International Co-operation on Theories and Concepts in Traffic Safety

External Human-Machine Interfaces for the Interaction of Pedestrians as Vulnerable Road Users with Highly Automated, Connected Vehicles in More Complex Road Traffic Scenarios: Can AR-based Interfaces Support Pedestrians?

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Introduction, including research aim and objectives: The ongoing development of highly automated, connected vehicles (HAV; SAE 4) and their introduction into existing road traffic offers both opportunities and challenges for the interaction of road users with these vehicles. Research to date shows that pedestrians as vulnerable road users in particular can experience disadvantages in certain situations with the elimination of a human driver, as they are currently depending on explicit communication, for example hand gestures, especially in ambiguous interaction situations, particularly in close-range situations. External Human-Machine Interfaces (eHMIs) can bridge this communication gap. However, there has been a lack of research into their usefulness in more complex traffic scenarios in which more than one HAV interacts with a pedestrian. But it is precisely for these frequently realistic, often urban, more complex interactions with several road users involving HAVs that many questions remain unanswered like how good and safe interaction can be designed and ensured via Human-Machine Interfaces. In the future, augmented reality (AR) could represent a promising solution to the disadvantages of previously proposed eHMIs. The aim of this experimental study was therefore to investigate the potential of previously researched light-based eHMIs compared to possible future AR-based eHMIs in more complex interactions of several HAVs with a pedestrian in road traffic.

Research methodology: By using a 4 x 4 within-subject design, participants (N = 41) experienced a shared space scenario in virtual reality (VR). In a shared space traffic environment, no lane markings or infrastructure segregations are present, and aside from the 'right before left' rule, all traffic participants had equal rights. In these unregulated traffic environments, interaction between different traffic participants plays a major role. The study participants took on the role of a pedestrian with the task of crossing the shared space and reaching a subway station. While crossing the shared space, participants had to interact with two HAVs approaching from the left and the right side. The HAVs communicated implicitly by yielding or not yielding to the pedestrian and explicitly via light-based, AR-based, combined, or no eHMI. Consequently, the crossing initiation time (CIT) and subjective perceived safety (PS) were assessed.

Results: Regarding the CIT, a rmANOVA with Greenhouse-Geisser correction showed a significant effect of eHMI design ($F(2.29, 91.59) = 60.43$, $p < .001$). As a result, participants

initiated their crossings earlier when the HAV was equipped with any eHMIs compared to a baseline without any eHMI. Further, the AR-based conditions led to earlier crossings compared to the light-based eHMI communication strategies. Also, the combined eHMI design (AR-based plus light-based) resulted in faster crossings compared to only the light-based condition. Furthermore, the rmANOVA with Greenhouse-Geisser correction revealed a significant effect of eHMI design on the subjective perceived safety ($F(2.52, 98.38) = 37.58$, $p < .001$). In line with the results of the CIT, participants felt safer while crossing when the HAV was equipped with any eHMIs compared to the baseline without eHMI. Again, participants felt significantly safer when the communication was done by an AR-based strategy compared to a light-based eHMI interaction strategy.

Discussion and conclusions: All tested eHMIs received significantly higher ratings regarding CIT and PS compared to a baseline without eHMI which only used implicit communication. This highlights eHMI benefits in clarifying the intentions of HAVs and reducing misunderstandings. Additionally, the positive impacts of eHMIs remained consistent across different vehicle yielding behaviours in terms of implicit communication, underscoring their reliability and effectiveness. However, AR-based eHMI communication strategies outperformed light-based strategies significantly, emphasizing the great potential of this futuristic modality for enhancing pedestrian safety. Finally, this study indicates that there are no negative impacts on pedestrians when using both light-based and AR-based communication strategies combined, supporting the feasibility of multiple forms of communication when traffic participants are equipped with AR-ready mobile devices.