < .001)*.

The main effect of message coding was statistically significant *(F(3.80, 193.72) = 2.93, p = .024,* η_G^2 *= .02)*. Notably, Ascending Sound led to significantly faster decision times compared to the baseline condition *(p = .043)*, highlighting that this message coding enhances decision-making efficiency.

The interaction effect between culture and message coding was not significant *(F(3.80, 193.72) = 2.07, p = .090,* η_G^2 *= .02)*. The lack of significance suggests that while culture and message coding each influence decision time, their effects did not seem to interact meaningfully.

Table 4

Descriptive Statistics of all subjective measures' ratings for the main effect of Culture.

Sample	EMM	SE	95% CI	SG
Ascend	8.10	0.18	7.74; 8.46	a
Descend	8.18	0.19	7.80; 8.56	ab
Anthro	8.18	0.25	7.68; 8.69	ab
Color	8.26	0.20	7.86; 8.65	ab
Symbol	8.34	0.24	7.86; 8.81	ab
Demo	8.59	0.21	8.16; 9.02	b
NoColor	8.84	0.30	8.23; 9.45	b
China	EMM	SE	95% CI	SG
Descend	9.62	0.27	9.08; 10.16	a
Color	9.68	0.28	9.11; 10.25	a
Anthro	9.69	0.36	8.98; 10.41	a
Ascend	9.74	0.26	9.23; 10.26	a
Symbol	10.23	0.34	9.55; 10.91	a
Demo	10.32	0.30	9.70; 10.93	a
NoColor	10.83	0.43	9.96; 11.70	a
Germany	EMM	SE	95% CI	SG
Symbol	6.44	0.33	5.78; 7.11	a
Ascend	6.46	0.25	5.96; 6.97	a
Anthro	6.68	0.35	5.98; 7.38	a
Descend	6.74	0.27	6.21; 7.27	a
Color	6.84	0.28	6.28; 7.39	a
NoColor	6.85	0.43	5.99; 7.70	a
Demo	6.87	0.30	6.27; 7.47	a

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, Sig. = Statistical Significance (p)

3.5.
Discussion

This study examined the influence of culture on the effectiveness of external Human-Machine-Interface (eHMI) message coding strategies. The findings reveal significant cultural differences in how pedestrians and car drivers respond to different message coding strategies, with implications for both universal and cultural-specific eHMI designs.

3.5.1.
Cultural Influence of eHMI Effectiveness

A key finding of the study is the significant main effect of culture across all subjective measures (i.e., intuitive comprehension, understanding of AVs, perceived safety, and acceptance of AVs). Chinese participants consistently rated eHMI more favorably than German participants, potentially due to cultural differences in familiarity with technology, risk perception, or general attitudes towards AVs. Cultural factors such as attitudes of risks, politeness, social desirability, and willingness to criticize may also introduce biases such as Leniency Bias or Central Tendency Bias *(Akbari et al., 2024; Douven, 2018)*.

The study also found a significant interaction effect between Culture and Message Coding, revealing that culture plays a crucial role in how message coding strategies are perceived. German participants showed higher sensitivity to message coding strategies, while Chinese participants exhibited a more generalized acceptance of different message coding strategies. These findings emphasize the need for eHMI message coding strategies and designs that consider cultural context.

3.5.2.
Effectiveness of Message Coding Strategies

Key findings indicated that message coding demonstrated significant impacts on participants' subjective experiences. Across cultural samples, Symbol emerged as the most effective universal message coding strategy for enhancing intuitive comprehension, understanding of AVs, perceived safety and acceptance of AVs. These findings reinforce that symbolic representations are widely understood and could serve as a universal coding strategy for eHMIs.

However, additional cultural nuances emerged. German participants exhibited clearer distinctions between strategies, with Symbol-based coding consistently rated as or amongst the most effective, while other strategies, such as Anthropomorphized and Color LED, also showed positive effects compared to no eHMI. In contrast, the Chinese sample demonstrated fewer significant differences, except for Anthropomorphized and Symbol for some measures. These findings suggest that while Symbol is a strong candidate for universal eHMIs, implementing cultural adaptations (i.e., Anthropomorphized) for the Chinese culture can also optimize effectiveness. These findings align with previous research which indicates that eHMI must consider necessary cultural adaptations *(Weber et al., 2019)*.

3.5.3.

Impact of Communication Partner

In contrast to Culture and Message Coding, Communication Partner (i.e., car driver vs pedestrian) did not have a significant main effect on eHMI effectiveness. This finding suggests that both traffic roles evaluated eHMI coding strategies similarly, reinforcing the potential for universal eHMI design. However, significant three-way interaction effects indicate that the combination of all three factors still shapes eHMI effectiveness. Specifically, German participants displayed role-specific preferences for coding strategies, particularly Anthropomorphic coding, which received higher ratings from pedestrians than car drivers and more generally in China. These findings could be due to the positive impact of eye contact on engagement and cooperative behavior in pedestrian scenarios, as well as its potential positive effect on decision time and the feeling of safety for pedestrians *(Cefkin et al., 2019; Chang et al., 2017).*

Despite this, in Germany, Anthropomorphic coding did not outperform Symbol-based coding, which consistently received the highest ratings across all conditions, suggesting greater universal applicability. Nonetheless, these findings suggest that the impact of communication partner should be carefully considered. While a universal message coding strategy may apply in some cultures, role-specific adaptations may be necessary in others. These findings align with prior research showing similar effects, emphasizing the need for culturally adaptive eHMI designs that account for varied traffic contexts and user roles *(Weber et al., 2019)*.

Additionally, the study also highlights cultural differences in the general rating of the baseline condition, with pedestrians consistently rating it lower than car drivers. This may suggest that

pedestrians tend to rely on and prefer more information than car drivers, which aligns with findings of previous research showing variations in communication interactions between different types of road users *(Fruhen et al., 2019; Habibovic et al., 2013)*. This insight could guide future eHMI strategies, particularly in enhancing pedestrian experiences.

3.5.4.

Cultural Influence on Decision Time

The results also indicate that culture significantly affects decision-making speed. Chinese participants exhibited significantly longer decision times than German participants, suggesting potential cultural differences in risk assessment, traffic safety, patience, crossing speed and yielding behavior *(Jiang et al., 2015; Theofilatos et al., 2021)*. However, the effect of message coding was small. The only coding strategy that resulted in improving decision efficiency was ascending sound coding, despite scoring lower on subjective measures.

The findings align with previous research advocating for auditory warnings and multi-modal eHMI designs including both auditory and visual modalities, particularly for safety-critical scenarios *(Florentine et al., 2016; Wang et al., 2021)*. Implementing such multi-modal eHMIs could provide useful in urgent situations or for assisting impaired HRUs *(Clercq et al., 2019; Weber et al., 2019)*.

3.5.5.

Future Research

The generalizability and robustness of the results could be improved by extending the sample size and including additional cultures, enhancing statistical power and increasing the influence of individual variability. Cultural factors beyond the selected cultural contexts could yield different responses to eHMI message coding, necessitating caution in extending these findings to broader traffic cultures. Similarly, extending the scope of implemented traffic scenarios could aid in safeguarding the crucial scalability of eHMI design *(Dey et al., 2021; Gao et al., 2023; Verstegen et al., 2021)*. Additionally, future research could conduct the study with participants who have physical or visual impairments to investigate the essential inclusivity considerations of eHMIs *(Colley et al., 2019; Colley, Walch, Gugenheimer, et al., 2020; Colley, Walch, & Rukzio, 2020; Dey et al., 2021; Löcken et al., 2020).*

To conduct this study, VR was relied on due to its immersion, replicability, and consistent scenario variability. Enhancing VR fidelity and realism of the environments by, for example, incorporating more moving HRUs could improve immersiveness and participant behavior, potentially enhancing the ecological validity of the study. Future research could also consider real-driving studies to validate the findings.

3.6.
Conclusion

This study examined the influence of culture, message coding, and communication partner on subjective and objectives measures related to eHMIs (external Human-Machine Interfaces). The results highlighted several key insights which inform the design of more effective eHMIs for Autonomous Vehicles (AVs) within and across cultures.

The findings highlight the critical role of culture in designing external Human-Machine Interfaces (eHMIs). With significant cultural differences observed in subjective ratings, the need to consider cultural perspectives in eHMI design is emphasized. Additionally, the study underscores the importance of considering the communication partner—whether the user is a car driver or a pedestrian. The interaction effects suggests that while a universal eHMI design may work in certain cultures, role-specific adaptations might be necessary in others. Pedestrians, for instance, may require more explicit and detailed signals in some cultures, whereas car drivers benefit from simplified signals enabling quick processing.

If automakers and policymakers aim to provide an optimal subjective experience for Human Road Users (HRUs), the findings indicate that culturally adaptive eHMIs should be relied on. Specifically, Symbol-based displays are most effective in Germany, while both Symbol-based displays and Anthropomorphic displays can be considered in China. As such, when seeking a universal eHMI solution, symbol-based visual cues present the strongest foundation. Symbol-based coding was well-received across different cultures, making them the recommended choice for creating standardized eHMI designs. However, if enhancing decision efficiency, and potentially improving traffic flow, is the goal, the implementation of ascending coding of directed sound beams is key, especially in urgent situations. These auditory cues ensure quicker decisions, which is critical in such high-risk scenarios.

Based on these results, the study strongly advocates for a multi-modal eHMI, integrating both auditory and visual signals to improve both subjective and objective experiences. Including Ascend Sound strategy would enhance decision efficiency, while the visual cues improve intuitiveness, understanding of AV's behavior, perceived safety, and general acceptance of AVs. These visual displays should rely on Symbol-based cues for universal application, or, for localized design, on Symbol for Germany and Symbol or Anthropomorphic for China. Multi-modal eHMI would be particularly beneficial in urgent situations and situations including impaired HRUs, where rapid decision-making and effective communication are essential.

Building on the Findings

The findings further highlight the critical role of culture on the effectiveness of eHMI message coding strategies. Building on these insights, the study in the following chapter focuses on comparing the effectiveness of two distinct eHMI coding strategies: learned representation-based designs, which utilize familiar traffic symbols and vehicle behavior, and universal cognitive innate tendency-based designs, which leverage innate human cognitive innate tendencies. The study explores more options for learned representation-based symbol designs (i.e., road markings and traffic signs), as well as cognitive innate tendencies-based coding strategies that may be less affected by cultural differences (i.e., directional motion-based and anthroporphized-based).

The aim is to determine which approach more effectively facilitates intuitive communication, understanding, safety, AV acceptance, and decision-making across cultures, identifying oportunites for the standardization of eHMIs. Additionally, the VR methodology is improved by including more uninvolved traffic participants and introducing visual and auditory noise to better simulate real-world, high-traffic environments. Objective measures, such as gaze time, will also be incorporated to provide a more comprehensive understanding of eHMI effectiveness in diverse traffic contexts.

| Table 5

Descriptive Statistics for the subjective measure of Intuitive Comprehension.

			Symbol	Anthro	Color	Descend	Ascend	No Color	Demo	Average
China	Pedestrian	EMM	6.13	6.20	5.90	5.53	5.37	5.07	4.97	5.60
		SE	0.18	0.24	0.30	0.28	0.28	0.27	0.27	0.16
		CI_L	5.76	5.72	5.31	4.96	4.80	4.54	4.43	5.27
		CI_U	6.50	6.68	6.49	6.10	5.94	5.60	5.51	5.92
	Driver	EMM	5.90	6.33	5.47	5.87	5.77	5.10	5.67	5.73
		SE	0.22	0.28	0.32	0.28	0.27	0.33	0.30	0.16
		CI_L	5.46	5.77	4.82	5.30	5.23	4.44	5.06	5.41
		CI_U	6.34	6.90	6.11	6.43	6.30	5.76	6.27	6.05
	Average	EMM	6.02	6.27	5.68	5.70	5.57	5.08	5.32	5.66
		SE	0.15	0.23	0.27	0.25	0.24	0.26	0.24	0.15
		CI_L	5.72	5.81	5.14	5.21	5.09	4.57	4.84	5.36
		CI_U	6.32	6.72	6.23	6.19	6.04	5.60	5.80	5.96
Germany	Pedestrian	EMM	6.11	5.37	4.93	3.67	3.59	2.19	1.85	3.96
		SE	0.19	0.25	0.31	0.30	0.30	0.28	0.28	0.17
		CI_L	5.72	4.87	4.30	3.07	2.99	1.63	1.28	3.61
		CI_U	6.50	5.87	5.55	4.27	4.19	2.75	2.42	4.30
	Driver	EMM	6.07	3.44	4.15	3.89	3.85	3.67	3.74	4.12
		SE	0.23	0.30	0.34	0.30	0.28	0.35	0.32	0.17
		CI_L	5.61	2.85	3.47	3.30	3.29	2.97	3.10	3.78
		CI_U	6.54	4.04	4.83	4.48	4.42	4.36	4.38	4.45
	Average	EMM	6.09	4.41	4.54	3.78	3.72	2.93	2.80	4.04
		SE	0.16	0.24	0.29	0.26	0.25	0.27	0.25	0.16
		CI_L	5.78	3.93	3.96	3.26	3.22	2.38	2.29	3.72
		CI_U	6.41	4.89	5.11	4.30	4.22	3.47	3.30	4.35
Average	Pedestrian	EMM	6.12	5.79	5.41	4.60	4.48	3.63	3.41	4.78
		SE	0.13	0.17	0.22	0.21	0.21	0.19	0.20	0.12
		CI_L	5.85	5.44	4.98	4.19	4.07	3.24	3.02	4.54
		CI_U	6.39	6.13	5.84	5.01	4.89	4.01	3.80	5.01
	Driver	EMM	5.99	4.89	4.81	4.88	4.81	4.38	4.70	4.92
		SE	0.16	0.20	0.23	0.20	0.19	0.24	0.22	0.12
		CI_L	5.67	4.48	4.34	4.47	4.42	3.90	4.26	4.69
		CI_U	6.31	5.30	5.28	5.29	5.20	4.86	5.14	5.15
	Average	EMM	6.05	5.34	5.11	4.74	4.64	4.00	4.06	NA
		SE	0.11	0.17	0.20	0.18	0.17	0.19	0.17	NA
		CI_L	5.84	5.00	4.71	4.38	4.30	3.63	3.71	NA
		CI_U	6.27	5.67	5.51	5.10	4.99	4.38	4.40	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

| Table 6

Descriptive Statistics for the subjective measure of Understanding of Autonomous Vehicles.

			Symbol	Anthro	Color	Descend	Ascend	No Color	Demo	Average
China	Pedestrian	EMM	6.17	6.17	5.80	5.33	5.43	5.03	5.00	5.56
		SE	0.21	0.25	0.27	0.25	0.31	0.25	0.25	0.17
		CI_L	5.76	5.68	5.26	4.83	4.82	4.53	4.50	5.22
		CI_U	6.58	6.66	6.34	5.83	6.05	5.54	5.50	5.91
	Driver	EMM	5.93	6.07	5.07	6.00	5.93	5.07	5.60	5.67
		SE	0.24	0.28	0.31	0.24	0.25	0.28	0.29	0.16
		CI_L	5.45	5.50	4.44	5.51	5.44	4.51	5.02	5.34
		CI_U	6.42	6.63	5.69	6.49	6.43	5.63	6.18	6.00
	Average	EMM	6.05	6.12	5.43	5.67	5.68	5.05	5.30	5.61
		SE	0.17	0.23	0.26	0.21	0.25	0.23	0.22	0.16
		CI_L	5.71	5.65	4.91	5.24	5.19	4.59	4.86	5.30
		CI_U	6.39	6.59	5.96	6.10	6.18	5.51	5.74	5.93
Germany	Pedestrian	EMM	5.74	5.04	5.00	3.70	3.85	2.44	1.96	3.96
		SE	0.22	0.26	0.29	0.26	0.32	0.26	0.26	0.18
		CI_L	5.31	4.52	4.43	3.18	3.20	1.92	1.44	3.60
		CI_U	6.17	5.55	5.57	4.23	4.50	2.97	2.49	4.33
	Driver	EMM	5.33	3.63	4.04	3.89	3.33	3.48	2.85	3.79
		SE	0.25	0.30	0.33	0.26	0.26	0.29	0.30	0.17
		CI_L	4.82	3.03	3.38	3.37	2.81	2.89	2.24	3.45
		CI_U	5.84	4.23	4.70	4.41	3.86	4.07	3.46	4.14
	Average	EMM	5.54	4.33	4.52	3.80	3.59	2.96	2.41	3.88
		SE	0.18	0.25	0.27	0.23	0.26	0.24	0.23	0.16
		CI_L	5.17	3.84	3.97	3.34	3.07	2.48	1.94	3.55
		CI_U	5.90	4.83	5.07	4.25	4.11	3.45	2.87	4.21
Average	Pedestrian	EMM	5.95	5.60	5.40	4.52	4.64	3.74	3.48	4.76
		SE	0.15	0.18	0.20	0.18	0.22	0.18	0.18	0.12
		CI_L	5.66	5.24	5.01	4.16	4.20	3.37	3.12	4.51
		CI_U	6.25	5.96	5.79	4.88	5.09	4.10	3.85	5.01
	Driver	EMM	5.63	4.85	4.55	4.94	4.63	4.27	4.23	4.73
		SE	0.18	0.21	0.23	0.18	0.18	0.20	0.21	0.12
		CI_L	5.28	4.44	4.10	4.59	4.27	3.87	3.81	4.49
		CI_U	5.98	5.26	5.01	5.30	5.00	4.68	4.64	4.97
	Average	EMM	5.79	5.22	4.98	4.73	4.64	4.01	3.85	NA
		SE	0.12	0.17	0.19	0.16	0.18	0.17	0.16	NA
		CI_L	5.54	4.88	4.60	4.42	4.28	3.67	3.53	NA
		CI_U	6.04	5.57	5.36	5.04	5.00	4.34	4.18	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

| *Table 7*

Descriptive Statistics for the subjective measure of Feeling of Safety.

			Symbol	*Anthro*	*Color*	*Descend*	*Ascend*	*No Color*	*Demo*	*Average*
China	**Pedestrian**	*EMM*	5.97	6.13	6.10	5.60	5.47	5.23	5.13	5.66
		SE	0.21	0.25	0.26	0.25	0.28	0.26	0.24	0.16
		CI_L	5.54	5.64	5.57	5.11	4.91	4.72	4.65	5.34
		CI_U	6.40	6.63	6.63	6.09	6.03	5.75	5.62	5.99
	Driver	*EMM*	5.80	6.07	5.43	6.00	6.03	5.20	5.50	5.72
		SE	0.25	0.28	0.29	0.23	0.23	0.28	0.27	0.17
		CI_L	5.30	5.51	4.86	5.53	5.57	4.63	4.95	5.39
		CI_U	6.30	6.63	6.01	6.47	6.49	5.77	6.05	6.05
	Average	*EMM*	5.88	6.10	5.77	5.80	5.75	5.22	5.32	5.69
		SE	0.18	0.23	0.24	0.20	0.21	0.22	0.22	0.15
		CI_L	5.52	5.64	5.28	5.39	5.32	4.77	4.87	5.39
		CI_U	6.25	6.56	6.26	6.21	6.18	5.66	5.76	5.99
Germany	**Pedestrian**	*EMM*	5.56	4.96	4.89	3.63	3.85	2.52	2.37	3.97
		SE	0.23	0.26	0.28	0.26	0.29	0.27	0.26	0.17
		CI_L	5.10	4.44	4.34	3.11	3.26	1.97	1.86	3.62
		CI_U	6.01	5.48	5.44	4.15	4.44	3.06	2.88	4.31
	Driver	*EMM*	5.30	3.56	4.15	4.07	3.81	3.74	3.33	3.99
		SE	0.27	0.29	0.30	0.25	0.24	0.30	0.29	0.17
		CI_L	4.76	2.97	3.54	3.58	3.33	3.14	2.76	3.65
		CI_U	5.83	4.15	4.76	4.57	4.30	4.34	3.91	4.34
	Average	*EMM*	5.43	4.26	4.52	3.85	3.83	3.13	2.85	3.98
		SE	0.19	0.24	0.26	0.21	0.22	0.24	0.23	0.16
		CI_L	5.04	3.78	4.00	3.42	3.38	2.66	2.39	3.67
		CI_U	5.81	4.74	5.03	4.28	4.28	3.60	3.32	4.30
Average	**Pedestrian**	*EMM*	5.76	5.55	5.49	4.61	4.66	3.88	3.75	4.82
		SE	0.16	0.18	0.19	0.18	0.20	0.19	0.18	0.12
		CI_L	5.45	5.19	5.11	4.26	4.25	3.50	3.40	4.58
		CI_U	6.07	5.91	5.88	4.97	5.07	4.25	4.11	5.05
	Driver	*EMM*	5.55	4.81	4.79	5.04	4.92	4.47	4.42	4.86
		SE	0.18	0.20	0.21	0.17	0.17	0.21	0.20	0.12
		CI_L	5.18	4.40	4.37	4.70	4.59	4.06	4.02	4.62
		CI_U	5.91	5.22	5.21	5.38	5.26	4.89	4.81	5.10
	Average	*EMM*	5.65	5.18	5.14	4.83	4.79	4.17	4.08	*NA*
		SE	0.13	0.17	0.18	0.15	0.15	0.16	0.16	*NA*
		CI_L	5.39	4.85	4.79	4.53	4.48	3.85	3.76	*NA*
		CI_U	5.92	5.51	5.50	5.12	5.10	4.50	4.41	*NA*

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

| *Table 8*

Descriptive Statistics for the subjective measure of Acceptance of Autonomous Vehicles.

			Symbol	*Anthro*	*Color*	*Descend*	*Ascend*	*No Color*	*Demo*	*Average*
China	**Pedestrian**	*EMM*	5.90	6.13	5.83	5.43	5.30	5.03	5.03	5.52
		SE	0.23	0.29	0.28	0.25	0.29	0.27	0.26	0.18
		CI_L	5.43	5.55	5.27	4.94	4.71	4.48	4.50	5.17
		CI_U	6.37	6.71	6.40	5.93	5.89	5.58	5.56	5.88
	Driver	*EMM*	5.60	5.90	5.17	5.80	5.77	4.97	5.40	5.51
		SE	0.26	0.30	0.32	0.26	0.25	0.27	0.30	0.18
		CI_L	5.09	5.31	4.53	5.28	5.27	4.42	4.80	5.16
		CI_U	6.11	6.49	5.80	6.32	6.26	5.51	6.00	5.87
	Average	*EMM*	5.75	6.02	5.50	5.62	5.53	5.00	5.22	5.52
		SE	0.19	0.26	0.26	0.20	0.23	0.24	0.25	0.16
		CI_L	5.36	5.50	4.97	5.21	5.06	4.53	4.72	5.19
		CI_U	6.14	6.54	6.03	6.02	6.00	5.47	5.71	5.85
Germany	**Pedestrian**	*EMM*	5.59	5.00	4.81	3.37	3.56	2.26	1.93	3.79
		SE	0.25	0.30	0.30	0.26	0.31	0.29	0.28	0.19
		CI_L	5.10	4.39	4.22	2.85	2.93	1.68	1.37	3.41
		CI_U	6.08	5.61	5.41	3.89	4.18	2.84	2.48	4.17
	Driver	*EMM*	5.37	3.37	3.93	3.96	3.56	3.37	3.11	3.81
		SE	0.27	0.31	0.33	0.27	0.26	0.29	0.31	0.19
		CI_L	4.83	2.74	3.26	3.41	3.04	2.80	2.48	3.44
		CI_U	5.91	4.00	4.59	4.51	4.08	3.94	3.74	4.18
	Average	*EMM*	5.48	4.19	4.37	3.67	3.56	2.81	2.52	3.80
		SE	0.21	0.27	0.28	0.21	0.25	0.25	0.26	0.17
		CI_L	5.07	3.64	3.81	3.24	3.06	2.32	2.00	3.45
		CI_U	5.89	4.73	4.93	4.10	4.05	3.31	3.04	4.14
Average	**Pedestrian**	*EMM*	5.75	5.57	5.32	4.40	4.43	3.65	3.48	4.66
		SE	0.17	0.21	0.20	0.18	0.21	0.20	0.19	0.13
		CI_L	5.41	5.15	4.92	4.04	4.00	3.25	3.10	4.40
		CI_U	6.08	5.99	5.73	4.76	4.86	4.05	3.86	4.92
	Driver	*EMM*	5.49	4.64	4.55	4.88	4.66	4.17	4.26	4.66
		SE	0.19	0.22	0.23	0.19	0.18	0.20	0.22	0.13
		CI_L	5.11	4.20	4.09	4.50	4.30	3.77	3.82	4.41
		CI_U	5.86	5.07	5.01	5.26	5.02	4.56	4.69	4.92
	Average	*EMM*	5.62	5.10	4.94	4.64	4.54	3.91	3.87	*NA*
		SE	0.14	0.19	0.19	0.15	0.17	0.17	0.18	*NA*
		CI_L	5.33	4.72	4.55	4.35	4.20	3.56	3.51	*NA*
		CI_U	5.90	5.48	5.32	4.94	4.88	4.25	4.23	*NA*

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

4.

Identifying Learned vs. Innate Message Coding

Some cues are instinctual. You hear a loud honk, and you immediately turn to locate the source. You see someone smile, and you instinctively know you are on the same page. These reactions are hardwired into us as humans and how we navigate traffic. Yet, many of the signals we rely on are learned behaviors, shaped by experience and context. A pedestrian might not instinctively understand a flashing display on an AV but could quickly learn to interpret it with enough exposure.

This chapter shifts focus from message coding to the broader question of whether learned or instinctively designed visualizations are more effective for eHMIs. Should we rely on instinctive cues that tap into human responses, such as flashing lights or rapid movement to grab attention? Or should we expect road users to learn how to interpret new visualizations in the traffic context? Understanding the balance between instinct and learned behavior is crucial to designing eHMIs that are both intuitive and effective.

By comparing both innate and learned approaches, we aim to determine which type of visualization is most effective in making AVs predictable and understandable. The goal is to create eHMI systems that seamlessly integrate AVs into human-driven traffic, ensuring clear communication and improving safety for all road users.

4.1.
Introduction

To enable Autonomous Vehicles (AVs) to communicate with encountered Human Road Users (HRUs), external Human-Machine Interfaces (eHMIs) are designed. These systems aim to improve the understanding of the vehicle's behavior and intentions. Without eHMIs, HRUs struggle to understand the actions and behavior of AVs, resulting in accidents and disrupted traffic flow *(Brill et al., 2023; Dietrich et al., 2018; Papadoulis et al., 2019; Rasouli & Tsotsos, 2020; Rothenbucher et al., 2016)*. However, designing effective eHMIs is challenging as different HRUs across diverse cultural contexts, have varying preferences for eHMI solutions *(Colley & Rukzio, 2020)*.

Several studies have investigated different communication modalities and message coding designs for eHMIs, examining elements such as text *(Bazilinskyy, Kooijman, Dodou, & Winter, 2021; Lim & Kim, 2022; Yamin & Park, 2023)*, symbols *(Bazilinskyy, Dodou, & Winter, 2019; Hudson, Deb, Carruth, McGinley, & Frey, 2019; Lim & Kim, 2022; Löcken, Wintersberger, Frison, & Riener, 2019; Wesseling, Mugge, van Grondelle, & Othersen, 2020)*, and anthropomorphized information *(Lim & Kim, 2022; Mahadevan, Somanath, & Sharlin, 2018)*. Overall, prior research suggests that explicit visual eHMIs can help AVs compensate for the lack of driver cues, improving the interaction experience between HRUs and the vehicle *(Deb et al., 2016; Dou et al., 2021; Mahadevan et al., 2018a)*. However, most existing studies focus on evaluating specific eHMI concepts in isolation, without comparing the relative effectiveness of different design strategies *(Ackermann et al., 2019; Clamann et al., 2017; Fridman et al., 2017; Rasouli & Tsotsos, 2020)*. With the growing demand for harmonized eHMIs and the introduction of overarching design guidelines, there is a pressing need for systematic and comprehensive comparisons of various eHMI coding alternatives based on subjective and objective measures measuring the effectiveness of eHMIs *(Wilbrink et al., 2023)*. These comparisons are crucial for identifying the most effective strategies to meet the needs of diverse HRUs, especially in cross-cultural contexts.

4.1.1.
Learned-based eHMIs

A significant portion of research on eHMIs has focused on learned representations—communication cues familiar through cultural exposure and traffic conventions, such as symbols, color codes, and gestures. Traffic lights, pedestrian signals, and vehicle indicators (i.e., blinkers) are examples of such learned cues, recognized based on cultural norms and prior experience. The effectiveness of these symbols is often explained by research suggesting that processing speed and accuracy improve when information is presented within familiar contexts *(Joubert et al., 2008; Nicholls et al., 2023; Wischnewski & Peelen, 2021)*. For instance, a red traffic light universally signals the need to stop, while a green traffic light signals the opposite, fostering an intuitive understanding that facilitates smoother traffic flow.

In the context of eHMI coding strategy, these learned representations are commonly conveyed through visual cues in display-based eHMIs, which utilize widely recognized symbols (e.g., arrows, pedestrian icons). Symbol-based eHMIs have been shown to transcend language barriers, ensuring recognition across cultures, and enhancing legibility from greater distances *(Bazilinskyy et al., 2019; Hudson et al., 2019; Lim & Kim, 2022; Löcken et al., 2019)*. Studies indicate a preference for symbol-based designs, as they are perceived as more intuitive, clearer, and faster in aiding decision-making, especially among pedestrians *(Lyu et al., 2024)*. Additionally, such eHMIs have been found to minimize visual demand, improving crossing times and enhancing pedestrian safety *(Lyu et al., 2024)*. However, most of these solutions primarily focus on traffic signs as the basis for symbol-based eHMIs, overlooking the potential of other traffic-related symbols, such as road markings, as viable alternatives.

Regardless, the reliance on learned representations may have limitations, especially in a global context. Such designs risk misinterpretation when road users come from diverse cultural backgrounds or lack familiarity with specific traffic systems. These differences stem from distinct cultural interpretations of symbols, colors, patterns, and cognitive styles *(Alexander et al., 2017; Rasouli & Tsotsos, 2020; Zhang & Zhang, 2019)*. In other words, the success of these learned representation-based designs is largely contingent on prior exposure, which may restrict their universality and effectiveness across diverse populations. Given that the primary objective of eHMIs is to enhance communication, it is not surprising that existing research underscores the crucial role of cultural considerations in eHMI coding strategy *(Lanzer et al., 2020; Wesseling et al., 2020)*. This raises the question of whether alternative design strategies exist that rely on more universal cognitive principles rather than culturally learned representations.

4.1.2.
Innate-based eHMIs

Designing eHMI relying on innate knowledge, or universal cognitive innate tendencies, may offer an alternative approach. These tendencies are rooted in innate human cognitive mechanisms, such as facial expression recognition, motion perception, and the understanding of common fate (the instinct to perceive objects that move together as related) *(Chalbi et al., 2019; Ye et al., 2021)*. These processes are universal, enabling humans to instinctively recognize emotions, predict movements, and interpret non-verbal cues without relying on prior experience or cultural context. This approach taps into evolutionary psychology, providing communication cues that are intuitive and accessible across cultures. By leveraging these universal cognitive mechanisms, eHMIs can be designed to be universally comprehensible, simplifying AV-road user interactions worldwide.

Research has proposed eHMI coding strategies that rely on anthropomorphized representations, such as a smiling vehicle to indicate yielding in priority negotiation scenarios *(Clercq et al., 2019; Deb et al., 2018; Holländer et al., 2019)*. This approach aligns with established social cues and has been shown to reduce pedestrian stress while increasing confidence and attentiveness *(Verma et al., 2019)*. Additionally, anthropomorphized eHMIs can express neutral states and enhance AV expressiveness *(Cefkin et al., 2019; Clercq et al., 2019; Mahadevan, 2019)*. However, while facial expression recognition is widely shared across cultures, research indicates culture-specific variations in interpretation and recognition accuracy *(Haidt & Keltner, 1999; Schimmack, 1996)*. Studies show that individuals tend to recognize expressions more accurately when posed by members of their own culture, demonstrating an in-group advantage *(Dailey et al., 2010)*. Yet, research also suggests that many facial expressions, such as joy, exhibit strong cross-cultural universality *(Brooks et al., 2024)*. This implies that the effectiveness of anthropomorphized eHMIs could either vary across cultural contexts or remain universal, highlighting the need for further investigation into how universally recognizable the used expressions in eHMI truly are.

Motion-based eHMIs, which capitalize on universal cognitive innate mechanisms like motion perception, have also been explored. Visual motion perception is a fundamental aspect of human survival, hardwired into the brain through specialized neurons in the primary visual cortex that detect motion, allowing humans to track moving objects, anticipate their trajectories, and make quick decisions *(Mather, 2011)*. The ability to interpret motion—whether it is an approaching vehicle or a pedestrian crossing the street—is crucial for human survival, making predictive motion cues a promising foundation for eHMI coding. Leveraging these cognitive mechanisms, LED-based motion eHMIs—such as animated strips or dynamic turn signals—have shown significant potential in improving pedestrian decision-making and reaction times *(Yamin & Park, 2023)*. Research indicates that LED designs—ranging from sweeping light segments to pulsing animations—are effective in conveying vehicle intentions, such as yielding *(Hensch et al., 2019, 2020)*. These motion-based cues,

particularly when depicting directional movement, enhance pedestrian-vehicle interaction success by fostering clearer understanding and quicker reactions *(Bazilinskyy et al., 2022; Lagström & Malmstem Lundgren, 2015)*.

Another important aspect of motion perception is the concept of common fate in Gestalt psychology, which states that objects moving together are perceived as related—a principle that underlies the perception of predictive motion *(Chalbi et al., 2019; Todorovic, 2008; Ye et al., 2021)*. In the context of AVs, predictive motion perception helps road users intuitively understand an AV's trajectory and anticipate its next action. Research suggests that motion perception is not merely a passive response to stimuli but an active, predictive process that evolves dynamically over time, integrating discrete movements into a cohesive gestalt *(Kanai et al., 2007)*. Applying Gestalt principles, particularly emphasizing the perception of dynamic, whole patterns rather than isolated components, further enhances the intuitive understanding of movement and intent *(Gao et al., 2023)*. Regardless of animation style or color scheme, motion-based LED eHMIs leveraging these principles have consistently demonstrated improvements in interaction success *(Mirnig et al., 2021)*.

Both learned representation-based and universal innate tendency-based approaches offer valuable strategies for eHMI coding, each presenting distinct advantages in facilitating AV-human communication. Within each approach, various design options exist, whose effectiveness may vary depending on factors, such as cultural context and the type of road user *(pedestrian or driver)*. Given these variables, it is crucial to systematically investigate and compare these design strategies to identify the most effective solutions for future implementation. Such comparative analyses could contribute to advancing eHMI research and development *(Jafary et al., 2018; Wilbrink et al., 2018)*.

4.1.3.
Aim of the Study

This study compares the effectiveness of two general eHMI coding strategies: learned representation-based designs, which rely on familiar traffic symbols, vehicle behavior and communication strategies, and universal cognitive innate tendency-based designs, which leverage innate human cognitive innate tendencies. Conducted as a cross-cultural study in China and Germany, it examines these strategies in both AV-to-pedestrian and AV-to-driver interactions, which prior research deemed to be crucial factors *(Carmona et al., 2021; Owens et al., 2018; Ranasinghe et al., 2020; Wilbrink et al., 2023)*. The research aims to determine which approach is more effective in facilitating intuitive communication, understanding, perceived safety, AV acceptance, distraction potential, and decision-making.

The findings will inform the development of culturally adaptive and universal eHMIs, identifying where a universal approach is effective and where culturally specific adaptations are desired. Ultimately, this research aims to guide the design of eHMI solutions that enhance communication between AVs and HRUs in diverse traffic environments.

4.2.
Method

The VR study utilized a 2x2x6 mixed design, examining the independent variables of culture *(between-subjects)*, communication partner *(driver vs. pedestrian; within-subjects)*, and eHMI coding strategies *(six eHMI conditions and 1 baseline condition (without eHMI); within-subjects)*.

4.2.1.
Participants

Participants were required to be native-born in China or Germany, with at least 5 years of current residency. To ensure consistency and minimize confounding factors, individuals with color perception or physical impairments were excluded to avoid interference with VR stimuli perception or behavior during traffic simulations. Participants from Chinese and German consumer panels were stratified and randomly sampled for balanced representation.

Six incomplete responses were removed, leaving 77 participants *(28.57% Female, 71.43% Male, 0% Other, 0% 'I prefer not to answer')* with a mean age of 41.04 years *(min = 23; max = 62; SD = 9.76 years)*. The Chinese group had 35 participants *(48.57% Female, 51.43% Male)* with a mean age of 39.54 years *(min = 27; max = 57; SD = 7.67 years)*. The German group comprised 42 participants *(11.90% Female, 88.10% Male)* with a mean age of 42.29 years *(min = 23; max = 62; SD = 11.14 years)*.

4.2.2.
Cultural Context within Virtual Reality

To promote natural behavior in Virtual Reality (VR), the environment replicated either Beijing or Berlin for cultural familiarity *(see Figure 29 - 30, next page)*, ensuring that the comprehension of the communicated information was not affected *(Eisele & Petzoldt, 2022)*. These VR environments were generated in Unity 3D (Version 2019.4.0f1 LTS *(Unity Technologies, 2019)*) with the SteamVR Plugin (Version 2.4.5, SDK 1.7.15 *(Valve Corporation, n.d.)*), the HTC Vive Pro headset and HTC Vive Base Stations. By ensuring uniform acoustic noise, traffic autonomy, weather conditions, initiation locations and start times for the different scenarios, replicability was safeguarded for comparability *(Camara et al., 2020; Colley & Rukzio, 2020; Deb et al., 2018; Holländer et al., 2019; Nuñez Velasco et al., 2019; Pillai, 2017)*.

4.3.
Stimuli

4.3.1.
Communication Partner

This study incorporated a driver cooperation scenario and a pedestrian crossing to investigate the impact of communication partner *(Clamann et al., 2017; Coeugnet-Chevrier, 2019; Dey, Habibovic, Löcken, et al., 2020; Dietrich et al., 2019; Färber, 2016; Lagström & Malmstem Lundgren, 2015; Mahadevan et al., 2018b)*.

In the pedestrian crosswalk scenario, participants had to safely cross the road in front of a yielding autonomous vehicle approaching from the right. Using a jerk-limited profile ($j = -2 / +2\ m/s^3$, $a_{max} = -2\ m/s^2$ *(Dietrich et al., 2020)*), braking started 1 s after scenario onset, decelerating the vehicle from 50 km/h to rest in 7.94 s over 55.2 m, while the initial time-to-collision (TTC) was 3.97 s at constant speed. All eHMIs were activated simultaneously with the deceleration maneuver so not to provide an advantage to the eHMI in comparison to the baseline condition *(Şahin et al., 2021)*.

In the cooperative driving scenario, an AV approaching from the left intended to turn right, encountering the participant's car at an intersection where the participant, without the right of way, was tasked with proceeding straight. To prevent motion sickness, the participant's car remained stationary in VR, and participants sat in a height-adjustable chair for optimal visual clarity *(Vasser*

& Aru, 2020). These traffic situations (see Figure 31) aligned with the behavioral patterns of both traffic cultures, avoiding confusion and encouraging natural behavior (Weber et al., 2019).

| ***Figure 29***

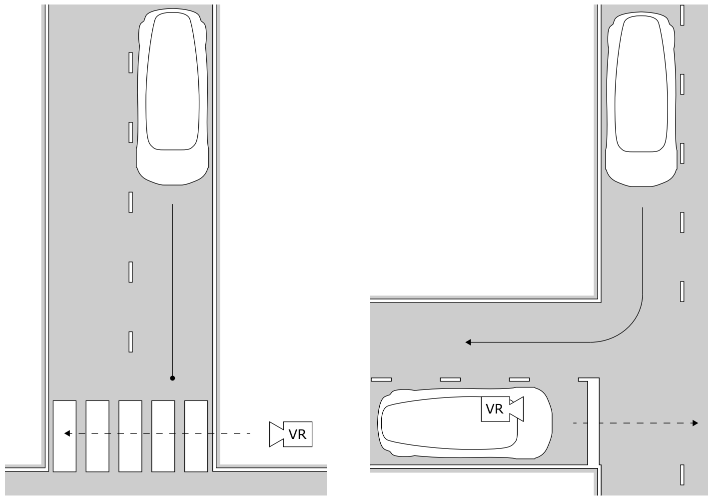
Visualization of the cultural environments of Beijing, China.

| ***Figure 30***

Visualization of the cultural environments of Berlin, Germany.

| ***Figure 31***

The scenarios: (l.t.r.) (1) Pedestrian crosswalk scenario, (2) Cooperative driving scenario.



4.3.2.

Design Strategies for eHMIs

The design strategies explored within this study rely on either (1) learned representations or (2) cognitive innate tendencies. Here, learned representations relied on symbols leveraging familiar traffic signage, requiring prior traffic experience or education (Bazilinskyy, Dodou, & Winter, 2019; Hudson, Deb, Carruth, McGinley, & Frey, 2019; Lim & Kim, 2022; Löcken, Wintersberger, Frison, & Riener, 2019; Wesseling, Mugge, van Grondelle, & Othersen, 2020).

- *Signs:*
  This concept relied on established traffic symbols—such as a pedestrian icon (representing a simplified human figure) and an arrow (mimicking turn indicators and traffic signals). Both symbols were dynamic, with the pedestrian icon animated in a walking motion and the arrow following a rolling movement in line with indicator animations.
- *Echo:*
  This design mimicked road markings, such as crosswalks or curvature lines, dynamically adapting to pedestrian movement by creating a rolling animation relative to the pedestrian and, in the driving scenario, moving together with the dynamic indicator.
- *Minimal:*
  Based on existing LED technologies in vehicles, this design extended turn indicators or pedestrian direction signals through simple motion patterns horizontally. This design was implemented to investigate whether this included technology would provide sufficient support for encountered HRUs (Bazilinskyy et al., 2022; Hensch et al., 2019, 2020; Lagström & Malmstem Lundgren, 2015; Yamin & Park, 2023). As the technologies have already been implemented in vehicles, this option could provide a cost-effective solution for eHMIs if effective.

Cognitive innate tendencies relied on instinctive processing, allowing users to interpret eHMIs without prior knowledge of traffic symbols.

- *Swarm:*
  This concept used abstract motion cues to indicate vehicle intent. A cluster of dots dynamically expanded or contracted to convey movement direction, utilizing fluid motion principles shown to effectively communicate AV intentions (Bazilinskyy et al., 2022; Dey, Temmink, et al., 2021). In other words, the swarm indicated the direction of the pedestrian or intended direction of the vehicle by copying the movement (i.e., Common Fate). Additionally, the spread of the dots increased and

as possible.

- *Retina:*
  Rooted in anthropomorphism, this concept displayed eyes and a mouth. The mouth dynamically transitioned from a neutral expression to a smile, leveraging research suggesting that facial expressions in eHMIs reduce stress, increase confidence, and enhance attention in pedestrians *(Cefkin et al., 2019; Clercq et al., 2019; Mahadevan, 2019; Verma et al., 2019)*.

By comparing these two design approaches, this study aimed to assess their effectiveness across cultural contexts and communication partner types. To exclude confounding factors, these designs *(see Figure 32 and 33)* all relied on the same type of color-coding of green, white and orange as recommended based on prior research and to complement, rather than replace, established communication practices in traffic (e.g., blinkers) *(Bazilinskyy et al., 2020, 2021; Dey, Habibovic, Pfleging, et al., 2020; Shmueli & Degani, 2023)*. Moreover, the eHMI was integrated in the bumper of the vehicle to align with scanning patterns of HRUs *(Bindschädel et al., 2022a)*.

4.3.3.

Measures & Procedure

As the study involved human participants, ethical approval was obtained, and relevant guidelines were followed. Participants received an introduction statement, privacy policy, data security details, and a voluntary consent form before participation. After providing consent, participants completed a demographic survey (e.g., gender, age) and were introduced to a culturally relevant virtual environment, allowing unlimited time to familiarize themselves with VR environment.

Participants then engaged in a randomized traffic scenario after receiving context explanations and task instructions. In the pedestrian scenario, participants started from a standardized position and crossed the road when comfortable. Decision time was not recorded due to the cognitive load of VR navigation. In the driver scenario, participants could adjust their chair according to their preferences. Participants were then tasked with pressing the spacebar when ready to drive, recording decision time. Here, decision time was relied on to measure the time needed for continuous perception, comprehension, and projection of environmental elements as these cognitive processes occur within decision-making (Endsley, 2016).

| ***Figure 32***

Concepts for pedestrian scenario plotted on the design directions of visualization and representation, including the baseline condition (bottom middle).

| ***Figure 33***

Concepts for driver scenario plotted on the design directions of visualization and representation, including the baseline condition (bottom middle).

The virtual environment autonomously recorded gaze time on the AV and its eHMI using collision events, which were triggered by head rotation and position, rather than eye-tracking, due to VR headset limitations. Only the central field of view was in focus to encourage head movement over peripheral vision reliance. Gaze time was recorded to investigate the distraction potential of the eHMI, with higher gaze time indicating significant and fluctuating cognitive workload demands *(Baldwin & Coyne, 2005; Habibovic et al., 2018; Verwey, 2000; Wickens, 2002, p. 20)*, which, amidst the anonymity and transience of traffic, causes negative effects such as distraction, insufficient processing time, and inaccurate perceptions *(Silva, 2014)*. In other words, the total gaze time captures the total time the AV and its eHMI are looked at in the encountered scenario, comparing it with the gaze time of the baseline condition, aiming to not increase gaze time significantly.

Participants completed all six conditions *(five eHMI concepts + baseline)* in random order for both traffic scenarios. After each condition, participants rated four statements on a 7-point Likert scale *(1 = Completely disagree, 7 = Completely agree)*, assessing perceived safety, user acceptance, and AV understanding which are considered important measures for assessing eHMI effectiveness *(Ackermann et al., 2019; Clamann et al., 2017; Coeugnet-Chevrier, 2019; Färber, 2016; Habibovic et al., 2018; Mahadevan et al., 2018a; Nastjuk et al., 2020; Oidekivi et al., 2021)*:

- This concept communicates in an intuitive manner.
- This concept improves my understanding of the autonomous vehicle.
- This concept would make me feel safer in traffic.
- I would accept autonomous vehicles more quickly if they implemented this concept.

After completing all conditions, participants ranked the eHMI concepts and could provide open feedback, resulting in a total study duration of 45–60 minutes per participant.

4.3.4.

Statistical Analyses

Analyses were conducted with R (v4.1.3) using various packages *(R Core Team, 2021b)*. For the subjective measures, ANOVAs for factorial designs were performed with the *afex* package calculating generalized eta-squared (η_G^2), using Type III Sum of Squares and Greenhouse-Geisser correction *(Singmann et al., 2021)*. Post-hoc pairwise comparisons were adjusted for multiplicity with Tukey HSD via the *multcomp* package *(Hothorn et al., 2008)*. Ranking scores were analyzed with the pmr packagem, employing Friedman Rank Sum Test and Dunn's Test from the *stats* and *rstatix* packages *(Kassambara, 2021; Lee & Yu, 2013; R Core Team, 2021a)*.

4.4.

Results

4.4.1.

Self-reported Evaluations

Three-way mixed ANOVAs were completed for each self-reported variable with Culture *(between-subject)*, Communication Partner *(within-subject)*, and Coding Strategy *(within-subject)* as fixed effects, and participant number *(No.)* nested within Coding Strategy and Communication Partner as the random effect. All descriptive statistics for the self-reported evaluations can be found at the end of this chapte *(see Table 16 - 19)*.

Main Effect of Culture

A significant effect was observed for intuitive comprehension ($F(1, 75) = 16.45, p < .001, \eta_G^2 = .056$), understanding of AV ($F(1, 75) = 14.56, p < .001, \eta_G^2 = .06$), perceived safety ($F(1, 75) = 13.13, p < .001, \eta_G^2 =.05$) and acceptance of AVs ($F(1, 75) = 18.90, p < .001, \eta_G^2 = .08$). The Chinese participants consistently evaluated the concepts more positively than German participants across all measures *(see Table 9)*.

Main Effect of Coding Strategy

The main effect for concept was significant for intuitive comprehension ($F(4.17, 312.74) = 30.22, p < .001, \eta_G^2 = .13$), AV understanding ($F(4.03, 302.43) = 32.04, p < .001, \eta_G^2 = .12$), perceived safety ($F(4.01, 300.37) = 33.55, p < .001, \eta_G^2 = .13$), and AV acceptance ($F(4.12, 308.96) = 32.37, p < .001, \eta_G^2 = .12$).

Post-hoc tests revealed significant differences from the baseline. The "Echo" and "Signs" concepts consistently received higher ratings across all self-reported evaluations *(see Figure 34)*. In contrast, the "Swarm" concept scored significantly lower than the baseline on intuitive comprehension ($p = .023$), perceived safety ($p < .001$), and AV acceptance ($p = .013$).

| *Table 9*

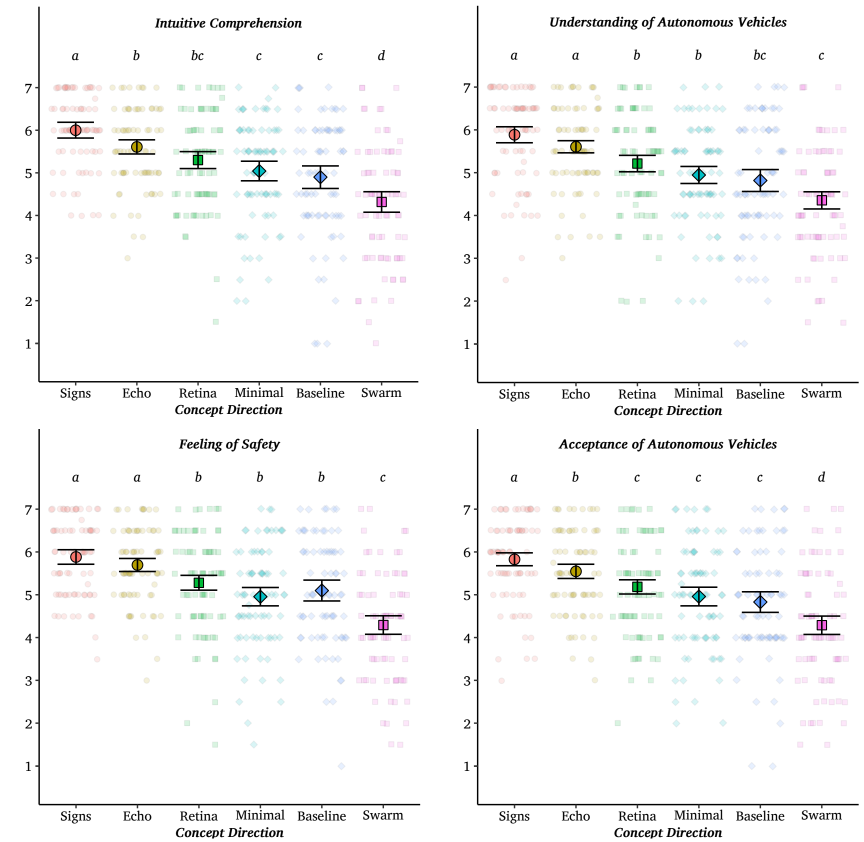
Descriptive Statistics of all subjective measures' ratings for the main effect of Culture.

	China			Germany			
	EMM	*SE*	*95% CI*	*EMM*	*SE*	*95% CI*	*Sig.*
Intuitive Comprehension	5.52	0.12	5.29; 5.76	4.86	0.11	4.64; 5.08	< .001
AV Understanding	5.48	0.14	5.21; 5.75	4.78	0.13	4.52; 5.03	< .001
Perceived Safety	5.51	0.13	5.26; 5.77	4.89	0.12	4.65; 5.12	< .01
AV Acceptance	5.51	0.14	5.24; 5.78	4.71	0.12	4.46; 4.95	< .001

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, Sig. = Significance (p)

| *Figure 34*

Main Effect of Message Coding for Intuitive Comprehension (UL), Understanding of Autonomous Vehicles (UR), Feeling of Safety (LL), and Acceptance of Autonomous Vehicles (LR).



Note: The graphs are displaying Estimated Marginal Means with Standard Errors and post-hoc grouping letters based on Tukey's Honestly Significant Difference (HSD).

Main Effect of Communication Partner

No significant main effect of communication partner was observed for intuitive comprehension *($F(1, 75) = 0.88, p = .350, \eta_G^2 < .01$)* or AV acceptance *($F(1, 75) = 3.38, p = .070, \eta_G^2 < .01$)*. In contrast, significant main effects emerged for AV understanding *($F(1, 75) = 4.76, p = .032, \eta_G^2 = .01$)* and perceived safety *($F(1, 75) = 8.08, p = .006, \eta_G^2 = .01$)*. Here, the pedestrian scenario received significantly higher ratings than the driver scenario for both measures *(see Table 10)*.

| *Table 10*

Descriptive Statistics of all subjective measures' ratings for the main effect of Communication Partner.

	Driver			Pedestrian			
	EMM	*SE*	*95% CI*	*EMM*	*SE*	*95% CI*	*Sig.*
AV Understanding	5.02	0.10	4.80; 5.25	5.25	0.10	5.04; 5.46	.032
Perceived Safety	5.07	0.10	4.87; 5.26	5.33	0.10	5.14; 5.53	.005

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, Sig. = Significance (p)

Interaction Effect between Culture and Coding Strategy

An Interaction Effect between Culture and Coding Strategy emerged for intuitive comprehension *($F(4.17, 312.74) = 5.32, p < .001, \eta_G^2 = .03$)*, AV understanding *($F(4.03, 302.43) = 4.37, p < .001, \eta_G^2 = .02$)*, perceived safety *($F(4.01, 300.37) = 3.22, p = .013, \eta_G^2 = .01$)*, and AV acceptance *($F(4.12, 308.96) = 5.28, p < .001, \eta_G^2 = .03$)* *(see Figures 35-38).*

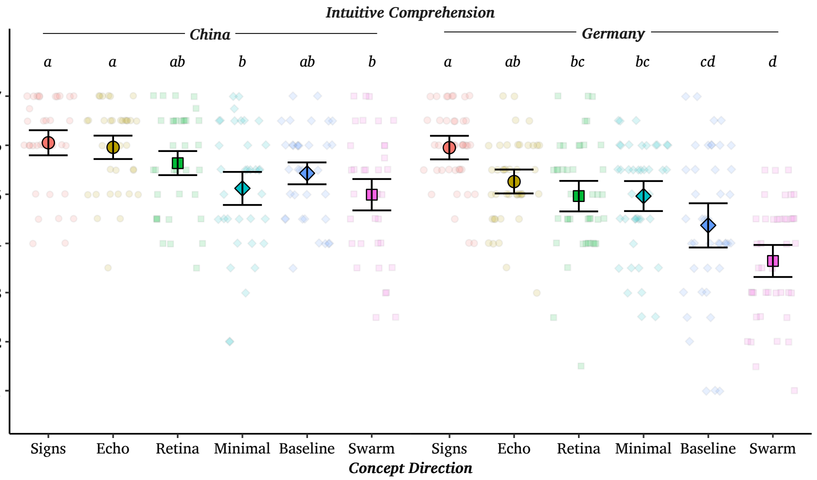
For the German subsample, self-reported evaluations consistently showed a positive effect for the "Echo" and "Signs" concepts compared to the baseline across all measures—intuitive comprehension *($p = .003, p < .001$)*, AV understanding *($p < .001, p < .001$)*, perceived safety *($p = .025, p < .001$)* and AV acceptance *($p = .001, p < .001$)*. In contrast, the "Swarm" concept negatively impacted the perceived safety relative to the baseline *($p = .003$)*. No significant differences were observed in the Chinese subsample when comparing any concept to the baseline.

Interaction Effect between Culture and Communication Partner

No interaction effect was found for intuitive comprehension *($F(1, 75) = 0.01, p = .915, \eta_G^2 < .01$)*, AV understanding *($F(1, 75) = 0.47, p = .493, \eta_G^2 < .01$)*, perceived safety *($F(1, 75) = 0.05, p = .824, \eta_G^2 < .01$)*, or AV acceptance *($F(1, 75) < 0.001, p = .978, \eta_G^2 < .01$)*.

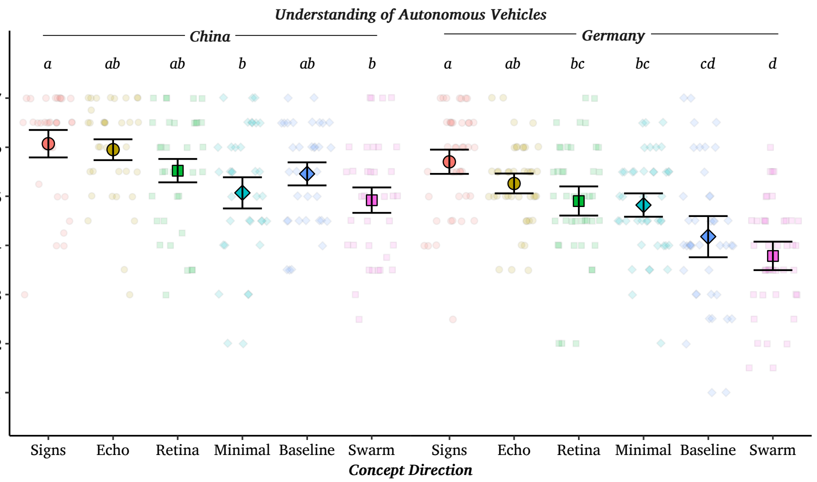
| Figure 35

Interaction Effect between Culture and Message Coding for Intuitive Comprehension.



| Figure 36

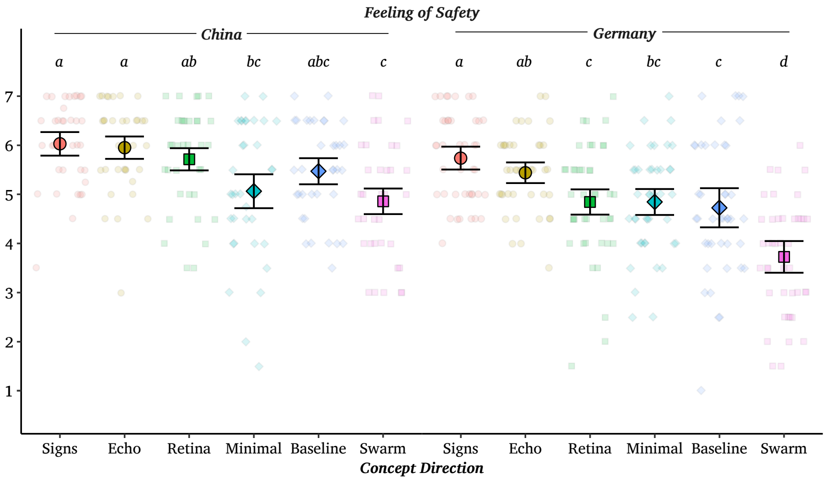
Interaction Effect between Culture and Message Coding for Understanding of Autonomous Vehicles.



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

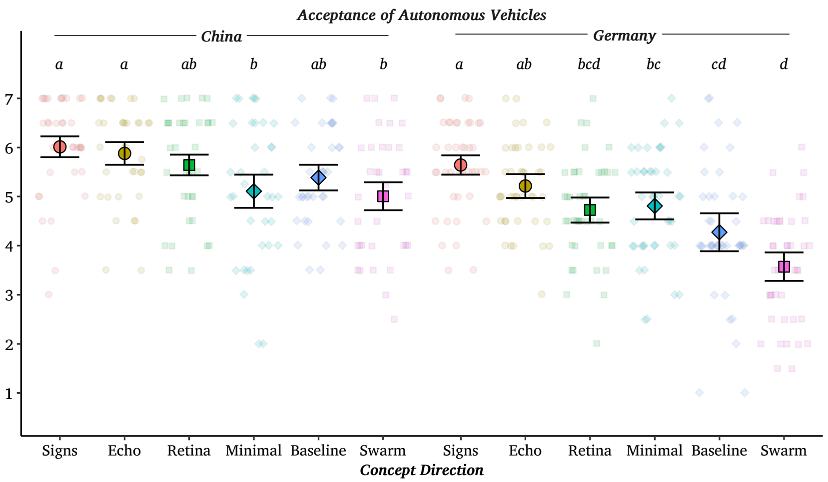
| Figure 37

Interaction Effect between Culture and Message Coding for Feeling of Safety.



| Figure 38

Interaction Effect between Culture and Message Coding for Acceptance of Autonomous Vehicles.



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

Interaction Effect between Communication Partner and Coding Strategy

A significant interaction effect between Communication Partner and Coding Strategy existed for intuitive comprehension $(F(4.58, 343.59) = 22.31, p < .001, \eta_G^2 = .07)$, AV understanding $(F(4.52, 338.77) = 23.33, p < .001, \eta_G^2 = .07)$, perceived safety $(F(4.59, 344.17) = 27.57, p < .001, \eta_G^2 = .08)$ and AV acceptance $(F(4.51, 338.16) = 24.06, p < .001, \eta_G^2 = .08)$ (see Figures 39-42).

For the driver level, post-hoc testing revealed a consistent negative impact of "Swarm" compared to the baseline across all self-reported evaluations *(all p < .001)*. The "Echo" concept had the highest positive effect on intuitive comprehension *(p = .033)*, AV understanding *(p = .011)*, perceived safety *(p < .001)*, and AV acceptance *(p < .001)*, surpassing the second-highest rated "Signs". While "Signs" was rated higher than the baseline for intuitive comprehension *(p = .006)* and AV understanding *(p = .049)*, no significant differences were found for perceived safety *(p = .130)* and AV acceptance *(p = .150)*. No other significant differences were observed for the driver level compared to the baseline.

For the pedestrian level, "Signs" received the highest ratings on all self-reported evaluation compared to the baseline *(all p < .001)*. Although "Signs" received the highest ratings, no significant difference was found between it and the second-highest rated "Retina" in any self-reported evaluation—intuitive comprehension *(p = .125)*, AV understanding *(p = .098)*, perceived safety *(p = .557)*, and AV acceptance *(p = .117)*. The "Retina" concept showed improved rating compared to the baseline for intuitive comprehension *(p = .006)*, AV understanding *(p = .003)*, and AV acceptance *(p = .001)*, but not for perceived safety *(p = .086)*. No other significant differences could be observed relative to the baseline.

Figure 39

Interaction Effect between Communication Partner and Coding Strategy for Intuitive Comprehension.

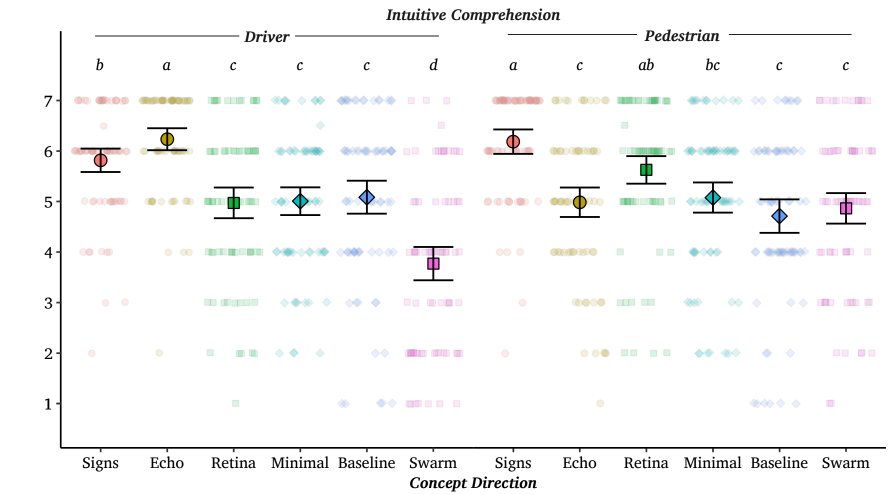
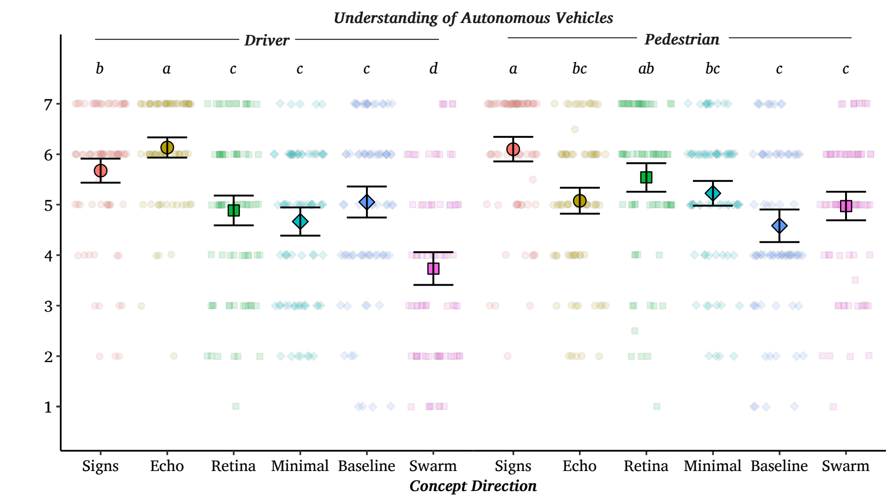


Figure 40

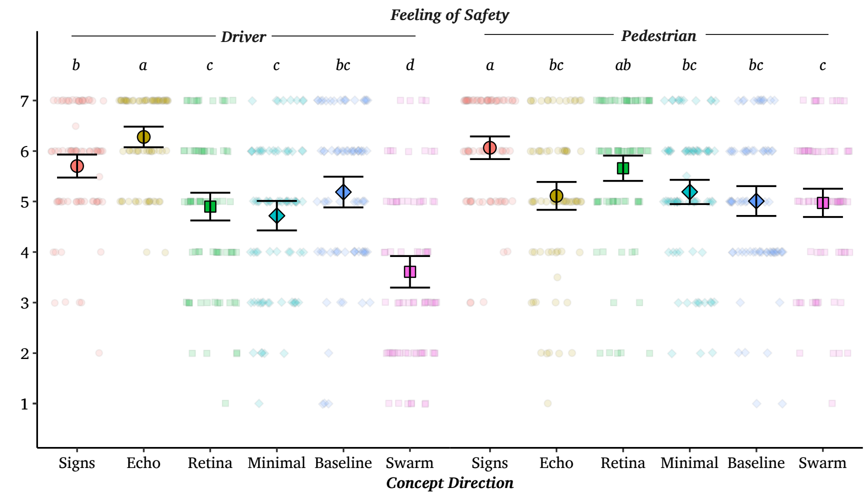
Interaction Effect between Communication Partner and Coding Strategy for Understanding of Autonomous Vehicles.



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

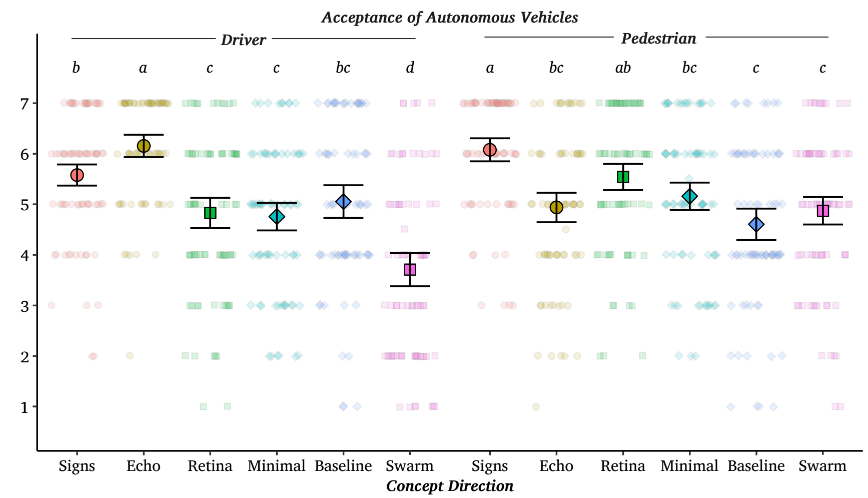
| **Figure 41**

Interaction Effect between Communication Partner and Coding Strategy for Feeling of Safety.



| **Figure 42**

Interaction Effect between Communication Partner and Coding Strategy for Acceptance of Autonomous Vehicles.



Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and post-hoc grouping letters within culture based on Tukey's Honestly Significant Difference (HSD).

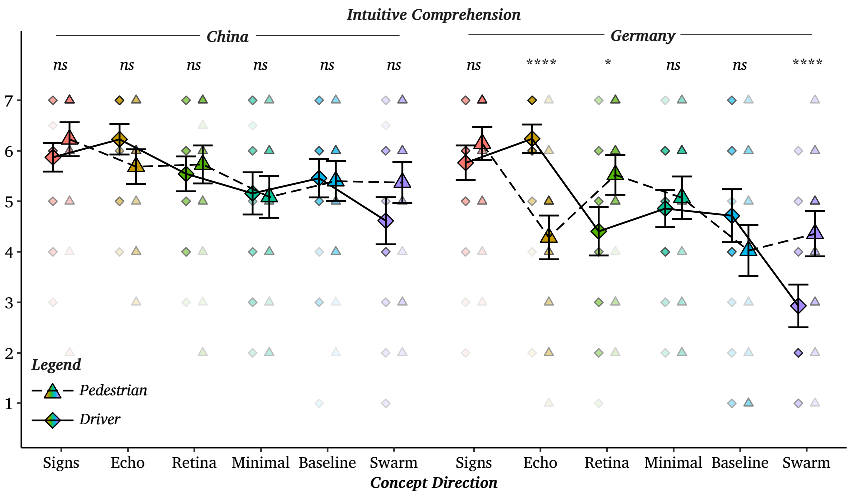
Three-way Interaction Effect

A significant three-way interaction effect was present for intuitive comprehension $(F(4.58, 343.59) = 6.21, p < .001, \eta_G^2 = .02)$, AV understanding $(F(4.51, 338.77) = 6.02, p < .001, \eta_G^2 = .02)$, perceived safety $(F(4.59, 344.17) = 7.85, p < .001, \eta_G^2 = .03)$, and AV acceptance $(F(4.51, 338.16) = 8.54, p < .001, \eta_G^2 = .03)$ *(see Figures 43-46)*.

No significant differences were observed in the Chinese subsample when comparing the concepts between the communication partners (*driver vs pedestrian*). In contrast, significant differences were found in the German subsample. Specifically, the "Echo" concept received significantly higher ratings in the driver role compared to the pedestrian role for all self-reported evaluations (all $p < .001$). In contrast, the ratings of pedestrian were significantly higher compared to driver for "Swarm" (all $p < .001$), and "Retina ($p = .022$, $p = .006$, $p < .001$, $p < .001$ respectively) for intuitive comprehension, AV understanding, perceived safety, and AV acceptance. It must be noted however that although these coding strategies received higher ratings in the pedestrian scenario, the strategies did not significantly differ from the baseline.

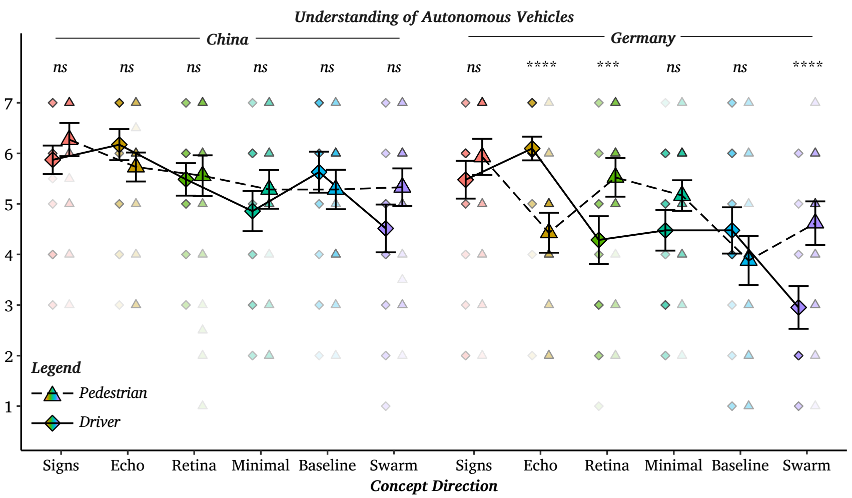
| **Figure 43**

Three-way Interaction Effect between Culture, Communication Partner and Message Coding for Intuitive Comprehension.



| **Figure 44**

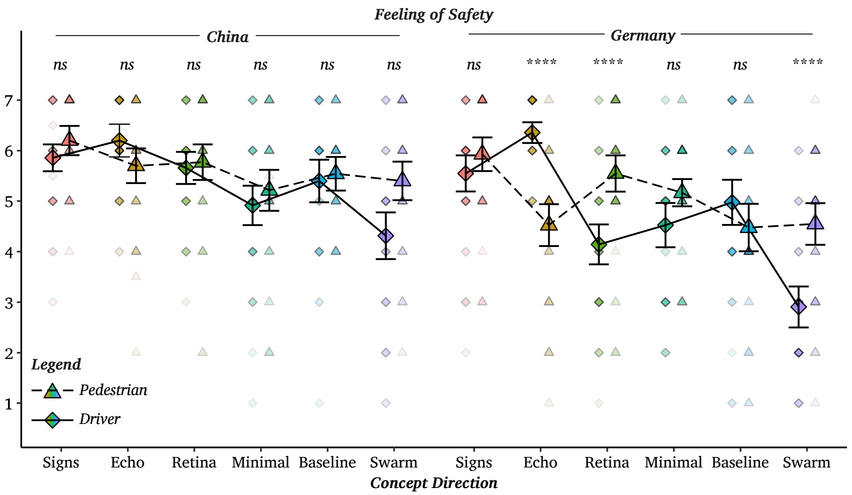
Three-Way Interaction Effect between Culture, Communication Partner and Message Coding for Understanding of Autonomous Vehicles



*Note: The graph is displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

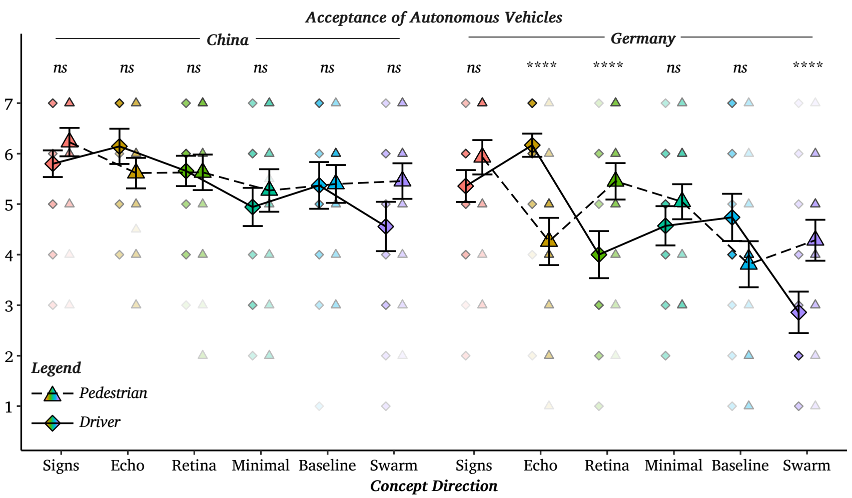
| **Figure 45**

Three-way Interaction Effect between Culture, Communication Partner and Message Coding for Feeling of Safety.



| **Figure 46**

Three-Way Interaction Effect between Culture, Communication Partner and Message Coding for Acceptance of Autonomous Vehicles.



*Note: The graph is displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

4.4.2.

Ranking

Friedman's Test revealed significant differences between the concepts across cultures (p < .001). The significance matrix *(see Table 11)*, based on Dunn's Test, indicates the significant differences between the concepts. The findings showed that both "Signs" (1.74) and "Echo" (2.04) ranked best across the sample. These concepts were followed by "Retina" (2.99), both Swarm (4.24) and Minimal (4.43), and, with Baseline (5.59) ranking last.

The sample ranking order was similar to that of each of the subsamples, although some significant differences between concepts were present. Friedman's Test revealed significant differences in both the Chinese and German subsample *(both p < .001)*. The Dunn's Test results are summarized in significance matrices *(see Table 11)*.

In the Chinese subsample, "Signs" (1.88) and "Echo" (2.08) received the highest rankings, with no significant difference between them. "Retina" (2.70) followed, then both Swarm (4.10) and Minimal (4.33), and lastly the baseline (5.92) ranked lowest. For the German subsample, "Signs" (1.50) and "Echo" (2.00) were again ranked highest. Retina (3.39) and Minimal (4.11) followed, although no significant difference between "Minimal" and "Swarm" could be found. Swarm (4.89) was rated lowest together with the baseline (5.11). In other words, although the ranking scores indicated that culture-specific preferences may exist, based on this study's sample, some universal trends may also exist for these eHMI concepts.

4.4.3.

Objective Measures

The objective measures capture participant behavior in the VR study, including driver decision time and total gaze time in both traffic scenarios. The two-way mixed ANOVA modelled decision and gaze time as dependent variables respectively, with culture *(between-subject)* and concept *(within-subject)* as fixed effects. Participant, nested within concept, was included as random effect.

Table 11

Descriptive Statistics of all subjective rankings within and across cultures.

Across Subsample	*Signs*	*Echo*	*Retina*	*Minimal*	*Swarm*	*Baseline*
(1.72) Signs	–	*ns*	***	****	****	****
(2.04) Echo	*ns*	–	**	****	****	****
(2.99) Retina	***	**	–	***	****	****
(4.24) Minimal	****	****	***	–	*ns*	****
(4.43) Swarm	****	****	****	*ns*	–	**
(5.59) Baseline	****	****	****	****	**	–

China	*Signs*	*Echo*	*Retina*	*Swarm*	*Minimal*	*Baseline*
(1.88) Signs	–	*ns*	****	****	****	****
(2.08) Echo	*ns*	–	**	****	****	****
(2.70) Retina	****	**	–	***	***	****
(4.10) Swarm	****	****	***	–	*ns*	****
(4.33) Minimal	****	****	***	*ns*	–	*
(5.59) Baseline	****	****	****	****	*	–

Germany	*Signs*	*Echo*	*Retina*	*Minimal*	*Swarm*	*Baseline*
(1.50) Signs	–	*ns*	****	****	****	****
(2.00) Echo	*ns*	–	**	****	****	****
(3.39) Retina	****	**	–	*ns*	***	****
(4.11) Minimal	****	****	*ns*	–	*ns*	*
(4.89) Swarm	****	****	***	*ns*	–	*ns*
(5.11) Baseline	****	****	****	*	*ns*	–

*Note: Dunn's Test Star Significance: ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

Driver - Decision Time

The main effect of culture was significant *($F(1, 103) = 74.86$, $p < .001$, $\eta_G^2 = .27$)*, with the Chinese subsample taking 2.20 seconds longer *(EMM = 6.99, SE = 0.18)* than that of the German subsample *(EMM = 4.79, SE = 0.18, p > .001)*. The main effect of concept was also significant *($F(4.52, 465.13) = 7.88$, $p > .001$, $\eta_G^2 = .04$)*, with "Echo," "Signs," and "Retina" significantly improving decision times *(all p < .05)* (see Table 12).

A significant interaction effect between culture and concept was also present *($F(4.52, 465.13) = 10.34$, $p > .001$, $\eta_G^2 = .05$)*. In the Chinese subsample, all concepts improved decision time compared to the baseline *(all p < .001)*, with no significant differences between concepts (see Table 13). For the German subsample, no concepts improved or worsened the decision time compared to the baseline *(all p > .241)*.

Driver – Total Gaze Time

The main effect of culture was significant *($F(1, 104) = 23.90$, $p < .001$, $\eta_G^2 = .15$)*. The Chinese subsample *(EMM = 7.61, SE = 0.20, CI 95% = [7.22; 8.00])* looked at the approaching vehicle 1.38 seconds longer than the German subsample *(EMM = 6.23, SE = 0.20, CI 95% = [5.83; 6.63], p < .001)*.

The main effect of concept was also significant *($F(3.86, 401.60) = 8.35$, $p > .001$, $\eta_G^2 = .02$)*. The concepts of "Minimal", "Retina" and "Swarm" resulted in a significantly higher driver gaze time in comparison to the baseline *(p = .004, p = .001 and p < .001, respectively)* (see Table 14). No other significant differences could be determined. In contrast, no interaction effect between culture and concept existed, $F(3.86, 401.60) = 0.86$, $p = .484$, $\eta_G^2 < .01$.

Pedestrian - Total Gaze Time

The main effect of culture was significant, $F(1, 104) = 5.00$, $p < .027$, $\eta_G^2 = .03$. The average pedestrian gaze time of the Chinese subsample *(EMM = 5.98, SE = 0.25, CI 95% = [5.49; 6.47])* was 0.80 seconds lower than the German subsample *(EMM = 6.77, SE = 0.26, CI 95% = [6.26; 7.28], p > .001)*.

Additionally, a main effect of concept was present *($F(4.44, 462.01) = 4.72$, $p > .001$, $\eta_G^2 = .02$)*. "Minimal" and "Echo" significantly increased the total gaze time compared to the baseline *(p > .001 and p = .049, respectively)*. No other concepts caused significantly different gaze times compared to the baseline (see Table 15). No interaction effect between culture and concept was revealed *($F(4.44, 462.01) = 1.18$, $p = .316$, $\eta_G^2 < .01$)*.

Table 12

Descriptive Statistics of all driver decision time across cultures.

	Across countries			
	EMM	*SE*	*95% CI*	*SG*
Echo	5.42	0.17	5.08; 5.77	a
Signs	5.63	0.17	5.30; 5.96	ab
Retina	5.76	0.15	5.46; 6.07	ab
Minimal	5.89	0.18	5.53; 6.26	abc
Swarm	6.11	0.17	5.76; 6.45	bc
Baseline	6.53	0.22	6.10; 6.97	c

Table 13

Descriptive Statistics of all driver decision time for the interaction effect of Culture and Concept.

	China				Germany			
	EMM	*SE*	*95% CI*	*SG*	*EMM*	*SE*	*95% CI*	*SG*
Echo	4.43	0.24	3.95; 4.90	a	6.42	0.25	5.92; 6.92	a
Signs	4.51	0.23	4.05; 4.96	a	6.76	0.24	6.28; 7.24	ab
Retina	4.28	0.21	3.86; 4.70	a	7.25	0.22	6.81; 7.69	c
Minimal	4.58	0.25	4.08; 5.09	a	7.21	0.27	6.68; 7.74	abc
Swarm	4.70	0.24	4.23; 5.18	a	7.51	0.25	7.01; 8.01	bc
Baseline	6.27	0.30	5.67; 6.87	b	6.80	0.32	6.17; 7.42	abc

Table 14

Descriptive Statistics of all driver total gaze time across cultures.

	Across countries			
	EMM	*SE*	*95% CI*	*SG*
Baseline	6.51	0.17	6.17; 6.85	a
Signs	6.67	0.18	6.33; 7.02	ab
Echo	6.95	0.16	6.64; 7.27	ab
Minimal	7.11	0.15	6.80; 7.41	b
Retina	7.13	0.16	6.81; 7.44	b
Swarm	7.14	0.16	6.81; 7.47	b

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, SG = Significance Grouping (a =5%)

| ***Table 15***

Descriptive Statistics of all pedestrian total gaze time across cultures.

	Across countries			
	EMM	*SE*	*95% CI*	*SG*
Baseline	5.97	0.19	5.59; 6.35	a
Signs	6.05	0.22	5.61; 6.49	ab
Swarm	6.46	0.24	5.98; 6.93	abc
Retina	6.48	0.23	6.04; 6.93	abc
Echo	6.50	0.23	6.05; 6.95	bc
Minimal	6.78	0.21	6.37; 7.19	c

Note: EMM = Estimated Marginal Mean, SE = Standard Error, 95% CI = 95% Confidence Interval, SG = Significance Grouping (a =5%)

4.5. Discussion

This study examined visual designs of eHMIs (external Human-Machine Interfaces), focusing on how learned representation-based designs (vehicle indicator, road markings and traffic sign-based) and cognitive innatetendency-based designs (motion-based and anthropomorphic) influenced both subjective and objective performance. The research examined two communication roles (driver vs pedestrian) in two distinct traffic cultures (China vs Germany), exploring cultural differences to inform future eHMI coding strategies that prioritize universal or culture-specific solutions.

4.5.1. Effectiveness of Message Coding Strategies

The study revealed that design strategies significantly affected all subjective measures of eHMI effectiveness. Across both cultural samples, the learned representation-based coding strategies of “Echo” and “Signs” designs were rated higher than the baseline, suggesting they are promising universal strategies. In contrast, the motion-based “Swarm” design received lower ratings in terms of intuitive comprehension, perceived safety, and AV acceptance, indicating that cognitive innate tendency-based motion designs may not be suitable for eHMI applications. This finding highlights a potential risk in relying on dynamic or complex motion designs, which might confuse or overwhelm users rather than providing clear and effective communication, regardless of cultural background.

Further supporting these findings, the ranking preference data revealed significant differences in eHMI preferences across cultures. Despite some cultural differences, the overall ranking order remained similar for both Chinese and German participants, suggesting potential universal trends in AV communication preferences. These universal trends align with the trend identified based on the subjective measures: learned representation-based coding strategies appear to be more universally intuitive and accepted.

These findings might be explained by the importance of expectations within traffic culture, which align with cues that are familiar within said context *(Das & Dutta, 2019)*. These traditional, learned representations may have aligned better with participant’s expectations, resulting in higher subjective ratings. Additionally, these expectations guide attention, allowing humans to reduce cognitive load, which could enhance the feeling of intuitive comprehension and contribute to higher ratings of effectiveness *(Endsley, 2016)*. Future research could benefit from exploring long-term effects to explore this consideration further.

The effectiveness of these eHMI strategies varied by culture. German participants showed clear preferences for “Echo” and “Signs”, rating them higher across all measures, while “Swarm” negatively impacted perceived safety. On the other hand, no significant differences were found within the Chinese subsample, suggesting a more uniform perception of the eHMI coding strategies in this group. This emphasizes the importance of considering cultural context when designing eHMI strategies, as user preferences vary by cultural background. These findings are supported by prior research that underscore the importance of considering necessary adaptations of eHMI coding strategies between cultures *(Colley et al., 2024; Weber et al., 2019)*. Not only that, these differences may also be caused by varying cultural expectations for the encountered cues *(Wesseling et al., 2020)*.

4.5.2. Impact of Communication Partner

The role of the Communication Partner (i.e., driver vs. pedestrian) significantly influenced AV understanding and perceived safety, with pedestrians generally rating eHMIs more positively than drivers. This may be due to pedestrians, as Vulnerable Road Users (VRUs), feeling more at risk in traffic and facing greater communication challenges *(Brill et al., 2023)*. Additionally, pedestrians often perceive drivers’ road behaviors as more dangerous *(Alonso et al., 2022)*, making effective eHMI coding strategies more impactful for pedestrians.

This is reflected in the significant interaction between Communication Partner and eHMI coding strategy. For drivers, the "Swarm" design received lower ratings, while "Echo" was rated highest, suggesting that designs based on learned representations, such as road markings, are more effective for drivers. For pedestrians, the "Signs" concept received the highest ratings, and the "Retina" design improved ratings across all measures, except for perceived safety. These findings align with previous research indicating that these traffic sign symbols and anthropomorphized design positively influence subjective experiences of pedestrians *(Cefkin et al., 2019; Clercq et al., 2019; Lyu et al., 2024, p. 20; Mahadevan et al., 2019; Verma et al., 2019)*.

These differences were detailed further by the significant three-way interaction between Culture, Communication Partner, and Coding Strategy across all measured variables. In the Chinese subsample, there were no significant differences between driver and pedestrian ratings, suggesting a more consistent perception of AV concepts regardless of the user's role. In contrast, German participants showed distinct preferences based on their role. Drivers rated the "Echo" concept significantly higher, indicating it was more intuitive for them, while pedestrians rated "Swarm" and "Retina" more favorably, albeit still not better than the baseline condition.

These findings highlight the importance of tailoring eHMI coding strategies to the specific needs of different types of Human Road Users (HRUs) and their cultural backgrounds, as the effectiveness of designs may vary between drivers and pedestrians. More specifically, German participants demonstrating role-dependent preferences, while Chinese participants showed more uniform evaluations. These differences may stem from distinct communication interactions and unique information needs for each HRU type *(Fruhen et al., 2019; Habibovic et al., 2013)*. Prior research also emphasizes the significance of considering different HRU types as well as cultural contexts when designing eHMIs *(Colley et al., 2024; Dey, Van Vastenhoven, et al., 2021; Gao et al., 2023; Weber et al., 2019)*.

4.5.3.

Cultural Influence of eHMI Effectiveness

This study demonstrates that culture significantly influences subjective measures of AV understanding, perceived safety, and acceptance. Across all variables, Chinese participants rated the eHMIs more positively than German participants, highlighting the impact of cultural differences on perceived AV effectiveness.

These differences can be partially explained by variations in Power Distance (PDI) *(Hofstede, 2011)*. High PDI cultures (i.e., China) tend to place greater trust in institutional endorsements, which signal reliability and reduce perceived risk, thereby increasing willingness to adopt new technologies. In contrast, low PDI cultures (i.e., Germany) emphasize individual decision-making, leading to greater scrutiny of new technologies. Multiple studies extend on this relationship, showing high PDI also positively correlated with the acceptance of AVs *(Muzammel et al., 2024; Taniguchi et al., 2022; Yun et al., 2021)*.

4.5.4.

Cultural Influence on Decision Time

The main effect of culture showed that Chinese participants took longer (+2.20 seconds) to make decisions than German participants. This difference may stem from varying acceptable follow distances, as Germans tend to accept shorter time headways *(Li et al., 2024)*.

The main effect of concept revealed that specific AV communication concepts, particularly "Echo," "Signs," and "Retina," significantly improved decision-making speed across the entire sample. These concepts helped participants make quicker decisions, suggesting their potential to enhance interaction speed and comprehension. The interaction effect showed that, while all concepts improved decision times in comparison to the baseline for the Chinese subsample, the German subsample did not experience notable changes in decision time compared to the baseline. This indicates that, although Chinese participants benefited from all the presented concepts, German participants' decision times were largely unaffected by the type of AV communication concept.

These findings suggest that, while certain concepts can improve decision times, cultural factors may play a stronger role in influencing decision speed than the specific eHMI used. Regardless, for universal application, the findings indicate that the highest universal potential for designs to improve design time are eHMI coding strategies based on learned representations (i.e., road markings and traffic signs) and the cognitive innate tendency-based anthropomorphic design.

4.5.5.

The Effect of Message Coding on Gaze Time

For drivers, the results revealed significant main effects for both culture and concept, but no significant interaction effect between the two. Regarding culture, Chinese participants spent significantly longer (+1.38 seconds) looking at the approaching vehicle than German participants. Since decision times were longer for Chinese participants, it is likely that part of this difference can be attributed to them having more time to observe the vehicle. Cultural differences in risk assessment, traffic safety, patience, crossing speed, and yielding behavior may explain this difference further *(Jiang et al., 2015; Theofilatos et al., 2021)*. More specifically, Chinese participants may be more cautious or focused on the vehicle, reflecting different behavioral tendencies or attitudes toward AVs. In terms of design strategies for drivers, certain AV communication concepts—specifically "Minimal," "Retina," and "Swarm"—resulted in significantly longer gaze times compared to the baseline. Since longer gaze times typically suggest a negative outcome, this implies that these concepts may have been more confusing or required additional cognitive effort to process. Notably, there was no significant interaction effect between culture and concept, meaning that the gaze time differences between cultures were consistent across the various eHMIs.

For pedestrians, the main effect of culture revealed that Chinese pedestrians had significantly shorter gaze times (by 0.80 seconds) compared to German pedestrians, suggesting they either processed the AV information more quickly or were less focused on the approaching vehicle. This could be due to differences in expectations regarding yielding behavior, as Chinese drivers tend to brake later and more aggressively than German drivers *(Jiang et al., 2017)*. Since the AV in the study initiated braking and the eHMI display at the same distance for both groups, Chinese pedestrians may have been triggered to respond earlier, resulting in quicker processing and shorter gaze times. This effect may be intensified by the generally shorter accepted gap for pedestrians in China compared to Germany *(Jiang et al., 2015)*. Another possibility is that higher levels of trust and acceptance of AVs in China, compared to Germany, may have led to quicker processing *(Muzammel et al., 2024; Taniguchi et al., 2022; Yun et al., 2021)*. For pedestrians, the main effect indicated that "Minimal" and "Echo" resulted in significantly higher gaze times compared to the baseline, suggesting the motion-based and road-marking designs may have prompted participants to focus more on the vehicle or required additional cognitive processing. Moreover, no significant interaction effect between culture and concept was found.

4.5.6.

Future Research

Further research could explore the long-term effects of learned representation-based eHMI coding strategies to assess whether repeated exposure enhances intuitive comprehension and decision-making efficiency across different cultures. Moreover, extending the type of HRUs could provide additional insight into the scalability of these learned representation-based eHMI coding strategies *(Dey, Van Vastenhoven, et al., 2021; Gao et al., 2023; Verstegen et al., 2021)*. Another promising direction involves refining role-specific eHMI strategies further, particularly in cultures where driver and pedestrian perceptions significantly diverge, to investigate whether such role-specific strategies can be recognized and provide sufficient distinction for effective communication. In such studies, it could be valuable to include additional message coding strategies to facilitate systematic comparisons between eHMI designs, addressing crucial gaps within the research field of eHMI *(Ackermann et al., 2019; Clamann et al., 2017; Rasouli & Tsotsos, 2020)*.

Further studies could also investigate the adaptability of eHMI designs in real-life mixed traffic environments, where both automated and human-driven vehicles coexist, to understand how these interfaces influence collective traffic behavior. Finally, expanding research to diverse cultural contexts beyond China and Germany, could provide insights into truly universal eHMI coding strategies and identify additional culture-specific adaptations for global AV deployment.

4.6.

Conclusion

This study investigated how different visual eHMI design strategies—based on learned representations and cognitive innate tendencies—affect user performance across driver and pedestrian roles. By comparing responses in China and Germany, it explored cultural influences to inform future eHMI solutions that balance universal and culture-specific design approaches.

The findings from this study highlight the critical influence of cultural context and communication partner types on the effectiveness of eHMI coding. The observed cultural differences in subjective ratings highlight the critical importance of incorporating cultural perspectives into eHMI coding. However, universal trends indicate opportunities for a universal eHMI coding.

Specifically, if automakers and policymakers aim to provide optimal subjective experiences for Human Road Users (HRUs), learned representations based on traffic signs or road markings ("Symbol" and "Echo" respectively) are generally easier to understand and accepted across cultures. Not only that, this type of learned representation design also positively influenced decision time, encouraging smoother traffic flow. This positive effect may be caused by increased processing speed and accuracy, as the road markings and traffic signs align with the traffic context and therefore align with what people expect to see (Joubert et al., 2008; Nicholls et al., 2023; Wischnewski & Peelen, 2021).

Furthermore, the study also emphasizes the need to account for the communication partner—whether the user is a driver or a pedestrian. The interaction effects indicate that while a universal eHMI coding may be effective in some cultural contexts, role-specific adjustments may be required in others to optimize the impact of eHMIs. More specifically, findings indicate that where pedestrians prefer the learned representation-based eHMI coding derived from traffic signs ("Signs") more than road markings ("Echo"), drivers show a slight preference for road markings ("Echo") over traffic signs ("Signs"). The objective measure of gaze time underscores different approaches for pedestrians and drivers as pedestrian gaze time was affected by road marking based eHMI coding strategies. By incorporating role-specific design strategies, automakers and policymakers could create more effective and scalable eHMIs that cater to both pedestrians and drivers in a context-sensitive manner, addressing inclusivity and scalability concerns (Colley et al., 2019; Colley & Rukzio, 2020; Dey, Van Vastenhoven, et al., 2021). In other words, role-specific design would allow AVs to indicate more clearly for whom the portrayed message is meant (i.e., surrounding driver or pedestrian).

Building on the Findings

The next chapter shifts focus from eHMI design strategies, which explored culture, communication partner roles, and message coding, to a novel aspect: the integration of branding into eHMI design. While previous studies highlighted the effectiveness of learned representations, particularly traffic sign-based symbols for pedestrians, this research expands by examining the impact of branding. Incorporating branding into eHMIs raises key questions about its effect on the core goals of providing clear, intuitive, and culturally relevant cues to road users. Specifically, this study investigates whether different levels of branding freedom can be applied in cultures like Germany and China without compromising these objectives. The findings aim to offer guidelines for integrating branding, providing valuable insights for automakers and policymakers to create effective, scalable, and culturally sensitive eHMI systems that meet the needs of diverse road users while maintaining the core principles of AV communication.

Table 16

Descriptive Statistics for the subjective measure of Intuitive Comprehension.

			Signs	Echo	Retina	Minimal	Baseline	Swarm	Average
China	Pedestrian	EMM	6.23	5.69	5.73	5.09	5.40	5.37	5.58
		SE	0.18	0.22	0.24	0.25	0.25	0.26	0.14
		CI_L	5.87	5.24	5.25	4.58	4.89	4.86	5.30
		CI_U	6.59	6.13	6.21	5.59	5.91	5.88	5.87
	Driver	EMM	5.87	6.23	5.54	5.16	5.46	4.61	5.48
		SE	0.19	0.17	0.24	0.23	0.28	0.26	0.14
		CI_L	5.50	5.89	5.06	4.69	4.89	4.10	5.19
		CI_U	6.24	6.57	6.02	5.62	6.02	5.13	5.76
	Average	EMM	6.05	5.96	5.64	5.12	5.43	4.99	5.53
		SE	0.15	0.15	0.19	0.21	0.22	0.21	0.12
		CI_L	5.76	5.66	5.26	4.71	4.98	4.58	5.29
		CI_U	6.34	6.25	6.01	5.53	5.87	5.41	5.77
Germany	Pedestrian	EMM	6.14	4.29	5.52	5.07	4.02	4.36	4.90
		SE	0.17	0.20	0.22	0.23	0.23	0.23	0.13
		CI_L	5.81	3.88	5.09	4.61	3.56	3.89	4.64
		CI_U	6.47	4.69	5.96	5.53	4.49	4.83	5.16
	Driver	EMM	5.76	6.24	4.40	4.86	4.71	2.93	4.82
		SE	0.17	0.16	0.22	0.21	0.26	0.24	0.13
		CI_L	5.42	5.93	3.97	4.43	4.20	2.46	4.56
		CI_U	6.10	6.55	4.84	5.28	5.23	3.40	5.08
	Average	EMM	5.95	5.26	4.96	4.96	4.37	3.64	4.86
		SE	0.13	0.14	0.17	0.19	0.20	0.19	0.11
		CI_L	5.69	4.99	4.63	4.59	3.96	3.26	4.64
		CI_U	6.22	5.53	5.30	5.34	4.78	4.02	5.08
Average	Pedestrian	EMM	6.19	4.99	5.63	5.08	4.71	4.86	5.24
		SE	0.12	0.15	0.16	0.17	0.17	0.17	0.10
		CI_L	5.94	4.69	5.30	4.74	4.37	4.52	5.05
		CI_U	6.43	5.29	5.95	5.42	5.05	5.21	5.43
	Driver	EMM	5.82	6.23	4.97	5.01	5.09	3.77	5.15
		SE	0.13	0.12	0.16	0.16	0.19	0.18	0.10
		CI_L	5.57	6.00	4.65	4.69	4.70	3.42	4.95
		CI_U	6.07	6.46	5.30	5.32	5.47	4.12	5.34
	Average	EMM	6.00	5.61	5.30	5.04	4.90	4.32	NA
		SE	0.10	0.10	0.13	0.14	0.15	0.14	NA
		CI_L	5.81	5.41	5.05	4.77	4.60	4.04	NA
		CI_U	6.20	5.81	5.55	5.32	5.20	4.60	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI..

| Table 17

Descriptive Statistics for the subjective measure of Understanding of Autonomous Vehicles.

			Signs	Echo	Retina	Minimal	Baseline	Swarm	Average
China	Pedestrian	EMM	6.27	5.73	5.56	5.29	5.29	5.33	5.58
		SE	0.21	0.22	0.25	0.23	0.25	0.24	0.15
		CI_L	5.86	5.29	5.05	4.83	4.79	4.85	5.27
		CI_U	6.68	6.16	6.06	5.74	5.78	5.80	5.88
	Driver	EMM	5.87	6.17	5.49	4.86	5.63	4.51	5.42
		SE	0.22	0.18	0.25	0.25	0.27	0.27	0.16
		CI_L	5.43	5.82	4.98	4.36	5.09	3.97	5.09
		CI_U	6.31	6.52	5.99	5.35	6.16	5.06	5.75
	Average	EMM	6.07	5.95	5.52	5.07	5.46	4.92	5.50
		SE	0.18	0.16	0.20	0.20	0.22	0.20	0.14
		CI_L	5.72	5.64	5.12	4.67	5.02	4.53	5.22
		CI_U	6.43	6.26	5.92	5.47	5.89	5.31	5.78
Germany	Pedestrian	EMM	5.93	4.43	5.52	5.17	3.88	4.62	4.92
		SE	0.19	0.20	0.23	0.21	0.23	0.22	0.14
		CI_L	5.56	4.03	5.06	4.75	3.43	4.19	4.64
		CI_U	6.30	4.83	5.99	5.58	4.33	5.05	5.20
	Driver	EMM	5.48	6.10	4.29	4.48	4.48	2.95	4.63
		SE	0.20	0.16	0.23	0.23	0.24	0.25	0.15
		CI_L	5.07	5.77	3.83	4.02	3.99	2.45	4.33
		CI_U	5.88	6.42	4.74	4.93	4.96	3.45	4.93
	Average	EMM	5.70	5.26	4.90	4.82	4.18	3.79	4.78
		SE	0.16	0.14	0.18	0.18	0.20	0.18	0.13
		CI_L	5.38	4.98	4.54	4.46	3.78	3.43	4.52
		CI_U	6.03	5.55	5.27	5.18	4.57	4.14	5.03
Average	Pedestrian	EMM	6.10	5.08	5.54	5.23	4.58	4.97	5.25
		SE	0.14	0.15	0.17	0.15	0.17	0.16	0.10
		CI_L	5.82	4.78	5.20	4.92	4.25	4.65	5.04
		CI_U	6.38	5.37	5.88	5.53	4.92	5.30	5.46
	Driver	EMM	5.67	6.13	4.89	4.67	5.05	3.73	5.02
		SE	0.15	0.12	0.17	0.17	0.18	0.19	0.11
		CI_L	5.38	5.89	4.55	4.33	4.69	3.36	4.80
		CI_U	5.97	6.37	5.23	5.00	5.41	4.10	5.25
	Average	EMM	5.89	5.61	5.21	4.95	4.82	4.35	NA
		SE	0.12	0.11	0.14	0.14	0.15	0.13	NA
		CI_L	5.65	5.39	4.94	4.68	4.53	4.09	NA
		CI_U	6.13	5.82	5.49	5.22	5.11	4.62	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

| Table 18

Descriptive Statistics for the subjective measure of Intuitive Comprehension.

			Signs	Echo	Retina	Minimal	Baseline	Swarm	Average
China	Pedestrian	EMM	6.20	5.70	5.77	5.21	5.54	5.40	5.64
		SE	0.18	0.23	0.24	0.23	0.23	0.24	0.15
		CI_L	5.84	5.24	5.29	4.76	5.09	4.93	5.35
		CI_U	6.56	6.16	6.25	5.67	5.99	5.87	5.93
	Driver	EMM	5.86	6.20	5.66	4.91	5.40	4.31	5.39
		SE	0.19	0.15	0.23	0.25	0.26	0.26	0.15
		CI_L	5.47	5.90	5.21	4.41	4.88	3.79	5.10
		CI_U	6.24	6.50	6.11	5.42	5.92	4.83	5.68
	Average	EMM	6.03	5.95	5.71	5.06	5.47	4.86	5.51
		SE	0.15	0.15	0.19	0.21	0.21	0.20	0.13
		CI_L	5.73	5.66	5.34	4.65	5.06	4.46	5.26
		CI_U	6.33	6.24	6.09	5.48	5.88	5.25	5.77
Germany	Pedestrian	EMM	5.93	4.52	5.55	5.17	4.48	4.55	5.03
		SE	0.17	0.21	0.22	0.21	0.21	0.22	0.13
		CI_L	5.60	4.11	5.11	4.75	4.06	4.12	4.77
		CI_U	6.26	4.94	5.98	5.58	4.89	4.98	5.30
	Driver	EMM	5.55	6.36	4.14	4.52	4.98	2.90	4.74
		SE	0.18	0.14	0.21	0.23	0.24	0.24	0.13
		CI_L	5.19	6.08	3.73	4.06	4.50	2.43	4.48
		CI_U	5.90	6.63	4.55	4.98	5.45	3.38	5.01
	Average	EMM	5.74	5.44	4.85	4.85	4.73	3.73	4.89
		SE	0.14	0.13	0.17	0.19	0.19	0.18	0.12
		CI_L	5.46	5.18	4.50	4.47	4.35	3.37	4.65
		CI_U	6.01	5.71	5.19	5.22	5.10	4.09	5.12
Average	Pedestrian	EMM	6.06	5.11	5.66	5.19	5.01	4.97	5.33
		SE	0.12	0.15	0.16	0.15	0.15	0.16	0.10
		CI_L	5.82	4.80	5.34	4.88	4.70	4.65	5.14
		CI_U	6.31	5.42	5.98	5.50	5.32	5.29	5.53
	Driver	EMM	5.70	6.28	4.90	4.72	5.19	3.61	5.07
		SE	0.13	0.10	0.15	0.17	0.18	0.18	0.10
		CI_L	5.44	6.08	4.60	4.38	4.84	3.26	4.87
		CI_U	5.96	6.48	5.20	5.06	5.54	3.96	5.26
	Average	EMM	5.88	5.70	5.28	4.95	5.10	4.29	NA
		SE	0.10	0.10	0.13	0.14	0.14	0.13	NA
		CI_L	5.68	5.50	5.03	4.68	4.82	4.02	NA
		CI_U	6.09	5.89	5.53	5.23	5.38	4.56	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

| Table 19

Descriptive Statistics for the subjective measure of Understanding of Autonomous Vehicles.

			Signs	Echo	Retina	Minimal	Baseline	Swarm	Average
China	Pedestrian	EMM	6.23	5.61	5.63	5.27	5.40	5.46	5.60
		SE	0.19	0.23	0.24	0.25	0.23	0.24	0.15
		CI_L	5.84	5.16	5.15	4.78	4.93	4.98	5.30
		CI_U	6.62	6.07	6.11	5.76	5.87	5.94	5.90
	Driver	EMM	5.80	6.14	5.66	4.94	5.37	4.56	5.41
		SE	0.21	0.18	0.23	0.25	0.27	0.27	0.16
		CI_L	5.38	5.78	5.19	4.45	4.83	4.03	5.10
		CI_U	6.22	6.50	6.12	5.43	5.91	5.09	5.72
	Average	EMM	6.01	5.88	5.64	5.11	5.39	5.01	5.51
		SE	0.16	0.16	0.18	0.21	0.20	0.20	0.14
		CI_L	5.69	5.56	5.29	4.68	4.98	4.61	5.24
		CI_U	6.34	6.19	6.00	5.53	5.79	5.41	5.78
Germany	Pedestrian	EMM	5.93	4.26	5.45	5.05	3.81	4.29	4.80
		SE	0.18	0.21	0.22	0.23	0.21	0.22	0.14
		CI_L	5.58	3.84	5.02	4.60	3.38	3.85	4.52
		CI_U	6.28	4.68	5.89	5.50	4.24	4.72	5.08
	Driver	EMM	5.36	6.17	4.00	4.57	4.74	2.86	4.62
		SE	0.19	0.17	0.21	0.23	0.25	0.24	0.14
		CI_L	4.97	5.84	3.58	4.12	4.25	2.37	4.33
		CI_U	5.74	6.50	4.42	5.02	5.23	3.34	4.90
	Average	EMM	5.64	5.21	4.73	4.81	4.27	3.57	4.71
		SE	0.15	0.14	0.16	0.19	0.19	0.18	0.12
		CI_L	5.34	4.93	4.40	4.42	3.90	3.21	4.46
		CI_U	5.94	5.50	5.05	5.20	4.64	3.93	4.95
Average	Pedestrian	EMM	6.08	4.94	5.54	5.16	4.60	4.87	5.20
		SE	0.13	0.16	0.16	0.17	0.16	0.16	0.10
		CI_L	5.82	4.63	5.22	4.83	4.29	4.55	4.99
		CI_U	6.34	5.25	5.86	5.49	4.92	5.20	5.41
	Driver	EMM	5.58	6.15	4.83	4.76	5.05	3.71	5.01
		SE	0.14	0.12	0.16	0.17	0.18	0.18	0.11
		CI_L	5.29	5.91	4.52	4.42	4.69	3.35	4.80
		CI_U	5.86	6.40	5.14	5.09	5.42	4.07	5.22
	Average	EMM	5.83	5.55	5.18	4.96	4.83	4.29	NA
		SE	0.11	0.11	0.12	0.14	0.14	0.14	NA
		CI_L	5.61	5.33	4.94	4.67	4.56	4.02	NA
		CI_U	6.05	5.76	5.43	5.25	5.10	4.56	NA

Note: EMM = Estimated Marginal Mean, SE = Standard Error, and 95% Confidence Interval with Upper and Lower CI.

5.

Exploring Branding Freedom

For many car enthusiasts like myself, the 1967 Ford Mustang Shelby GT500—affectionately known as Eleanor from Gone in 60 Seconds (2000, the remake)—cars represent much more than just a mode of transport. Cars are iconic symbols of personal identity, passion, freedom, and even status. Cars evoke emotions through their design, sound, and branding. A Mustang's throaty roar or the precision of an Audi's engineering stirs feelings that go beyond functionality. Branding is at the heart of this emotional connection, shaping how car aficionados around the world interact with vehicles.

It is therefore no surprise that vehicle designers strive to express the core brand elements throughout the design of the whole vehicle. With the rise of Autonomous Vehicles (AVs), a new challenge arises: How does branding fit into the design of eHMIs, which prioritize clear and effective communication? Can branding coexist with the goal of creating intuitive, communicative eHMIs, or does it complicate the process? This chapter explores these questions, investigating whether branding can influence the design of eHMI systems or if it must be subordinated to the need for clarity in communication. We examine how branding influences eHMI effectiveness within and across cultures to determine the amount of branding freedom in eHMIs.

5.1.
Introduction

The future of safe autonomous driving hinges on designing alternative ways for self-driving vehicles to communicate with human road users – enter the critical role of external Human-Machine Interfaces (eHMIs).

These eHMIs play a crucial role in ensuring safety and efficiency in traffic as current interaction strategies will likely prove ineffective *(Färber, 2016)*. In traditional vehicles, communication between human road users is made possible through a combination of vehicle-centric and human-centric cues *(Habibovic et al., 2018; Šucha et al., 2017)*. However, as human drivers may no longer be involved, human-centric cues (e.g., eye contact, gestures, and body language *(Dey & Terken, 2017; Habibovic et al., 2019; Moore, Currano, et al., 2019; Risto et al., 2017)*) are no longer able to be used to communicate with human road users. Not only that, as self-driving vehicles cannot understand many human-centric cues, these cues can also no longer be used to communicate towards the vehicle *(Hagenzieker et al., 2020; Jafary et al., 2018; Mahadevan et al., 2018)*. Although the vehicle-centric cues (e.g., forward pitch during braking *(Schieben et al., 2019)*) remain, these cues may differ from that of traditional vehicles due to the vehicle's reduced anticipatory capabilities and increased response times. Consequently, this could result in more abrupt movements and closer proximity to surrounding road users, causing self-driving vehicles to exhibit a different behavior than traditional vehicles *(Dey et al., 2017; Tapiro et al., 2019; Wagner, 2016)*.

The eHMIs serve as indispensable tools in overcoming the subsequent gap in communication between self-driving vehicles and human road users. Presently, a variety of sensory modalities have been proposed for communicating by eHMI, including visual, auditory, and tactile signals, to convey messages related to intent, awareness, mode, or a combination of these aspects. Although no consensus exists about the eHMI exact design, research does agree that explicit eHMIs must possess several core abilities. These abilities are the ability to (1) effectively and efficiently reestablish communication between self-driving vehicles and human road users, (2) improve perceived safety and comfort *(Habibovic et al., 2018)*, (3) enhance the interaction experience *(Deb et al., 2016; Mahadevan et al., 2018)*, and (4) facilitate the decision-making process of human road users in traffic *(Mahadevan et al., 2018)*. Together, these ultimately contribute to improved acceptance of, and trust in, self-driving vehicles *(Hoff & Bashir, 2015; Lee & See, 2004; Parasuraman & Riley, 2016)*. As these core abilities of eHMI are refined, another important consideration emerges: the role of branding in eHMI design.

5.1.1.
Branding Design of eHMI

The automotive industry is built on and structured by deeply rooted emotional values such as heritage, status, and adventure, which are captured in brand identities, the aim of which is to offer customers a unique distinctive proposition *(van Grondelle et al., 2023a)*.

Branding in the automotive industry is exemplified by the iconic automotive emblem—a representation of a brand's identity, aesthetics, heritage, and values *(Wang, 2023)*—and a vehicle's grill in which it is often placed *(van Grondelle, 2016)*. These iconic elements serve as a tangible link between a company's past, present, and future. From there, this brand narrative deepens in both the exterior and interior design, as well the overall experience of the vehicle. In the realm of (automotive) branding design, there exists a delicate balance between recognizable and novel design elements signifying the brand's evolution (i.e., design freedom). Balancing these elements is crucial in the automotive industry: too much deviation risks diluting brand recognition, while stifling design freedom may alienate customers as their ever-evolving desires remain unmet *(Burnap et al., 2016)*.

While autonomous driving presents a short-term opportunity for car manufacturers to gain a strategic edge, it is also expected to reduce long-standing brand differentiators—such as vehicle dynamics and driving experience—in the long term. As a result, maintaining a strong brand identity through user experience becomes increasingly important. The design of user-vehicle interactions must reflect and reinforce this identity. For surrounding human road users (HRUs), the vehicle's exterior—including the eHMI—plays a key role in conveying the brand's street presence *(Fiorentino et al., 2023; van Grondelle, 2023b)*. Achieving a seamless integration of the eHMI into the overall brand experience therefore requires sufficient design freedom.

Given the great importance of branding in the automotive industry and the absence of standardized guidelines for eHMI design, automotive brands may freely explore branding of eHMIs. However, the potential inclusion of branding is dependent on ensuring its implementation does not compromise the core abilities of eHMIs. This study therefore investigates the impact of branding to determine the necessity of specific guidelines. Given the diverse cultural expectations for eHMI communication in countries such as Germany and China, incorporating branding elements into eHMI design adds complexity to achieving universally effective and culturally appropriate solutions *(Shmueli & Degani, 2023).*

5.1.2.

Cultural Design of eHMI

Cultural differences complicate the design of eHMIs. Colors, symbols, and gestures can have different meanings across different cultures, leading to different expectations, behavior and comprehension of the same information *(Alexander et al., 2017; Leonard et al., 2009; Rasouli & Tsotsos, 2020; Zhang & Zhang, 2019)*. These cultural differences could potentially lead to misunderstandings or incorrect interpretations of the eHMI, and thus vehicle's behavior. Therefore, it is unsurprising that previous research has found that eHMIs cannot be blindly adopted from one culture to another without considering potential implications of cultural differences *(Lanzer et al., 2020)*. Interestingly, while previous research indicates culture-specific preferences for information needs, universal trends were found to exist for the technological modality of eHMIs *(Wesseling et al., 2020)*. In other words, while the adoption of eHMIs across different cultures necessitates a careful consideration of cultural differences, it is encouraging to note that universal trends exist. In conclusion, these findings highlight the need for further research into the interplay between cultural differences and universal trends in eHMIs.

Research has yet to address the impact of branding design of eHMI within and across cultures. Developing branded eHMIs for the traffic context further complicates this challenge as communication in traffic demands rapid processing of complex information amidst anonymity and transience *(Habibovic et al., 2018)*. This constant demand for information processing may result in distractions, insufficient processing time, inaccurate perceptions, and affecting decision-making due to volatile mental workloads *(Baldwin & Coyne, 2005; Silva, 2014; Verwey, 2000; Wickens, 2002)*. Consequently, any adaptations of eHMI designs to incorporate branding must be approached cautiously, as it could potentially lead to increased confusion and hazardous situations in the already complex interactions between road users. Given this challenge, this paper aims to explore how branding influences eHMI in different cultures.

5.1.3.

Aim of the Study

The aim of this study is to contribute to the development of guidelines for external Human-Machine Interfaces (eHMIs) that facilitate effective communication between self-driving vehicles and human road users in different cultural contexts. The study seeks to understand the level of branding freedom that can be incorporated in different cultures (i.e., Germany and China) without affecting the core abilities of eHMIs: providing effective and efficient cues, improving perceived safety and comfort, enhancing the interaction experience, and supporting decision-making processes in traffic.

5.2.

Methodology

To examine the influence of branding on eHMIs across different cultural contexts, a 2x5 mixed-design online experiment was conducted by an investigator. The experiment gathered subjective data in eHMI performance metrics, which assessed the impact of branding by measuring the core abilities of eHMI through several self-evaluations and the objective measure of decision time.

5.2.1.

Participants

A total of 250 participants *(50.4% Female, 49.6% Male, 0% Other, 0% I prefer not to answer)*, participated in the study. The average age of the participants was 37.22 years *(SD = 11.38, min = 18, max = 65)*. The study, aimed at comparing the cultures of Germany and China, treated culture as an independent factor resulting in two distinct subsamples within the sample. The Chinese subsample consisted of 125 participants, with 49.6% female, and an age range of 18 to 59 years *(M = 36.25, SD = 10.24)*. The German subsample also included 125 participants, with 51.2% female, and an age range of 19 to 65 years *(M = 38.18, SD = 12.38)*.

These selected participants met several criteria to ensure cultural and balanced representation. Eligible participants had to be either native to China or Germany with at least five years of current residency or have lifelong residency if they held other nationalities. To avoid confounding factors, individuals with color perception impairments were excluded. The eligible participants were then selected from a consumer panel through random stratified sampling based on demographics (i.e., age range and gender).

5.2.2.

Stimuli

The stimuli consisted of a series of videos depicting a pedestrian crosswalk with an approaching self-driving vehicle. Participants viewed these scenarios from the perspective of a pedestrian intending to cross the road. The videos showed an approaching self-driving vehicle slowing to a stop before the crosswalk while communicating through an eHMI.

The eHMI was integrated into the vehicle's grille and consistently communicated the message *"I am aware of you"* to the participant using a visual representation of a pedestrian symbol. The symbol's appearance varied depending on the participant's position relative to the self-driving vehicle and whether the pedestrian was stationary (i.e., a standing pedestrian symbol) or was actively crossing the road (i.e., an animated walking pedestrian) *(see Figure 47)*. The eHMI relied on this pedestrian symbol as previous research indicates that symbols are widely employed in traffic, transcend language barriers, thus ensuring universal recognizability across cultures, as well as offer legibility from considerable distances *(Bazilinskyy et al., 2019; Hudson et al., 2019; Lim & Kim, 2022; Löcken et al., 2019)*. Additionally, such symbol coded designs are also preferred by human road users and deemed to be more intuitive *(Holländer, Colley, et al., 2019)*.

| Figure 47

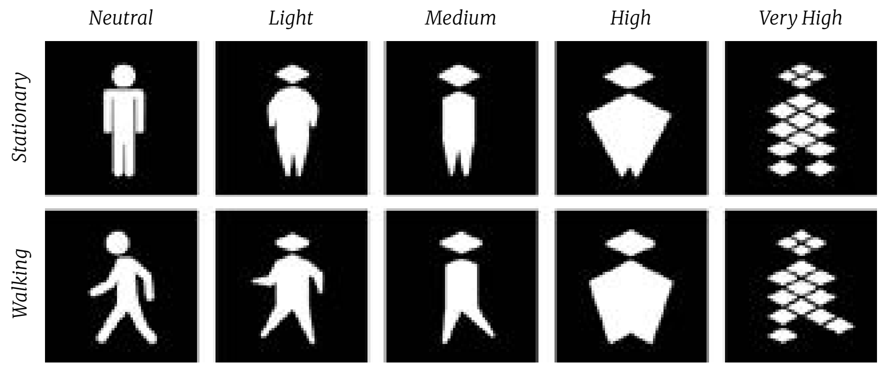
The eHMI with the symbol's appearance adjusting based on the participant's position and pedestrian activity, displaying either a stationary (left) or animated walking pedestrian (right).

To measure the impact of branding design, the eHMIs displayed varying levels of branding. These levels ranged from the pedestrian symbol to a pedestrian symbol solely consisting of diamond shapes. This diamond shape aimed to represent a brand's guiding form principle (i.e., a unique

design element unifying a product's appearance *(Grondelle et al., 2011)*). Intermediate steps between these extremes were created, thereby allowing a systematic examination of different levels of branding on eHMI perception and comprehension *(see Figure 48)*.

| Figure 48

Branding level design in eHMI visualizations, from left to right increasing in abstraction.



To ensure that cultural unfamiliarity did not affect the comprehension of the encountered traffic scenario and its corresponding information, the environment in the video replicated either Beijing or Berlin aiding immersion and recognition for Chinese and German participants *(see Figure 49 and 50) (Eisele & Petzoldt, 2022)*. Additionally, the videos were prepared in Virtual Reality software to ensure consistency across scenarios. The vehicle's stop from 50 km/h was modeled with a jerk-limited profile ($j = -2 / +2\ m/s^3$, $a_{max} = -2\ m/s^2$ *(Dietrich et al., 2020)*), with braking commencing 1 s after the scenario began, achieving a braking time of 7.94 s, a distance of 55.2 m, and an initial TTC of 3.97 s assuming no speed reduction. Each video had identical starting points, distances, eHMI visibility and activation times, involved vehicles, surrounding uninvolved traffic, and speed conditions. This uniformity allowed for accurate comparisons within our data analysis across different cultural environments.

5.2.3.

Measures & Procedure

Ethical approval was secured and guidelines for human participant research were adhered to. At the initial study invitation, participants were presented with an introduction statement, privacy policy, data security descriptions, and voluntary consent declarations. All communication adapted

| ***Figure 49***

Video frame (taken at 3s.):

Chinese traffic environment.

| ***Figure 50***

Video frame (taken at 3s.):

German traffic environment.

to the participants' language preferences. Following completion of these documents and voluntary consent, participants were asked to provide demographic data (i.e., gender and age).

Then, to inform participants, a video preview depicting a no eHMI scenario was shown, allowing them to understand what to expect and enabling them to ask questions about the video depicted to the investigator. Participants were also afforded the opportunity to try the "cross the road" button after receiving instructions describing its function: to signify their decision to initiate crossing the road, once they felt safe to do so. Participants had the option to repeat this process.

The videos were then presented in a randomized order to prevent order effects. Several decoys were included in this randomized order where the vehicle continued driving to minimize learning effects. For each video, participants were instructed to press the 'cross the road' button to indicate their decision to cross, thereby capturing the objective decision time measure. To facilitate an unhurried decision-making regarding crossing, the vehicle approaching the crosswalk remained stationary after coming to a stop, ensuring that participants were able to make their decision without time constraints.

After completing each video, the investigator guided the participants to the several statements that were to be rated on an anchored 7-point Likert scale *(i.e., (1) completely disagree, (2) disagree, (3) somewhat disagree, (4) neutral, (5) somewhat agree, (6) agree, and (7) completely agree*).

To measure the impact of branding on the core abilities of eHMIs (i.e., Performance Metrics), four statements were included. To evaluate the effectiveness and efficiency of the communication between self-driving vehicles and human road users, the experiment included the statement of: *"The concept communicates: "I am aware of you" intuitively"*. For perceived safety and comfort, the statements implemented were: "*This concept would make me feel safer in traffic"* and "*This concept is comfortable in interaction"*. Lastly, the determine the perceived interaction experience, the statement of "*This concept is clear and easy to understand"* was included.

For the branding manipulation check, the statements included were: *"I can confidently conclude that this symbol refers to a pedestrian"*, *"The symbol represents me as a pedestrian"*, and *"After seeing the symbol, a pedestrian immediately comes to mind"* as informed by Endsley's situation awareness model levels of perception and comprehension *(Endsley, 2016)*. These statements collectively comprised the 3-item branding manipulation check, which exhibited excellent reliability as indicated by the Cronbach's alpha coefficient of *a = .935*. As a final step in the study, participants were able to provide feedback about the study, resulting in a total study duration of 20 to 35 minutes per participant.

5.2.4.

Data Collection

In this study, the online experiment guided by an investigator was conducted via a secure platform, which was chosen as the primary method of data collection due to several key advantages. First, structured online interviews ensured consistent questioning and allowed for the possibility of clarifications during the introduction. Such clarifications were crucial to ensure that participants correctly understand the video scenario, as the data's validity depended on this comprehension. Interviewers also ensured that the objective measure of decision time was recorded correctly and accurately, mitigating potential issues through observation and data-checking (e.g., mis-clicking). This method combined the standardization of online surveys with the flexibility of an online format, facilitating comprehensive and precise data collection in a conveniently accessible manner to participants across various time zones.

5.2.5.

Data Analysis

Data analyses were conducted in R (version 4.1.3) utilizing several packages (R Core Team, 2021b). ANOVA estimations for the factorial designs were performed with the afex package (Singmann et al., 2021). Here, generalized eta-squared (η_G^2), utilizing Type III Sum of Squares and Greenhouse-Geisser correction, was relied on to estimate effect size. Post-hoc testing was completed using the graphics package for pairwise comparisons with Tukey HSD (R Core Team, 2021a).

5.3.

Results

This chapter first presents the findings of the 3-item branding manipulation check, followed by the impact of branding on the core attributes of eHMI, including effectiveness, perceived safety, comfort, and interaction experience. All two-way mixed ANOVAs analyzed the self-reported values with Culture *(between-subject)* and Branding *(within-subject)* as fixed effects, and participant number *(No)* nested within the concept as a random effect *(Error)*. Lastly, the objective measure of decision time is presented.

5.3.1.

Branding Manipulation Check

Here, the findings derived from the 3-item branding manipulation check are detailed, which assessed the impact of different branding levels on the perception and comprehension of messages displayed on eHMIs.

Main Effect of Culture

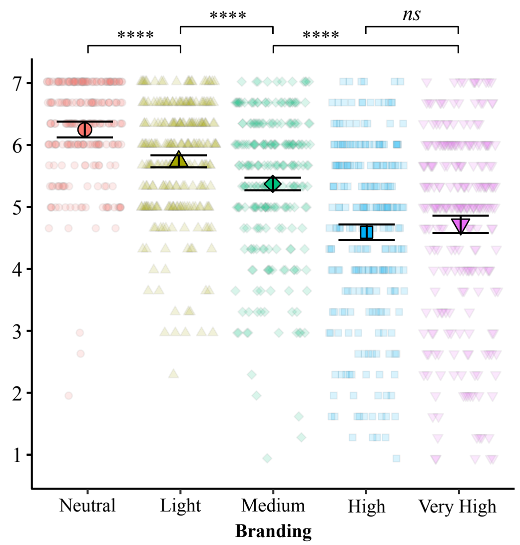
A significant main effect of culture was present *($F(1, 248) = 16.74, p < .001, \eta_G^2 = .03$)*, with the Chinese subsample *(EMM = 5.55, SE = 0.07, 95% CI [5.40; 5.69])* showing higher recognition of pedestrian symbols than the German subsample *(EMM = 5.12, SE = 0.07, 95% CI [4.98; 5.27], (p < .001)*. This suggests that cultural background influences the ability to process and recognize eHMI branding.

Main Effect of Branding

Findings highlighted a main effect of branding level on the branding manipulation check *($F(2.87, 711.76) = 138.04, p < .001, \eta_G^2 = .22$)*. Post hoc comparisons indicated that recognition ratings declined with increasing levels of branding abstraction (see Figure 51).

| **Figure 51**

*Main Effect of Branding with Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*



Neutral level received the highest ratings, followed by Light *(p < .001)*, and then Medium *(p < .001)*. Very High and High were rated lowest *(both p < .001)*, and did not significantly differ from each other *(p = .50)*, suggesting that increased abstraction reduces symbol recognition effectiveness. The results indicate that higher branding levels reduce symbol recognition, suggesting that more abstract branding is less effective for eHMI design. Additionally, no significant difference was found between the High and Very High branding levels, meaning they have a similar impact and are indistinguishable in their effect (see Table 20).

| **Table 20**

Branding Manipulation Check.

	Branding	***EMM***	***SE***	***95% CI***	***SG***
	Neutral	6.24	0.05	[6.14; 6.33]	a
	Light	5.73	0.06	[5.62; 5.85]	b
Across Cultures	Medium	5.37	0.07	[5.24; 5.51]	c
	Very High	4.73	0.09	[4.54; 4.91]	d
	High	4.60	0.09	[4.43; 4.77]	d
	Neutral	6.11	0.07	[5.97; 6.24]	a
	Light	5.94	0.08	[5.78; 6.10]	ab
China	Medium	5.74	0.10	[5.21; 5.50]	b
	Very High	5.00	0.13	[4.73; 5.26]	c
	High	4.95	0.12	[4.70; 5.19]	c
	Neutral	6.37	0.07	[6.23; 6.50]	a
	Light	5.52	0.08	[5.36; 5.68]	b
Germany	Medium	5.00	0.10	[4.81; 5.19]	c
	Very High	4.46	0.13	[4.19; 5.72]	d
	High	4.26	0.12	[4.01; 4.50]	d

Note: Estimated Marginal Means (EMM), Standard Errors (SE), 95% Confidence Intervals (95% CI) and Significance Grouping (SG).

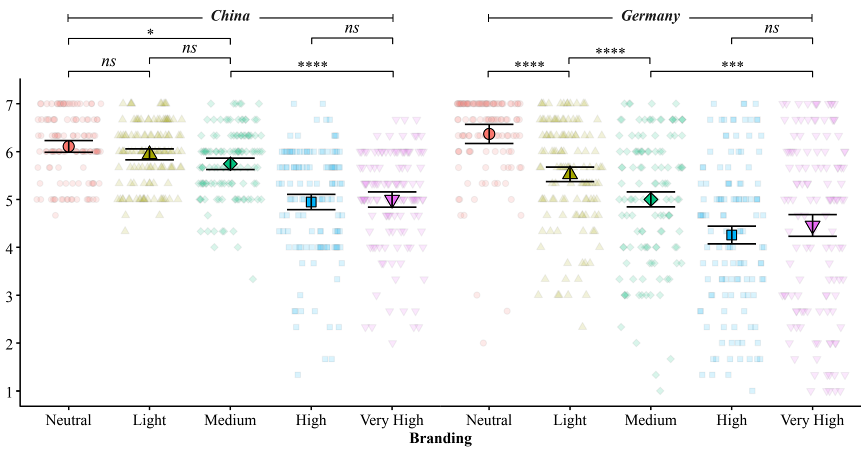
Interaction Effect between Culture and Branding

The analysis demonstrated a significant interaction effect *($F(2.87, 711.76) = 12.05$, $p < .001$, $\eta_G^2 = .02$).* While both cultures exhibited a decline in recognition with increased branding abstraction *(see Figure 52)*, the Chinese subsample showed fewer significant differences between branding conditions, suggesting a more uniform response, indicating that branding may have a less pronounced impact on their evaluations *(see Table 20)*. No significant variations were detected for the Chinese ratings, other than between Neutral and Medium *($p = .015$)*, and Medium and both Very High and High *(both $p < .001$)*

German participants demonstrated greater sensitivity to branding variations, with stronger distinctions between them *(see Table 20)*. Specifically, Neutral received higher ratings for the branding manipulation check than Light *($p < .001$).* In turn, Light was rated higher than Medium *($p < .001$).* Furthermore, Medium was rated higher than both the Very High and High branding levels *(both $p < .001$)*, with no significant difference observed between the latter two *($p = 0.74$).*

| **Figure 52**

Interaction Effect between Culture and Branding.



*Note: The graph is displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if $p > .05$, * if $p \leq .05$, ** if $p \leq .01$, *** if $p \leq .001$, and **** if $p \leq .0001$.*

5.3.2.

Subjective Performance Metrics of eHMIs

This section covers the eHMI performance metrics to the impact of branding on intuitive comprehensibility, message clarity, perceived safety, and interaction comfort.

Main Effect of Culture

Significant cultural effects were observed across all eHMI performance metrics: intuitive comprehensibility *($F(1, 248) = 17.78$, $p < .001$, $\eta_G^2 = .04$)*, message clarity *($F(1, 248) = 22.55$, $p < .001$, $\eta_G^2 = .04$)*, perceived safety *($F(1, 248) = 21.89$, $p < .001$, $\eta_G^2 = .05$)*, and interaction comfort *($F(1, 248) = 24.78$, $p < .001$, $\eta_G^2 = .05$).*

These effects were evident in the significant differences in the self-reported evaluations, with the Chinese subsample scoring significantly higher than the German subsample for all performance metrics, suggesting that Chinese participants perceived eHMIs as more effective and comfortable than their German counterparts *(see Table 21)*.

| Table 21

Performance Metrics - Main Effect of Culture.

	Culture	EMM	SE	95% CI	SG
Intuitive Comprehensibility	China	5.61	0.08	5.45; 5.77	< .001
	Germany	5.13	0.08	4.97; 5.29	
Message Clarity	China	5.61	0.08	5.45; 5.77	< .001
	Germany	5.07	0.08	4.91; 5.23	
Perceived Safety	China	5.44	0.09	5.26; 5.61	< .001
	Germany	4.86	0.09	4.69; 5.03	
Interaction Comfort	China	5.51	0.08	5.35; 5.67	< .001
	Germany	4.93	0.08	4.77; 5.09	

Note: Estimated Marginal Means (EMM), Standard Errors (SE), 95% Confidence Intervals (95% CI) and significant differences (Sig.)

| Table 22

Performance Metrics - Main Effect of Branding.

	Branding	EMM	SE	95% CI	SG
Intuitive Comprehensibility	Neutral	6.09	0.06	[5.97; 6.21]	a
	Light	5.60	0.07	[5.47; 5.73]	b
	Medium	5.36	0.07	[5.21; 5.50]	c
	High	4.84	0.09	[4.66; 5.02]	d
	Very High	4.96	0.09	[4.77; 5.14]	d
Message Clarity	Neutral	6.10	0.06	[5.98; 6.22]	a
	Light	5.64	0.06	[5.51; 5.76]	b
	Medium	5.39	0.08	[5.24; 5.54]	c
	High	4.78	0.10	[4.59; 4.97]	d
	Very High	4.80	0.10	[4.61; 4.99]	d
Perceived Safety	Neutral	5.92	0.07	[5.79; 6.05]	a
	Light	5.54	0.07	[5.41; 5.67]	b
	Medium	5.19	0.08	[5.04; 5.34]	c
	High	4.56	0.09	[4.37; 4.75]	d
	Very High	4.53	0.10	[4.34; 4.72]	d
Interaction Comfort	Neutral	5.97	0.06	[5.85; 6.10]	a
	Light	5.52	0.07	[5.38; 5.65]	b
	Medium	5.24	0.07	[5.09; 5.38]	c
	High	4.70	0.09	[4.53; 4.88]	d
	Very High	4.67	0.10	[4.48; 4.87]	d

Note: Estimated Marginal Means (EMM), Standard Errors (SE), 95% Confidence Intervals (95% CI) and Significance Grouping (SG)

Main Effect of Branding

A significant main effect of branding was present for intuitive comprehensibility *($F(3.02, 748.25) = 72.62$, $p < .001$, $\eta_G^2 = .12$)*, message clarity *($F(3.06, 760.08) = 78.1$, $p < .001$, $\eta_G^2 = .14$)*, perceived safety *($F(2.86, 709.48) = 104.1$, $p < .001$, $\eta_G^2 = .15$)*, and interaction comfort *($F(3.14, 778.7) = 82.03$, $p < .001$, $\eta_G^2 = .13$)*.

Tukey's Honestly Significant Difference (HSD) (see Table 22) revealed consistent patterns in the ratings of branding levels across all performance metrics. Specifically, ratings for each performance metric followed a descending order from Neutral (highest), to Light (second highest), Medium (third highest), and, as no significant could be determined, Very High and High (lowest).

These results indicated that as branding levels increase, there was a corresponding decrease in the perceived effectiveness of eHMIs in facilitating communication, safety on the road and interaction comfort of human road users. And, no significant difference was observed between High and Very High branding conditions, suggesting a plateau effect at high branding abstraction levels.

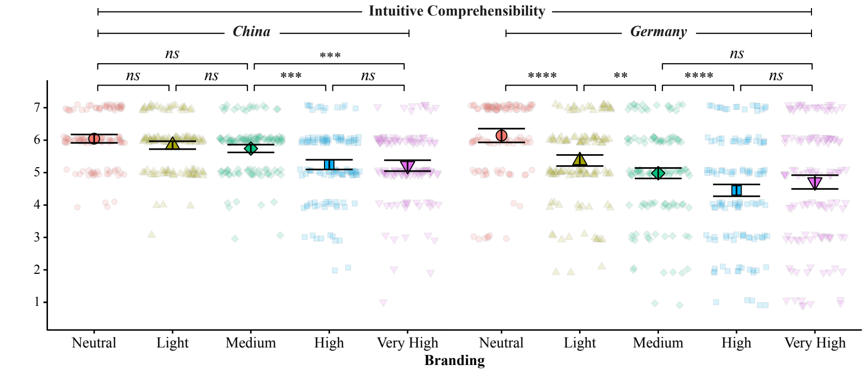
Interactions Effects of Culture and Branding

The results showed significant interaction effects of culture and branding for intuitive comprehensibility *($F(3.02, 748.25) = 9.05$, $p < .001$, $\eta_G^2 = .02$)*, message clarity *($F(3.06, 760.08) = 5.42$, $p < .001$, $\eta_G^2 = .01$)*, perceived safety *($F(2.86, 709.48) = 5.1$, $p = .002$, $\eta_G^2 = .01$)*, and interaction comfort *($F(3.14, 778.7) = 5.11$, $p = .001$, $\eta_G^2 = .01$)*, indicating that the relationship between branding and each self-reported evaluations varied depending on their cultural background.

Post hoc testing showed several noticeable differences between the subsamples for the different eHMI performance metrics (see Figure 53 - 56). In the Chinese subsample, no significant differences were determined between Neutral and Light, and Light and Medium. For safety and comfort, significant differences were found between Neutral and Medium. In contrast, in the German subsample, a significant difference was present between the highest-rated Neutral and second-highest Light level, indicating that the lightest form of branding significantly affected each eHMI performance metric.

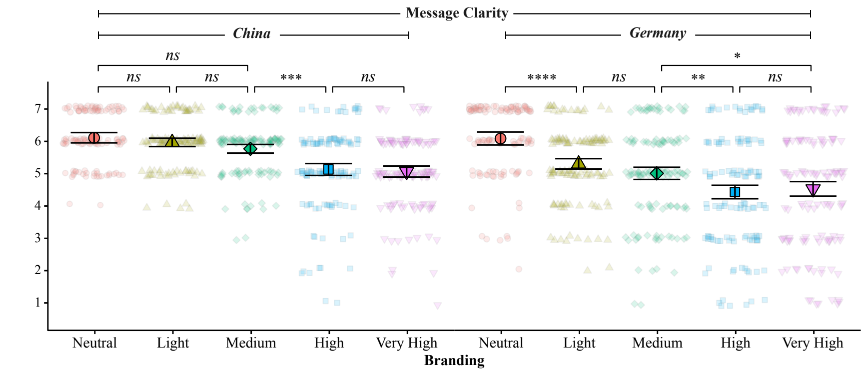
| Figure 53

Interaction Effect between Culture and Branding for the eHMI Performance Metric of Intuitive Comprehensibility.



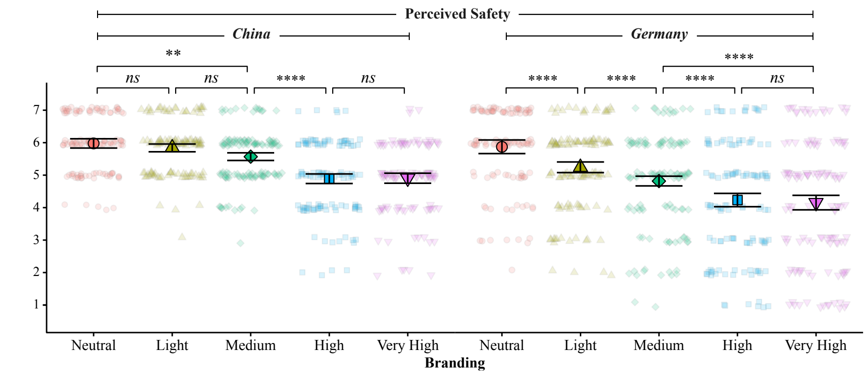
| Figure 54

Interaction Effect between Culture and Branding for the eHMI Performance Metric of Message Clarity



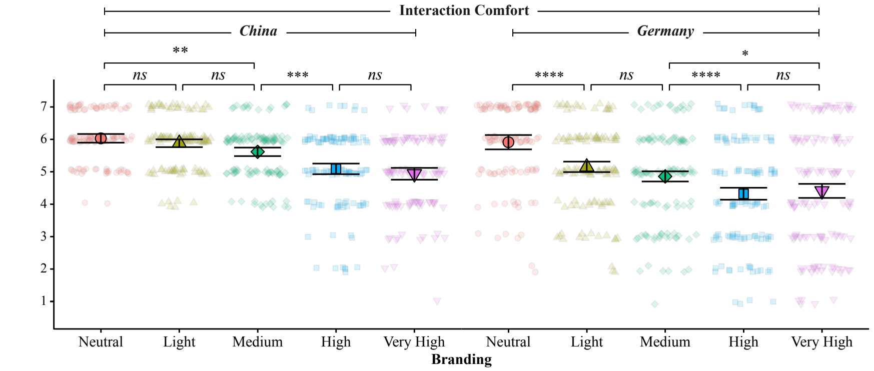
| Figure 55

Interaction Effect between Culture and Branding for the eHMI Performance Metric of Perceived Safety



| Figure 56

Interaction Effect between Culture and Branding for the eHMI Performance Metric of Interaction Comfort.



*Note: The graphs are displaying Estimated Marginal Means (EMM) with Standard Errors (SE) and significant differences with ns if p > .05, * if p ≤ .05, ** if p ≤ .01, *** if p ≤ .001, and **** if p ≤ .0001.*

A consistent observation for both subsamples was the decline in ratings for the High and Very High branding levels, with these levels being rated the lowest. This result indicated that higher levels of branding abstraction negatively eHMI effectiveness across different cultural contexts.

5.3.3.

The Impact of Branded eHMIs on Decision Time

This section reports the results of decision time, evaluating the efficacy of eHMIs in supporting the decision-making process of human road users in traffic scenarios.

A significant main effect of culture was present $(F(1, 248) = 123.69, p = < .001, \eta_G^2 = .19)$. The decision time of the Chinese subsample *(EMM = 13.95 seconds, SE = 0.41, 95% CI [13.15; 14.76])* was significantly slower than the German subsample *(EMM = 7.54 seconds, SE = 0.41, 95% CI [6.74; 8.35])*, indicating that Chinese participants tended to wait longer before deciding to cross the road.

No significant main effect of Branding was detected $(F(3.29, 815.74) = 1.52, p = .203, \eta_G^2 = .003)$, nor was there a significant interaction effect between culture and branding $(F(3.29, 815.74) = 1.58, p = .189, \eta_G^2 = .003)$. The lack of significance suggests that branding did not have a significant impact on decision time within and across cultures.

5.4.
Discussion and Conclusions

The results of this study provide valuable insights into the impact of branding on eHMI performance metrics (i.e., intuitive comprehensibility, message clarity, perceived safety, and interaction comfort) across different cultural contexts.

Branding and eHMI Effectiveness

Findings suggest that to maximize positive impact on human road users, it is recommended to forego branding altogether *(i.e., Neutral level)* when establishing universal guidelines for eHMIs. This approach maximizes the effectiveness of communication cues, enhances perceived safety and comfort, improves interaction experiences without affected decision-making processes in traffic. This aligns with the current understanding that clear and unambiguous messages are essential in traffic safety contexts, as communication in traffic requires rapid information transmission amidst anonymity and transience *(Habibovic et al., 2018)*.

Findings suggest that to maximize positive impact on human road users, it is recommended to forego branding altogether *(i.e., Neutral level)* when establishing universal guidelines for eHMIs. This approach maximizes the effectiveness of communication cues, enhances perceived safety and comfort, improves interaction experiences without affected decision-making processes in traffic.

However, cultural differences significantly influence eHMI performance metrics of branded eHMI designs. This finding extends on previous research highlighting cultural influences on eHMI design and the differences between traffic cultures *(Atchley et al., 2014; Lanzer et al., 2020; Moeckli & Lee, 2007; Nordfjærn et al., 2012; Wesseling et al., 2020)*. Therefore, culture is crucial to consider when developing effective universal or culture-specific branded eHMIs. The Chinese subsample exhibited greater openness to branding, with no significant differences found between the Neutral and Light branding levels. This indicates that Light branding may be feasible in Chinese contexts without significantly compromising eHMI effectiveness. In contrast, the German subsample demonstrated that increased branding affected subjective eHMI performance metrics, indicating no opportunity for implementing branding in eHMIs.

Maximizing Branding Freedom

Given the competitive nature of the market and the value of brand expression, exploring some degree of branding is likely to offer benefits to the automotive industry *(Burnap et al., 2016)*. Although branding in eHMIs may offer opportunities for automotive brand expression, it is crucial to note that subjective ratings of eHMI performance decreased with higher levels of branding. However, Branding did not lead to adverse effects on decision time, which serves as an indicator for behavioral changes that may disrupt traffic flow.

OEMS may argue that a mild decrease in subjective evaluations could be deemed acceptable in some contexts, due to the strategic advantage of branding for the automotive industry. If considering this perspective, Light branding in eHMIs could be implemented in both German and Chinese contexts. This approach would facilitate some branding freedom, while ensuring that the subjective impact is achieved, even if it is suboptimal.

Limitations and Future Research

Despite the valuable insights gained from this study, it is important to acknowledge its limitations, which point to opportunities for future research facilitating a more comprehensive understanding of branded eHMIs.

Focusing solely on a pedestrian crosswalk scenario allowed for a controlled examination of branded eHMIs, yet this limited scope does not fully capture the complexity of real-world traffic interactions *(Colley & Rukzio, 2020; Dey, Habibovic, Löcken, et al., 2020)*. Future research would benefit from expanding this scope by considering different types and quantities of encountered road users, as well as different intended messages displayed by the eHMI *(Colley & Rukzio, 2020; Dey, Habibovic, Löcken, et al., 2020)*. This would allow for the investigation of scalability of eHMIs and may provide additional insight into branding and universalization or localization of (branded) eHMI design *(Dey, Van Vastenhoven, et al., 2021; Y. Gao et al., 2023; Verstegen et al., 2021)*.

Extending the range of investigated unique branding elements, derived from different brands, for branded eHMIs could further enhance generalizability. Automotive brands' strategies and diverse branding approaches can significantly impact how branding is incorporated into eHMIs, making it challenging to generalize findings across brands or even within the same brand over time.

Alternative types of data collection may also provide additional benefits for data gathering as immersive environments facilitate valuable additional data streams. Examples of such alternative methods are Virtual Reality and real-driving studies with a Wizard of Oz approach. Moreover, future research could consider the inclusion of road users with impairments, ensuring inclusivity considerations in proposed eHMI guidelines, which are considered crucial consideration in previous research *(Colley et al., 2019; Colley, Walch, Gugenheimer, et al., 2020; Dey, Van Vastenhoven, et al., 2021; Löcken et al., 2020)*.

In this research, branded eHMI components were designed as fixed visual elements. However, current technologies allow for dynamic variation. Future investigations could explore whether the potential negative impact of branded eHMIs on subjective interaction experiences can be mitigated through context-aware design—specifically, by suppressing branding in safety-critical situations and displaying a neutral, non-branded signal instead.

Conclusion

This study demonstrates that higher levels of branding abstraction increasingly affect eHMI effectiveness and symbol recognition across different cultural contexts. When striving for optimized eHMI subjective impact, foregoing branding altogether is recommended for universal application. However, acknowledging significant cultural differences, particularly the contrasting attitudes observed between Chinese and German participants towards branding, suggests the potential for culture-specific approaches in eHMI design. Here, Chinese participants showed a higher openness to branding, whereas Germany participants showed none. Considering the strategic advantage of branding for the automotive industry, Light branding could be considered in both German and Chinese contexts, but caution is advised to prevent compromising communication efficacy. This approach would allow for branding opportunities with positive subjective eHMI effectiveness and no negative impact on decision time, as thus traffic flow.

6.

Findings, Discussion and Conclusions

Traffic is a system of constant negotiation—an intricate dance where drivers, pedestrians, and cyclists rely on signals, instincts, and learned behaviors to navigate safely. With the arrival of Autonomous Vehicles (AVs), this dynamic is shifting. Throughout this thesis, we have explored how AVs communicate with human road users (HRUs), the role of cultural influences in eHMI design, the impact of instinctual versus learned cues, and even how branding fits into this new reality. Each chapter has examined a key piece of the puzzle, revealing the complexities of designing communication systems that are both effective and universally understood.

Now, we step back to see the bigger picture. How do these findings come together? What patterns emerge when we compare different cultural perspectives, cognitive responses, and expectations for AV communication? And most importantly, what do these insights mean for the future of AV integration into human-centric traffic systems?

This chapter synthesizes the key takeaways from our research, identifying overarching principles that can guide the future of eHMI development in proposed design guidelines and contributions to both science and practice. We reflect on the methodologies and the broader implications of our findings—how they shape AV deployment, policy-making, and global traffic safety. Finally, we consider the next steps: What challenges remain? What questions are still unanswered? And how can this research contribute to a world where AVs not only function efficiently but also communicate in ways that are intuitive, inclusive, and seamless for road users across cultures?

6.1.

Discussion of Main Findings

This thesis investigated how culture and branding influence the design of external Human-Machine Interfaces (eHMIs) by exploring three research questions, being:

- *RQ 1.* How do cultural differences shape HRU expectations and preferences of for eHMI?
- *RQ 2.* How do cultural factors affect performance and effectiveness of specific eHMI components in communicating with HRUs?
- *RQ 3.* How does branding impact performance of eHMI systems?

This section discusses the most important findings for each research question and compares them to existing literature and theories, highlighting how the findings advance existing knowledge.

6.1.1.

How do cultural differences shape HRU expectations and preferences for eHMI?

Chapter 2 indicates that culture significantly shapes certain user expectations and preferences for eHMI design. Specifically, culture influences what type of information users expect, which technology modalities that HRUs prefer, what perceptions of the modalities' usability are, as well as what the impact on users' general trust in Autonomous Vehicles (AVs) is. These findings are consistent with theoretical behavior models, which describe that culture shapes expectations, performance, perception and attitudes, which in turn shape intentions and behavior *(Auinger et al., 2011; Rozkwitalska, 2013; Weber et al., 2019)*. Moreover, prior studies have demonstrated that eHMI solutions cannot be transferred across cultural contexts, further validating the critical role of culture in eHMI design *(Lanzer et al., 2020; Weber et al., 2019)*. Insights from the broader research fields of Human-Machine Interfaces (HMI) and Human-Computer Interaction (HCI) also highlight the cruciality of culture for shaping expectations and preferences of users *(Heimgärtner, 2007b; Heimgärtner et al., 2017; Khan et al., 2016; Khan & Williams, 2014)*. Taken together, this evidence clearly indicates that culture must be a foundational consideration in the design of eHMIs to ensure the effectiveness, usability, acceptance and trust in AVs across and within cultural contexts.

Chapter 2 also reveals that certain universal trends exist. One significant universal trend is the universal preference for an egocentric perspective—where eHMIs convey information from the AV's point of view. This consistent universal preference stands out as prior research reported contradictory findings. For instance, some research argues for an allocentric perspective—where eHMIs convey information from the HRUs' point of view *(Ackermann et al., 2019; Bazilinskyy et al., 2019; Deb et al., 2019; Faas et al., 2020)*. These studies theorized that this preference originates from certain communication methods in traffic that rely on the allocentric perspective (e.g., a traffic light indicating: "*You may go.*") which may reduce interpretation freedom. In contrast, other research argues that the egocentric perspective aligns more closely with regulations, minimizing liability concerns *(Holländer, Wintersberger, et al., 2019; Merat et al., 2018; Rouchitsas & Alm, 2019)*. Therefore, the universal preference for the egocentric perspective observed within the study is significant, as it aligns with the call for universal standards in eHMI design *(Jafary et al., 2018)*. Adopting the egocentric perspective universally could enhance the clarity and universal comprehensibility of eHMIs, potentially reducing the regulatory challenges associated with implementing AVs. Another universal trend was identified based on perceived usability and trust, particularly in both safety-critical and non-safety-critical scenarios. The findings suggest that employing the technology modalities of Displays, Smart Infrastructure or Augmented Reality hold significant potential for eHMI design. Adopting the egocentric perspective, along with utilizing the indicated technology modalities, could allow for a universal eHMI design that improve the usability, clarity and trust of eHMIs, while simultaneously addressing regulatory challenges.

Chapter 2 also identified significant cultural differences in preferences for non-driving-related scenarios. Specifically, German and U.S. participants showed a strong preference for Display, whereas Chinese participants preferred Augmented Reality (AR), Smart Infrastructure and Smart Assistants. More importantly, the findings also highlight cultural differences in information preferences, indicating that information needs vary significantly across cultures. This cultural influence may help to explain why previous eHMI studies in information needs yielded contrasting results *(Clamann et al., 2017; Colley & Rukzio, 2020; Färber, 2016; Habibovic et al., 2018; Lagström & Malmstem Lundgren, 2015; Mahadevan et al., 2018; Matthews et al., 2018)*. Importantly, legal constraints on messaging—specifically the restrictions on command or instruction message types—together with the reliance on the egocentric perspective, reduce the range of potential message types in eHMIs. Specifically, the options for message type are narrowed down to advisory (i.e., What is going to happen?) or answer-related (i.e., What is currently happening) *(Colley & Rukzio, 2020)*. These message type allow for the communication of information related to status, intent and awareness, which are considered crucial to enhance comfort, safety and aid in crossing decision *(Habibovic et al., 2018; Mahadevan et al., 2018; Matthews et al., 2018)*.

Taken together, while some aspects of eHMI design can be universalized, others require cultural guidelines when aiming to optimize user experience and address cultural information needs. Specifically, findings indicate that Chinese HRUs seem to have greater information needs compared to their German and U.S. counterparts, highlighting the need for tailoring the presented eHMI information to align with cultural preferences and expectations.

6.1.2.

How do cultural factors influence the subjective performance and objective effectiveness of specific eHMI components in communicating with HRUs?

Chapter 3 extends on the previous findings by investigating the role of culture as well as factors such as message coding, visualization type, communication modalities, and the type of communication partner (i.e., pedestrian, driver) in Virtual Reality (VR). One key finding was the importance of considering the type of communication partner, when assessing the impact of eHMIs on HRUs. The findings highlight that different type of traffic partners each have specific preferences and expectations that vary from each other. This finding aligns with previous research that consider both cultural traffic context and type of communication partner to be foundational considerations in eHMI design *(Weber et al., 2019)*. The study described in *Chapter 4* presents similar evidence, further supporting these findings. Another significant outcome was the universal effectiveness of symbolic communication. This type of message coding improved the subjective interaction experience, suggesting its potential as a universal eHMI standard. Furthermore, the application of color-coding significantly improved the effectiveness of the LED solution, indicating that color-coding is an effective manner to improve eHMI design. The colors used must either be traffic light colors (restricted by SAE regulations) or, alternatively, cyan and white for presenting neutral information. By relying on cyan and white, eHMIs avoid negative associations and triggering alertness in HRUs *(Shmueli & Degani, 2023)*. The study also found that ascending auditory cues were the only eHMI modality that resulted in faster decision times. This finding indicates the potential utility of ascending auditory cues in safety-critical scenarios, where quick responses are of upmost importance. Considering these findings, a multi-modal eHMI that utilizes symbol message coding for non-critical scenarios and adds ascending auditory messages in critical traffic scenarios, could offer the most effective approach for improving interactions and safety.

Chapter 4 examined learned and instinctive visualizations for eHMI design in VR. The study found that learned visualizations were universally preferred, receiving higher subjective ratings

without affecting decision time and gaze time. This may indicate that the traffic flow is not affected. Such familiar, learned cues seem to hold the highest potential for eHMIs, as they reduce ambiguity and improve user trust across cultural contexts consistently. These findings could be explained by prior research indicating that processing speed and accuracy increases if information or objects are placed within compatible contexts *(Joubert et al., 2008; Nicholls et al., 2023; Wischnewski & Peelen, 2021)*. Yet, differences in subjective evaluations and objective measures were observed between the roles of the communication partner (e.g., pedestrian vs. driver), with these differences varying across cultures. These findings emphasize the need for culturally adapted eHMIs that adjust to cultural-specific road user types.

Building on these findings from *Chapter 3* and 4, this research proposes a set of design guidelines that facilitate safe, efficient and intuitive communication between AVs and HRUs across the selected cultures of China and Germany. These guidelines provide designers, policymakers and industry practitioners with an important resource in their pursuit of designing eHMI systems that are culturally sensitive and respect the diverse needs and expectations of users in different cultures.

6.1.3.

How does branding impact performance of eHMI systems?

The final study, presented in *Chapter 5*, investigated the impact of branding on the performance of eHMIs in different cultural contexts. The findings demonstrate that culture significantly influences how open HRUs are to branding of eHMI design. Specifically, the ratings for subjective experiences of German participants were affected when including any type of branding. In contrast, the subjective experience of Chinese participants remained unaffected when including light branding. The inclusion of branding also only affected the subjective experience of HRUs, whereas the objective measure for decision-making process remained unaffected.

Yet, considering the call for universal standards by policymakers, it could also be recommended to forego branding all together when aiming to optimize both the subjective and objective performance for universal eHMIs. In other words, by excluding branding in universal eHMIs, the HRUs' interaction experience is optimized, without compromising decision-making processes. However, when considering the value of brand expression for OEMs for brand differentiation and the consistency in aesthetics, it might still be worthwhile to consider suboptimal subjective experiences. Despite that subjective evaluations were significantly lower in branded designs, no evidence was found for negative effects on decision-making process across and within both cultures. These findings provide automakers with some optimism about incorporating light branding into eHMI.

6.2.
Core Contributions

6.2.1.
Exploring the Influence of Culture on eHMI

One contribution of this thesis lies in highlighting the influence of culture on eHMI effectiveness, usability, acceptance and trust in AVs across and within cultural contexts, indicating that culture must be a foundational consideration when designing eHMIs. While prior research has recognized that culture shapes traffic behavior, communication styles, and expectations of HRUs, no systematic investigation had been conducted to determine where, when, and how culture influences eHMI design *(Ackermann et al., 2019; Auinger et al., 2011; Clamann et al., 2017; Fridman et al., 2017; Rasouli & Tsotsos, 2020; Rozkwitalska, 2013; Weber et al., 2019)*.

This thesis addresses the need for both universal and localized standards in eHMI design *(Ford & Kotzé, 2005; Habibovic et al., 2018; Jafary et al., 2018)*. Universal standards ensure compatibility across brands, car models and cultures, while localized standards indicate opportunities to optimize clarity and prevent misunderstandings. By addressing both, this research deepens our understanding of how culture shapes user expectations and behavior in traffic interactions with AVs. In turn, it enables insights into which aspects of eHMI design should be adjusted locally to cultural preferences.

6.2.2.
Evaluation of Design Freedom for eHMI Branding

A key contribution of this thesis is the evaluation of eHMI branding in different cultures, examining if branding design can be implemented without compromising eHMI performance. This perspective is an original contribution, as no prior studies have investigated branding opportunities in eHMI design.

Balancing branding opportunities with safety-critical communication in traffic contexts is essential. While the automotive industry depends on branding for product differentiation, ensuring traffic safety must take precedence. Understanding cultural differences, in how eHMI branding influences both subjective and objective experiences, provides valuable insights for standardization efforts. Sequentially, these insights offer policymakers with important reference points for developing clear and effective eHMI regulations.

The findings show that branding causes a negative effect on subjective interaction experiences without significantly influencing decision time. This presents a trade-off between exploiting eHMI branding and perceived clear, universally understood communication in traffic scenarios. Automotive manufacturers and policymakers need to carefully evaluate whether the benefits of branding, such as customer loyalty and market differentiation, outweigh potential drawbacks.

6.3.
Recommendations for Practice

This research provides actionable insights for practitioners involved in the development and deployment of eHMIs and AVs. These recommendations, captured in part by design guidelines, aim to ensure that eHMI solutions are intuitive, culturally adaptable, and foster trust and acceptance among HRUs.

6.3.1.
Implement a Modular Multi-Modal eHMI

This thesis presents a key recommendation for practice: the adoption of a modular, multi-modal eHMI. This modular eHMI approach supports universal hardware, allows for localized software-based adaptations, and includes the possibility of a branding overlay. By adopting this approach, the eHMI can facilitate culturally sensitive, effective communication while keeping development costs manageable.

The proposed modular, multi-modal eHMI system incorporates universal technology modalities, but adapts the use of these modalities based on the type of scenario encountered—non-ambiguous, ambiguous, or urgent/dangerous.

- *Non-ambiguous scenarios:* In these situations, the eHMI remains inactive, relying solely on the vehicle's standard cues (e.g., movement, signals) to avoid overwhelming the Human Road User (HRU) with unnecessary information. This approach reduces mental overload and ensures clarity by maintaining a minimalist design.

- *Ambiguous scenarios:* When the situation is unclear or uncertain, the eHMI activates with color-coded, learned representation-based symbols on the display. These symbols are designed to optimize the subjective experience of HRUs, making it easier for them to interpret the information. Importantly, these symbols adapt based on the HRU type. For human car drivers, symbols based on road markings are used, while for pedestrians, traffic sign-based symbols are displayed. This differentiation not only enhances the relevance of the information but also supports scalability by accommodating different types of HRUs.

- *Urgent or dangerous scenarios:* In high-stake situations, the eHMI intensifies the communication by adding ascending auditory tones to the visual display. This multi-sensory warning ensures quicker decision-making by grabbing the HRU's attention more effectively, although it may come with slightly lower positive subjective responses. Given the urgency of these situations, the focus shifts to ensuring rapid comprehension and response rather than improving comfort.

These modalities stack progressively as the criticality of the situation increases, ensuring that the right amount of information and urgency is delivered at the right time to maximize safety and understanding.

An additional software-based layer allows for branding integration. If branding is necessary, light branding can be applied. However, in more urgent situations, branding could be turned off to avoid distracting from the critical information. Branding can also be tailored according to cultural preferences, ranging from neutral to light branding, ensuring it is sensitive to cultural expectations.

Culture plays a central role as the primary contextual factor that influences the overall behavior of the eHMI system. Cultural factors shape parameters such as acceptable follow distances, traffic gaps, and the use of horns. For example, in some cultures, a shorter follow distance may be acceptable, while in others, a larger gap is preferred. The eHMI system adapts its responses accordingly to match these cultural norms, ensuring a more personalized and effective interaction. Additionally, the specific traffic scenario, shaped by cultural context, fine-tunes system responses, determining the

most appropriate type of information to convey and the priority of the receiver(s). These localized adaptations ensure that the eHMI system aligns with traffic behavior expectations specific to each cultural context.

To illustrate the application of this system, let us consider the following examples. A pedestrian crossing the road is classified as a non-ambiguous scenario, and the regulations state that pedestrian have the right of way. This cultural context determines the AVs behavior (i.e., yielding), the desired effect (i.e., the pedestrian crossing the street) and the acceptable distance for initiating yielding. The AV first communicates its intent through vehicle behavior (i.e., braking tilt of vehicle and trajectory). If the pedestrian hesitates, the scenario is reclassified as ambiguous, and the eHMI responds with a visual display, offering further reassurance through a white pedestrian symbol. For cultures where pedestrians do not have the right of way, this traffic situation may be reclassified this scenario as ambiguous, offering higher supportive information from the beginning. This approach ensures that the eHMI adapts dynamically to the cultural and situational context, providing effective communication between the AV and human road users.

This contribution is particularly important because it addresses the practical constraints of the automotive industry, which operates within strict regulatory frameworks and cost limitations. By proposing a scalable, adaptable solution, this thesis advances the field of eHMI research and provides a viable path forward for manufacturers seeking to implement culturally responsive designs.

6.3.2. Design Guidelines for eHMI

The thesis provides eight eHMI design guidelines, drawn directly from the empirical findings.

1. Modality - Use Displays for Ambiguous Scenarios Universally

The consistent preference for displays in eHMI indicates that this communication medium holds the highest potential across and within cultures, offering improved subjective safety, acceptance, comfort, understanding and intuitiveness.

2. Modality - Prioritize Learned Representations Over Instinctive Visualizations

Prioritizing learned visualizations (e.g., familiar traffic cues) over instinctive visualizations in eHMI design aligns with user expectations in traffic environments. Learned visualizations are preferred across cultures and ensure consistency with familiar traffic norms, enhancing the intuitive understanding of AV behavior. This results in improved user confidence, safety perception, and traffic flow without increasing decision times.

3. Modality - Rely on Color-Coding to Improve Comprehension

Including color in the eHMI message improves the intuitive comprehensibility, understanding of AVs, perceived safety in traffic and acceptance of AVs, thereby significantly improving the subjective experience of HRUs across cultures. The colors used should be either white or align with the learned meanings within the traffic system (i.e., traffic lights), while avoiding restricted colors (i.e., colors reserved for emergency vehicles).

4. Modality – Adding Sound in Urgent/Dangerous Scenarios

Multi-modal eHMI systems should combine learned, color-coded visual symbols on displays with ascending auditory cues in safety-critical scenarios. Auditory cues, while less preferred subjectively, significantly improve decision times, especially in pedestrian interactions during safety-critical situations. Adding multi-modal elements enhances both the speed and clarity of communication, improving overall road safety.

5. Message - Implement the Egocentric Perspective for Universal Clarity

Using the egocentric perspective (i.e., where the viewpoint aligns with the AV) as the default communication method in eHMI systems, improves the unambiguousness of messages across cultures and facilitates a universally understandable system. It reduces potential confusion, especially when users are interacting with AVs in different cultural contexts. In addition, this perspective abides by legal constraints. Thereby limiting the potential message types to advisory (*i.e., What is going to happen?*) and answer-related (*i.e., What is currently happening*) from the AVs' perspective.

6. Message - Account Cultural Differences for Information Needs

Due to the extensive cultural differences in information needs, determining what type and amount of information is required for each traffic scenario must be determined for each culture. The communicated information must resonate with users' cultural preferences to enhance the overall user experience. It is crucial to uncover whether HRUs require information in the encountered scenario, and if they do whether the egocentric perspective of advisory (*i.e., What is going to happen?*) or answer-related (*i.e., What is currently happening*) is recommended.

7. Receiver - Ensure Flexibility in eHMI Communication Partner Design

Communicated information must consider the type of communication partner. For pedestrians traffic sign-based symbols or anthropomorphized coding should be considered. In contrast, for drivers, road marking-based symbol are recommended. All in all, eHMIs must prioritize clarity and simplicity for pedestrians, while communication with other AVs or drivers may involve more complex interactions. Adapting eHMI designs for specific user roles ensures clear, targeted, and effective communication across the traffic ecosystem, facilitating scalability in eHMIs.

8. Branding Module - Carefully Balance Branding and Subjective Experiences

Avoid branding in eHMI designs for universal use if you wish to optimize the subjective experience of HRUs. More specifically, branding negatively impacts the perceived clarity and safety of eHMIs, especially in regions like Germany. A neutral eHMI design ensures optimal subjective experiences. However, if the value of branding outweighs the need for optimal subjective experiences, branding is possible without negatively impacting the traffic flow. Determining the correct balance is key.

By deriving culturally informed design guidelines, this research makes a significant contribution to the field of eHMI. By identifying universal and culture-specific preferences in eHMI design—such as the role of displays, color-coding, auditory cues, and egocentric perspectives—this work ensures that AVs can communicate effectively across and within diverse traffic environments. Moreover, the research highlights the trade-offs between branding and user experience, offering practical insights for industry stakeholders to create more responsive, adaptive, and user-friendly eHMI solutions, while also addressing the challenges of cultural variability.

6.4. Recommendations for Scientific Research

The next section describes several directions for future research, derived from both the methodological choices made in this thesis and the broader context of autonomous driving. By exploring the lessons learned and expanding beyond the scope of this thesis, several opportunities can be found which may help to push the boundaries of eHMIs.

6.4.1.

Addressing Methodological Limitations

Several potential research directions emerge from the methodological choices of this thesis. These opportunities highlight areas of improvement for the validity and generalizability of the findings.

Generalizability: Extending Cultures and Sample Sizes

As the aim of the thesis was to explore the effects of culture, focusing on few, distinct cultures allowed for the controlled comparison of the eHMI preferences and effectiveness across not only culture, but also different traffic scenarios and communication messages, designs and styles. The selected cultures—chosen for their contrasting traffic cultures, traffic behavior and market importance—represented a logical starting point. This approach aligned with the nature of and the feasibility constraints associated with this thesis. The generalizability of the findings could be improved by including additional cultures while simultaneously increasing sample sizes.

As results indicate that the effectiveness of eHMI varies widely depending on cultural context due to the vastly differing social norms and communication styles, it would be recommended to expand the scope to encompass a wider array of cultures *(Ranasinghe et al., 2020; Weber et al., 2019)*. This would provide a more comprehensive understanding of whether the found universal trends hold true, providing further evidence and direction for future research in eHMIs.

The approach of all studies also assumes a level of homogeneity within the cultural samples that may not reflect the reality within cultures. By not accounting for variables such as urban versus rural residency, prior experience with AVs, or socio-economic background in the sampling strata, the diversity of preferences for eHMI solutions within each culture may not have been captured. This limitation could affect the reliability of the conclusions, as intra-cultural variability might significantly influence eHMI effectiveness.

By integrating a larger, more diverse sample for each culture, future research could provide a more comprehensive understanding of cultural dynamics and provide more actionable insights for eHMI. A larger sample would also enhance statistical power, increasing reliability and validity. This is especially important for mitigating sampling error effects, which is particularly pronounced in cultural studies *(Kitayama & Tompson, 2010)*. Moreover, stratified sampling could further mitigate these effects through balanced demographic representation *(Zhou & Cacioppo, 2010)*.

Methods and Measures: Beyond Surveys and Virtual Reality

The presented studies relied heavily on surveys, videos and VR-environments. While these methods have several advantages, alternative approaches (e.g., real-world and longitudinal studies) may provide a deeper understanding of how interactions evolve over time and occur in a natural context.

The controlled environment of VR provides an efficient way to gather data. This environment allows for the flexible simulation of a wider range of traffic scenarios in different digital contextual environments providing perfect replicability by ensuring uniform acoustic noise, traffic autonomy, weather and consistent scenario variability, including initiation locations and times *(Camara et al., 2020; Colley & Rukzio, 2020; Deb et al., 2018; Holländer, Colley, et al., 2019; Nuñez Velasco et al., 2019; Pillai, 2017)*. These different digital contextual environments allowed for the surroundings of the visual environment, expected traffic behavior, signage and traffic regulations to be adapted to the respective cultures and avoid a negative effect on the representativeness of the findings caused by cultural unfamiliarity *(Eisele & Petzoldt, 2022)*. Additionally, the added acoustic and visual noise addressed concerns of previous research, which stated that the lack of included visual or cognitive distraction could reduce the representativeness of the gathered results *(Winter & Dodou, 2022)*. Lastly, for the completion of the studies in several cultures, VR provided a cost-effective manner, avoiding the logistical and safety challenges of real-world testing.

Despite these advantages, conducting studies in VR come with certain limitations. One of the most notable limitations is the potential lack of ecological validity, as studies have found that behaviors observed in simulated environments do not fully replicate those in real-world settings *(Wilbrink, Lau, et al., 2021)*. Similarly, studies comparing real-world and VR for gaze precision showed that the results in VR may be significantly worse than the results gathered in real-world *(Pastel et al., 2021)*. Not only that, when replicating the same study design in video, VR, and real-world (i.e., Wizard of Oz) significant differences in results were found *(Fuest et al., 2020)*.

Another used data collection method was surveys as they were a cost-effective manner to quickly gather data from a larger sample while ensuring anonymity. Additionally, the anchored Likert-scales, one of the most frequently used instruments to measure psychological constructs, offer highly reliable person ability estimates and data that can be easily compared *(Nemoto & Beglar, 2014)*. However, these types of survey do introduce certain limitations as they are heavily dependent on the participant's introspective ability, interpretation of the encountered questions, and ability to accurately recollect events, and can be prone to biases, such as social desirability bias *(Grimm, 2010)*.

To address these limitations, future research should incorporate real-world field studies, such as Wizard of Oz experiments. The benefit of this approach is the ability to gather insights into user perceptions and interactions in a more naturalistic setting. Longitudinal studies would also be a valuable research continuation, as they could measure the evolution of trust, reliance, cognitive load and interaction behaviors of HRUs over extended periods of time. Through such studies, a more complete picture of the learning effects and potential unexpected outcomes could be gathered. These findings may help to identify whether over-reliance, mistrust, misuse or abuse of AVs and eHMI systems occurs.

Additionally, the quantitative measures used in the current studies, while including both subjective and objective data, are limited in scope. Research methodologies increasingly emphasize mixed-methods strategies, gathering both quantitative and qualitative data *(Kaß et al., 2020)*. Expanding these methods to include qualitative data by employing interview or participatory design methods could actively involve users from different culture in the development process of eHMIs and identify what lays behind a culture's unique needs and preferences *(Chen et al., 2023)*. Further research could also include measures such as cognitive load assessments, eye-tracking and physiological measures (e.g., heart rate variability) to offer deeper insight into the emotional and cognitive impact of eHMI and AVs on HRUs.

Scalability: Extending Interaction Paradigms

The current research focused on relatively simple interaction paradigms. These interaction paradigms depend on several factors.

First, how many involved parties are considered in the interaction. This research primarily examined scenarios where a single AV interacts with a single HRU. Investigating single AV-HRU interactions offered controlled environments for testing foundational eHMI designs. This focus also isolated key variables in a manageable, feasibly scope and excluded the introduction of additional interaction effects. However, traffic scenarios often involve more communication partners. These interactions vary greatly and can include multiple AVs, multiple HRUs, and mixed traffic environments to ensure scalability, which is an important, yet underexplored aspect of eHMI *(Colley, Walch, & Rukzio, 2020; Dey, Van Vastenhoven, et al., 2021; Y. Gao et al., 2023)*. In contrast, additional pedestrians may also influence crossing decisions as they may look to others for cues instead *(Wilbrink, Nuttelmann, et al., 2021)*. Future research should include situations where multiple AVs and HRUs are interacting simultaneously. This would provide valuable insights into how eHMIs function in more crowded or chaotic environments, where signaling between multiple parties must be coordinated and happen simultaneously. The challenge for eHMIs lies in ensuring that the attention of multiple users can be managed without causing confusion or misinterpretation.

Secondly, the urgency and type of scenario—such as a pedestrian needing to cross quickly or emergency braking—also impacts the design requirements for eHMIs. In urgent situations, pedestrian require immediate and clear communication that fosters quick decisions (*Dey, Matviienko, et al., 2021; Dey, Temmink, et al., 2021)*. Similar findings have been found in study 1, which indicated that HRUs prefer different types of eHMI depending on the urgency of the situation, however these urgent scenarios have not been considered in the following studies. Yet, these different needs require the development of dynamic and responsive eHMI designs that adapt to the urgency of the situation. Additionally, HRUs encountering non-urgent scenarios that have little to no ambiguity—such as pedestrians crossing the street on a green pedestrian light in front of a stopped AV—may require no additional information provided by eHMIs. Additional information may even lead to negative effects due to "*over information*" or misalignment with expectations, or worse, if the eHMI and traffic lights give opposing information. Not only that, depending on the communication partner involved, it may also change as they have different information needs and expectations *(Auinger et al., 2011; Colley & Rukzio, 2020; Rasouli & Tsotsos, 2020; Weber et al., 2019)*. Future research would benefit from investigating when to communicate and in which traffic scenarios eHMIs are most beneficial. For example, exploring urgent safety-critical situations, as such scenarios could benefit greatly from clear and immediate communication. Research should classify different traffic scenarios and examine how eHMIs could improve outcomes in each type. By doing so, clear guidelines can be developed that could support research foci and aid policymakers in the development of regulations for eHMI.

Expanding the scope of these interaction paradigms will lead to the development of eHMI systems that have higher scalability, ensuring that eHMI designs work effectively in a variety of traffic scenarios, from simple one-on-one interactions to complex multi-actor environments. Additional insights into which traffic scenarios genuinely benefit from eHMIs will also help to create more context-sensitive communication systems and reduce information "*pollution*", in eHMI which could overstimulate HRUs or reduce the impact of eHMI in general.

6.4.2.

Reflections in a Broader Context

Beyond the methodological considerations, placing the findings of this thesis within the broader technological, societal, and regulatory landscapes reveals new challenges and opportunities. AVs are rapidly evolving, with artificial intelligence (AI) and automation reshaping the way they behave in traffic. The role of eHMIs, the future of traffic systems, and the automotive industry itself will be heavily influenced by these advancements. This section discusses the broader implications of this research, highlighting key areas for future exploration and consideration.

Transition Phase Towards Autonomous Driving

The transition towards fully autonomous vehicles (FAVs) will not be immediate. In the short to medium term, a mixed traffic environment is expected, where HRUs encounter both traditional vehicles and AVs with varying levels of autonomy. One of the critical questions during this phase is whether HRUs should be able to easily identify the level of autonomy of vehicles.

While transparency is often emphasized in the literature as a way to ensure HRUs feel confident interacting with AVs, the constant signaling of a vehicle's autonomy level may not always be beneficial. Overloading HRUs with information about the autonomy of surrounding vehicles could lead to cognitive overload, resulting in lower situation awareness, affected decision-making, inaccurate perceptions, and confusion *(Endsley, 2016; Silva, 2014; Vidulich & Tsang, 2012)*. In other words, this increased complexity in traffic may hinder rather than help HRUs.

The continuous signaling of an AV's autonomous driving mode could lead to additional challenges. If HRUs are aware that an approaching vehicle is autonomous, they might alter their approach or interaction with it, especially since many HRUs are unfamiliar with such vehicles during the transition phase. This uncertainty can, in turn, cause the AV to become unsure of how to respond. This sets off a feedback loop: the HRUs, feeling uncertain from their previous encounter, become more hesitant in future interactions. The AV, in turn, "*learns*" this hesitation and adjusts its driving model accordingly, further perpetuating the cycle of uncertainty and anomalous behavior, affecting traffic safety *(Dey et al., 2017; Rothenbucher et al., 2016; Tapiro et al., 2019; Wagner, 2016)*. On the other hand, if HRUs were unaware of the vehicle's autonomous status, they might approach the AV more naturally, without the added layer of hesitation, which could result in smoother, more predictable interactions.

Given the potential for cognitive overload and introducing negative feedback loops, it is essential to explore whether signaling autonomy levels should be a norm or an exception. Research should focus on whether long-term exposure to AVs would reduce the need for explicit autonomy signaling, and whether other forms of communication—such as consistent AV behavior patterns—might be more effective.

Psychological Impact of Long-Term Interaction with AVs (and eHMIs)

Humans are highly adaptive creatures. While the introduction of AVs and eHMIs may initially lead to uncertainty, HRUs will likely adjust quickly. However, this adaptation could bring both positive and negative effects. On one hand, AVs could become an accepted part of traffic, leading to smoother interactions. On the other hand, skill degradation among human drivers, misuse, abuse, and mistrust—or over-trust—of AVs could emerge as long-term challenges.

While the assumption is that well-designed eHMIs can facilitate balanced interactions, long-term exposure might lead to problematic shifts in behavior. Research has already shown that some pedestrians overestimate the capabilities of AVs *(Hochman et al., 2024; Rezwana & Lownes, 2024)*. Cyclists also seem to take advantage of predictable AV behavior, and drivers exhibit aggressive behaviors toward AVs *(Deshmukh et al., 2023; Gaio & Cugurullo, 2023)*. These behavior shifts could result in unsafe or inefficient traffic patterns.

A well-designed eHMI should strike a balance: it should not encourage blind reliance, nor should it evoke unnecessary skepticism. However, AVs must also be designed to prevent misuse—both from those who place too much faith or reliance in automation and those who seek to exploit it *(Parasuraman & Riley, 2016)*. In other words, eHMIs should be designed to generate appropriate trust and reliance in order to support the successful introduction of both AVs, eHMIs and other automated systems *(Hjetland, 2015; Holländer, Wintersberger, et al., 2019; Körber et al., 2018; J. D. Lee & See, 2004)*. Long-term studies investigating strategies that prevent over-trust and promote responsible interactions will be crucial in shaping the future of AV-HRU communication *(Oravec, 2022)*. Understanding these long-term psychological impacts will allow designers to develop systems that remain resilient over time, thereby promoting safe, effective traffic interactions.

The Future of eHMI

Currently, eHMIs provide a reliable method for conveying AV intentions and addressing cultural differences by standardizing cues. This approach works within the technological constraints of today's autonomous driving models, which is still developing its ability to fully interpret and adapt to human behavior. However, the data used to train these models may unintentionally reinforce undesirable behavior patterns. Currently, AVs exhibit anomalous behavior, which negatively affects traffic safety *(Dey et al., 2017; Rothenbucher et al., 2016; Tapiro et al., 2019; Wagner, 2016)*. HRUs encountering such behavior may respond with hesitation or confusion, which, when fed back into the system, perpetuates the cycle of anomalous behavior. This results in both AVs and HRUs struggling to adapt to each other's actions, ultimately compromising safety. Therefore, further research is essential to optimize AI and eHMI communication to avoid these adverse effects.

Artificial Intelligence (AI) has the potential to significantly enhance eHMIs. With the rapid advancement of AI capabilities, AVs are likely to become increasingly sophisticated. These advancements may enable AVs to recognize who they are communicating with and seamlessly adapt eHMI design to fit to the cultural expectations of different HRUs. Furthermore, AI could enable data-driven personalization, allowing eHMIs to tailor communication to individual needs, optimizing user experience, reducing decision times, and improving traffic safety. This could lead to smoother traffic flow and greater inclusivity on a global scale. Research in this area could result in more culturally sensitive and intuitive communication, enhancing safety and user satisfaction.

Alternatively, standardization of eHMI design may provide a more practical solution. By ensuring consistency, standardization enables road users from diverse backgrounds to interact smoothly with AVs. However, even when communication methods are standardized, cultures often adapt them to fit their specific needs. To address this, future eHMIs may need to incorporate AI-driven adaptability to adjust eHMI settings based on real-world interactions. This would allow communication systems to evolve over time while maintaining a standardized baseline. Nevertheless, eHMI standardization should be guided by input from industry leaders, governments, and road users, with researchers and human factors experts playing a key role in ensuring these systems remain effective and intuitive.

Looking ahead, as AI, AVs, and Human-Computer Interface (HCI) technology advances, the need for explicit eHMIs may diminish. While eHMIs are currently a primary method for AVs to communicate with HRUs, alternative technologies could eventually replace or complement them. For instance, Brain-Computer Interfaces (BCIs), Augmented Reality (AR), and Vehicle-to-Vehicle (V2V), Vehicle-to-Network (V2N), or Vehicle-to-Infrastructure (V2I) systems could bridge the communication gap without requiring eHMI integration on vehicles. BCIs enable direct

communication between humans and vehicles via brain signals, allowing AVs to sense pedestrians' intentions without the need for external displays or gestures. These technologies could lead to more immersive and intelligent communication methods integrated into the traffic infrastructure, reducing the number of signals shown and decreasing cognitive load for HRUs, minimizing misinterpretations. Moreover, this would ensure that the right information is shown at the right time, even in multi-actor environments.

As AI technology continues to evolve, the need for explicit eHMIs could become obsolete. With AI capable of perfectly mimicking human driving behavior and understanding the subtle nuances of human communication, AVs could anticipate and respond to human intentions with the same precision as a human driver. This would reduce anomalous behavior and facilitate more natural interactions. In such a scenario, implicit communication methods—such as adjusting a vehicle's suspension to signal braking or tilting forward when accelerating—could replace explicit visual cues. This would make eHMIs redundant, as the vehicle's behavior would naturally communicate its intentions, fostering seamless interaction between AVs and HRUs.

Future research should focus on optimizing AI algorithms to improve AV behavior, reducing anomalous actions and enhancing natural human-AV interactions. Additionally, studies should explore the potential of AI-driven eHMI adaptability and data-driven personalization, evaluating their effectiveness across diverse cultural contexts. Research into alternative communication technologies, such as Brain-Computer Interfaces and Vehicle-to-Infrastructure systems, should also be pursued to assess their viability in replacing or complementing traditional eHMIs.

Ethical and Legal Considerations in eHMI Development

The ethical dilemmas surrounding AVs and eHMIs are unavoidable. The well-known "*Trolley Problem*" serves as a metaphor for the dilemma's that AVs face in critical situations, where decisions must be made between conflicting moral outcomes in life-and-death situations *(Thomson, 1984)*.

The "*Trolley Problem*" typically involves a runaway trolley headed toward five people tied to a track. You, as an observer, can pull a lever that will redirect the trolley onto another track where only one person is tied. The question is:

Should you pull the lever to save the five people at the cost of one person's life, or should you refrain and allow the trolley to kill five, preserving the life of one?

The ethical dilemma arises from asking yourself: *Who should live and who should die? Is it better to act or not act? And, how do we weigh the value of lives?* These situations can be endlessly adjusted and adapted to reinitiate the moral considerations and highlight different values that factor into these decisions.

Since AVs and eHMIs are programmed to make choices without human drivers at the wheel, they would theoretically face similar moral dilemmas, such as deciding how to prioritize the lives of pedestrians, passengers, and others in various emergency scenarios. There is also the broader question of fairness and equity. *Will these systems work effectively across different user groups, including vulnerable populations such as elderly pedestrians or those with disabilities?*

Additionally, AVs face legal dilemma which includes determining where liability lies in the case of failure or loss of life: *With the OEM, the insurance company, the policy makers, the programmers, or the non-driver/owner of the vehicle?* The list goes on. The ethical and legal dilemmas are a well-known discussion point *(Adnan et al., 2018; Maurer et al., 2016; Santoni De Sio, 2017)*.

While discussions on ethics often focus on how AVs should make moral choices, another are legal dilemma's such as determining liability. *If an accident occurs, who is responsible? The manufacturer? The software developer? The policymaker? The non-driving vehicle owner?* While uncomfortable, history has shown that societies are capable of assigning value to human life in legal and financial contexts. It is likely that policymakers will develop a framework to quantify and mitigate AV-related risks. However, these ethical dilemmas must be solved in a way that ensures public trust and fairness. Not only that, the final resolution of these questions may also define how AVs are integrated into society.

Research into the ethical and legal implications of eHMI systems should provide critical insights into how these technologies should be regulated and deployed. Understanding these considerations will ensure that eHMI systems are safe, equitable, and legally sound, fostering public trust and protecting vulnerable HRUs.

The Future of Branding in the Automotive Industry

Platform sharing — where OEMs use the same underlying technologies and platforms for their AVs to reduce development costs — is becoming increasingly common in the automotive industry.

The rise of electric vehicles (EVs) seems to have accelerated this trend further. However, platform sharing limits opportunities for brand differentiation in vehicle design. This raises the question of how traditional branding strategies might need to adapt. With fewer opportunities for brand expression in vehicle design, OEMs may be forced to find new ways to differentiate their products and safeguard their brand differentiation and equity. This may include incorporating branding elements into features like eHMIs with small software adjustments, regardless of negative effect on interaction experience of HRUs. Moreover, the contrast between an 'unbranded' eHMI and the stylized design of a vehicle's exterior may lead to unidentified side effects that warrant further exploration, such as confusion, increased mental workload, and surprise.

Hence, future research would benefit from developing branded eHMI solutions in collaboration with different car brands to investigate if different types of branding designs or brand-free designs perform well for a wide range of vehicle models and types. With this approach, future research could complete structured comparisons between different types of vehicles with branded and unbranded eHMIs and better determine the nuances in the impact of branding on HRUs. Moreover, researchers, policy makers and OEMs should work together to determine whether some type of negative subjective effect is acceptable as the value of this effect may outweigh the value of brand expression. Additional deep dives into the long-term effects of branding of the effectiveness of eHMIs could provide additional benefits, especially when exploring the long-term effects between no branding and branded eHMIs.

Beyond eHMI

This thesis provides valuable insights not only for the design of eHMIs but also for a broader range of design disciplines and future research fields. By exploring how cultural differences shape expectations and preferences in human-machine communication, the findings have implications for industries beyond AVs.

Sectors like wayfinding, navigation, and branding can benefit from this research. Especially in international settings, such as airports or hospitals, where people from various cultural backgrounds interact, designing culturally sensitive signs and visualizations becomes crucial. Similarly, in digital design fields—such as websites and smartphone interfaces—understanding how culture affects user interaction will become more important as globalization and digitization continue to influence behavior. This thesis points towards multi-modal communication systems (incorporating visual, auditory, and haptic elements) and learned representations—like color coding and symbol usage—both of which can significantly improve user experience across diverse contexts for potential starting points in these different disciplines and research fields.

Moreover, design in a globalized world may require to increasingly adopt modular approaches. Such an approach would combine universal design elements that ensure compatibility across cultures and industries with localized adaptations that optimize the user experience in specific cultural contexts. For example, some design components, like basic navigation symbols or color codes, should be standardized globally to ensure consistent understanding, while others, like specific content or interface features, should be tailored to reflect cultural preferences. This balance can reduce development costs and improve the overall effectiveness of designs by making them more relevant and accessible in different cultural environments.

Moreover, as human-machine interaction (HMI) continues to evolve, especially with the rise of AI, the way we communicate with machines is also changing. As more people interact with AI and similar technologies, we can expect AI-natives—individuals who have grown up with ubiquitous AI technology—to have different expectations and communication preferences compared to previous generations. While this thesis did not uncover any immediate, large-scale paradigm shifts, considering the ongoing integration of AI into daily life may be important in the future. Over time, as people become more accustomed to AI, comfort and familiarity will increase, and future generations will likely develop new norms for communicating with these technologies, resulting in different expectations and challenges for HMI.

6.5.
Concluding Remarks

This thesis addresses a pressing societal issue: how to bridge the communication gap created by the removal of human drivers in AVs. By developing eHMI systems that enable AVs to signal their intentions clearly and intuitively, this research contributes to improving road safety, reducing misunderstandings in traffic, and facilitating the wider adoption of AVs.

The thesis aims to make significant contributions to the field of eHMI by exploring cultural influences, developing design guidelines, exploring branding freedom, and proposing an adaptive multi-modal eHMI system that navigates the tension between the conflicting demands of cultural adaptation and global standardization.

The presented research shows clearly that culture plays a role in shaping how human road users perceive and interact with AVs, requiring us to rethink global design approaches for eHMIs and approach these types of solutions with caution. Furthermore, the research highlights that branding in eHMI design is a precarious consideration, as its impact varies across cultural contexts and must therefore also be carefully considered.

The proposal for a culturally adaptive yet technologically universal multi-modal eHMI framework strikes a balance between the need for standardization and customization, offering a promising direction for future eHMI systems.

Ultimately, this work not only advances academic understanding of eHMIs but also offers design guidelines and insights for practice. As AVs become an integral part of our traffic system, the future of eHMI design will likely require further interdisciplinary collaboration, iterative testing, and careful consideration of both cultural, ethical, legal and technological developments.

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Curriculum Vitae

Anne-Marie Julie Barthe Wesseling was born on 11 September 1992 in Woerden, the Netherlands. She completed her pre-university education at Scala College in 2011. From 2011 to 2015, she studied Industrial Design Engineering at Delft University of Technology, including an Automotive Minor, and obtained a Bachelor of Science. She continued with a Master of Science in Integrated Product Design at Delft University of Technology, graduating in 2018.

In 2017, she completed an internship at Volkswagen AG within Group Innovation, during which she wrote her Master's thesis entitled "Augmented Reality-based Driver Interaction – Aspects of Situational Awareness, Automotive Branding and User Experience." From December 2018 to November 2022, she was a Doctoral Candidate at Volkswagen AG, conducting research on external Human-Machine Interfaces for Autonomous Vehicles. This doctoral research is conducted at Volkswagen AG in collaboration with the Faculty of Industrial Design Engineering at Delft University of Technology. Her dissertation, entitled "Teaching Cars How to Speak Human," explores cultural differences and automotive branding related to communication systems between autonomous vehicles and human road users. Since December 2022, she has been working full-time as a UX Designer & Researcher at Volkswagen Group Innovation in Wolfsburg, Germany, while continuing to work on her doctoral dissertation in her free time.

Publications associated with this thesis

Wesseling, AM.J.B., Mugge, R., van Grondelle, E., Othersen, I. (2020). *Exploring Universal and Cultural Preferences for Different Concepts of Autonomous Vehicles' External Communication in China, USA and Germany.* In: Rau, PL. (eds) Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments. HCII 2020. Lecture Notes in Computer Science, vol 12192. Springer, Cham. *https://doi.org/10.1007/978-3-030-49788-0_49*

Manuscripts ready for submission

Wesseling, A.J.B., Mugge, R., van Grondelle, E.D. (2025). *Identifying Cultural and Universal Guidelines for Message Coding of External Human-Machine Interfaces: A VR-based Approach.* Manuscript ready for submission.

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