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Comparing implicit communication via longitudinal driving dynamics: A cross-cultural study in Germany and the UK

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A B S T R A C T

To ensure safe and uninterrupted traffic flow, (semi-)automated vehicles must be capable of providing comprehensible and agreeable implicit communication cues to human drivers. This driving simulator study investigated the assessment of implicit communication at a motorway slip road through longitudinal driving dynamics (acceleration, deceleration, and maintaining speed). The second aim of the study was to determine whether expectations of automated vehicles are different from those of human drivers. And thirdly, we investigated whether these findings are country-specific or can be (partially) generalised to other countries. The perception of three means of communication in connection with the presence of a labelling as an automated vehicle (eHMI) was examined in two samples in Germany and England. 27 participants drove from a slip road onto the motorway and interacted with another vehicle. After a stretch on the motorway, they passed a second slip road on which there was a vehicle merging onto the participants lane. This was repeated six times to test all variables. After each situation, the perceived cooperativity and criticality was recorded, as well as the time headway (THW) to the other vehicle. This paper presents the findings from the UK sample and compares them with the German results, which were previously published. Results show, that when the cooperating vehicles are on the slip road, participants from both countries prefer this vehicle to decelerate. However, when participants themselves are on the slip road, expectations for vehicles on the target lane are ambiguous in the UK sample. Except for one aspect (perceived cooperativity of decelerating vehicles on the slip road), the perception of automated vehicles is similar to those of manual drivers. Also, UK participants do not maintain a different safety distance from these vehicles, while this is the case in the German sample. This paper contributes valuable insights into the cross-cultural evaluation of driving dynamics, shedding light on implications for the development and acceptance of automated vehicles.

1. Introduction

Successful communication between all road users is one of the key contributors to safe and smooth road traffic. Communication of drivers can either be explicit (e.g., through indicators, flashing lights or hand signals), or implicit (Ceunynck et al., 2013; Imbsweiler,

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Ruesch, Weinreuter, Puente León, & Deml, 2018; Lee et al., 2021). Implicit means of communication in road traffic primarily include vehicle dynamics, i.e., lateral or longitudinal movements like decelerating or accelerating (Schaarschmidt et al., 2021). In a previous study, the evaluation of these tangential movements for implicit communication at motorway slip roads was investigated, using a sample of German drivers (Ehrhardt, Roß, & Deml, 2023). In addition to using three communicative behaviour patterns (decelerating, accelerating, and maintaining speed), the influence of a status eHMI, that labelled the vehicle as automated, was investigated. The aim of the study was to investigate if participants have different expectations on the implicit communication of automated vehicles than for human drivers. The present study adds one more aspect to these questions, namely that of cultural influence. To this end, the original German study was replicated in the UK and the results from both driving simulator studies are compared in this paper. The findings are aimed at contributing to the design of more human-centred automated vehicles by determining which implicit means of communication are preferred and whether this preference applies equally to manual and automated vehicles. The results are also expected to provide indications as to whether automated vehicles need to have country-specific modes or whether the similarities between at least some countries are similar enough to allow the vehicles to cross national borders without the need for adaptation.

1.1. Theoretical background

The gradual introduction of automated driving is already leading to the presence of partially automated vehicles (AVs; SAE Level 2 or higher) on our roads, sharing the traffic infrastructure with manually controlled vehicles (MVs). This results in a mixed traffic setting. According to Markkula et al. (2020), this mixed traffic will lead to so-called "space-sharing conflicts" between AVs and MVs. Space-sharing conflicts are defined as situations in which "two or more road users are intending to occupy the same region of space at the same time in the near future" (Markkula et al., 2020, p. 736). A particular example of a space-sharing conflict is a motorway slip road. These often include merging path conflicts and represent a critical traffic situation in human–human interactions. At the same time, driving on the motorway is one of the first driving situations where automated driving is possible. In 2021, the first vehicle in Germany received approval for automated driving at SAE Level 3 for the "Drive Pilot" (Mercedes-Benz Group, 2021), an automated assistant for driving on the highway up to 60 km/h. SAE level 3 refers to "conditional driving automation" (On-Road Automated Driving Committee, 2021) and describes a driving function in which the vehicle takes over longitudinal and lateral control, but the driver must be ready to take control at all times. The Operational Design Domain (ODD) of the "Drive Pilot" is currently limited to the motorway itself, while motorway slip roads lie outside the ODD.

1.1.1. Communication on motorway slip roads

Communication in road traffic is often described using the Shannon-Weaver model (Shannon & Weaver, 1949), which was originally developed to improve telecommunications. The model can be applied very well to automated driving, as it is used to describe short, directed messages, which are often prevalent in fast-moving traffic. According to the model, a message is encoded by a transmitter, decoded by the receiver, and possibly impaired by noise during transmission. In the case of the motorway slip roads, for example, the vehicle on the slip road is the transmitter, communicating the intention to change lanes behind another vehicle by braking slightly. This signal must be understood and correctly interpreted by the receiver (drivers of adjacent vehicles). Such communication may of course be impaired by poor visibility or distraction of the driver. For automated vehicles to be part of a successful communication with human drivers, they must be able to encode the manually driven vehicle's behavioural intention, as humans do. In addition to the communication just described above via driving dynamics (braking to indicate the intention to perform an action after another person), there are many other means of communication used by humans in road traffic. For a list, see Schaarschmidt et al. (2021).

These means of communication are often divided into implicit and explicit. Hand gestures, headlight flashes or indicators are seen as explicit communication, while driving dynamics (e.g. braking, accelerating) are classified as implicit communication (Ceunynck et al., 2013; Imbsweiler, 2019; Kauffmann, Winkler, Naujoks, & Vollrath, 2018; Rettenmaier & Bengler, 2021). According to Lee et al. (2021) and Ceunynck et al. (2013), implicit communication is the most commonly used, while explicit communication signs rarely occurred in the examined scenario.

The perception of vehicle dynamics as a means of communication between drivers has mainly been investigated in urban traffic (Björklund & Åberg, 2005; Imbsweiler, 2019; Rettenmaier & Bengler, 2021; Rettenmaier, Dinkel, & Bengler, 2021). According to Imbsweiler (2019), accelerating or maintaining speed tends to be perceived as an aggressive signal by other road users, whereas braking is perceived as defensive. In a naturalistic driving study, they found that accelerating is understood as a clear signal of the intention to perform a manoeuvre in front of another road user, in this case driving through an intersection before another vehicle. Accelerating is also rated as less cooperative than yielding in unambiguous situations, while being considered more cooperative in complex situations (Imbsweiler, 2019). Other studies also show that accelerating or maintaining speed is associated with the intention to drive (first), while braking is understood as yielding (Björklund & Åberg, 2005; Rettenmaier et al., 2021). As the studies just mentioned all relate to urban traffic, we will attempt a further approach to implicit communication on motorway slip roads through the following study considering lane changes on the motorway.

In a driving simulator study Kauffmann et al. (2018) investigated the effect of lateral driving dynamics on perceived willingness to cooperate and perceived criticality during lane change on motorways. They found that a slower lane change duration on the motorway is perceived as more cooperative, but the duration of the lane change does not influence drivers' perceived criticality. In this study, the longitudinal acceleration affected drivers' perceived criticality, with a delayed longitudinal acceleration being perceived as more critical. In a second study, the participants changed lanes in heavy traffic and evaluated the behaviour of the vehicle in front of which they were merging (Kauffmann et al., 2018). The more the vehicle in the rear braked when the participants changed lanes, the more cooperative and less critical its driving behaviour was rated. However, both studies relate to unforced lane changes (which are not mandatory but serve the comfort or the maintenance of the speed), while lane changes on motorway slip roads are considered foced lane changes (Balal, Cheu, Gyan-Sarkodie, & Miramontes, 2014).

Using a video-based setup, Ehrhardt et al., 2023 investigated lateral driving dynamics at motorway slip roads, to study the effect of the position and duration of the lane change on the rating of cooperativity and criticality. Results showed that a slow lane change (6 s) is rated as more cooperative and less critical than a quick lane change (2 s). In addition, a lane change in the middle of the acceleration lane is rated most positively.

Stoll, Weihrauch, and Baumann (2020) investigated the preference for drivers' own longitudinal driving behaviour on motorway slip roads. They found that drivers preferred to decelerate when a vehicle was next to them on the motorway slip road. The original study to this present replication study investigated the other perspective of this situation, namely which longitudinal driving behaviour is preferred in the cooperating vehicle (Ehrhardt et al., 2023). It was shown that participants on the slip road consider decelerating or maintaining the speed of vehicles which are already on the motorway to be the least critical and the most cooperative. When driving on the motorway themselves, they rated deceleration by vehicles on the slip road as less critical and more cooperative than when the merging vehicles accelerated.

1.1.2. Status external human–machine interfaces (eHMIs)

External HMIs are part of the external communication of automated vehicles. Based on their function, they can be divided into four categories (Schieben et al., 2019): eHMIs in the first category (A) inform other road users about the vehicle's driving mode (also known as status eHMI). The other three categories (B-D) include more active information, such as information about future driving manoeuvres, the AV's perception of the environment and cooperation capabilities. The status eHMI (Category A) is particularly relevant for this paper. Discussions are currently taking place on whether automated vehicles should be required to display such a status display as soon as they are no longer driven by a human (Stilgoe, 2022). One argument in favour of this display status is that automated vehicles cannot always be reliably identified by surrounding traffic even if their driving behaviour deviates (Stanton, Eriksson, Banks, & Hancock, 2020). The authors suspect that this has a negative impact on road safety, as drivers use implicit means of communication on the road that an automated vehicle may not be able to understand and utilise. They therefore recommend using a status eHMI to enable drivers of manually controlled vehicles in the surrounding traffic to adapt their expectations and their own behaviour to the driving mode of the AVs. Stange, Kühn, and Vollrath (2022) expect long-term effects from status eHMIs. For example, they suggest that continuing interaction with marked AVs can help us to successively build a mental model of their driving behaviour. Creating the right mental model of an AV's behaviour during space-sharing scenarios would allow drivers of manually controlled vehicles to make more accurate predictions about the AV's future behaviour and enhancing their situation awareness (Endsley, 1995). On the other hand, some studies that suggest that vehicles labelled as automated could be outsmarted by other drivers, as it is assumed that the AVs act more passively (Liu, Du, Wang, & Da Young, 2020; Moore, Currano, Shanks, & Sirkin, 2020).

In view of this discussion, it is important to understand how a status eHMI from an AV affects other road users' response and behaviour. A number of studies have considered the effect of such status eHMI on the perception and behaviour of vulnerable road users, such as pedestrians and cyclists (Faas, Mathis, & Baumann, 2020; Hagenzieker et al., 2020; Lundgren et al., 2017). For example, Faas et al. (2020) showed that a status eHMI resulted in pedestrians feeling significantly safer when interacting with an AV and indicating more positive ratings of trust and user experience, than when the eHMI was absent. However, results are missed and other studies have failed to find such effects, especially in relation to the evaluation and behaviour by other drivers (Ehrhardt, Graeber, et al., 2023; Fuest, Feierle, Schmidt, & Bengler, 2020; GATEway Project, 2017; Stange et al., 2022).

For example, using a driving simulator study, Stange et al. (2022) investigated the effect of different penetration rates of AVs and the influence of a status eHMI on perceived safety, comfort, and perceived efficiency, as well as measuring drivers' average speed and minimum time headways. The results showed that, although the status eHMI helped drivers identify the automated vehicles in traffic, it had no influence on the subjective ratings or driving behaviour of the participants. In another driving simulator study (Fuest et al., 2020), participants followed a lead vehicle through three scenarios (roadworks, traffic jam, lane change). The lead vehicle was either labelled as automated with a status eHMI or non-automated. Regardless of the eHMI it strictly adhered to the traffic rules throughout the journey, making it stand out from the surrounding traffic. The eHMI had no significant influence on the subjective assessment of driving behaviour or distance behaviour (Time Headway, THW). Similarly, other studies did not find an effect of an eHMI on factors like gap acceptance (GATEway Project, 2017) or on the perceived criticality and perceived cooperation (Ehrhardt et al., 2023). However, the latter found that in one of the two examined situations, the participants kept a significantly greater safety distance to vehicles with eHMI.

1.1.3. Intercultural aspects

Vehicles in general, but also automated vehicles, are usually not only used in the country in which they were originally manufactured, but also (e.g. for holiday trips or through sales) in neighbouring countries or even around the world. The two countries analysed, the UK and Germany, have close relations, but at the same time differences exist in terms of infrastructure (e.g. left-hand vs. right-hand traffic). The question therefore arises as to whether the similarities or differences in traffic conditions and culture outweigh and whether automated vehicles could operate in the two countries without programming adjustments. The selected countries are very well suited to answering the question in that there is a high degree of cultural similarity, whereas apparent differences exist in the infrastructure. If cultural proximity outweighs differences in infrastructure, communication in countries with similar cultural proximity and smaller differences in infrastructure should be even more similar and, by implication, the implicit external communication of automated vehicles should also work in neighbouring countries.

Differences in road traffic between countries can be attributed to various causes. One aspect is the different infrastructure in different countries. The main difference in the road layout between Germany and the UK is obvious: in Germany, vehicles drive on the right, in the UK on the left. This results in the layout being mirrored. The structure of motorway slip roads differ beyond this aspect in that they are generally single-lane and often curved in Germany. In the UK, they mostly have two lanes and a straighter layout. The speed on motorways also differs between the two countries. In the UK a speed limit of 70 mph (approx. 114 km/h) applies, whereas in Germany there is no general speed limit on motorways, but a recommended speed of 130 km/h (approx. 81 mph).

However, this is only part of the picture, as in addition to infrastructural aspects, the culture of traffic significantly influences what is considered acceptable driving behaviour (Özkan, Lajunen, Chliaoutakis, Parker, & Summala, 2006). In psychological and sociological research, cultural differences are often classified according to the cultural dimensions of Hofstede (2011): Six relevant cultural dimensions are used to categorise a country's culture: (1) power-distance, (2) individualism vs collectivism, (3) masculinity vs femininity, (4) uncertainty avoidance, (5) long term orientation, and (6) indulgence. The UK and Germany have very similar or even identical values in four of the scales. They differ in the two scales "uncertainty avoidance" and "indulgence" (Culture Factor Group, 2023). Germany has a substantially higher score in "uncertainty avoidance", which is reflected in a greater need for control and less flexibility. This is also apparent in the road traffic regulations of the two countries, with Germany's being much more detailed and extensive than the UK's. "Indulgence" is much more pronounced in the UK than in Germany, which means that there is a greater tendency in this culture to act on impulse, to be optimistic, and to enjoy pleasure and leisure (Culture Factor Group, 2023).

While intrinsic (e.g. age or gender) and extrinsic factors such as formal traffic rules, as well as informal norms influence driving behaviour (Edelmann, Stümper, & Petzoldt, 2021; Özkan et al., 2006; Tennant et al., 2021), we do not anticipate differences in these factors between Germany and the UK, given their geographical proximity and similar scores in Hofstede's dimensions. None of the studies analysed the difference in traffic culture between the UK and Germany, but the following individual aspects are of relevance to the present study: German road culture places a high value on safety on the one hand (Wang, Cheng, Li, André, & Jiang, 2019), but also on individual freedom on the other. This can be observed in the widespread resistance to a general speed limit for motorways. British drivers score very low in terms of aggressive offences on the road, but are more likely than other countries to be guilty of "speeding on the motorway" and "pulling out, and forcing your way out" (Özkan et al., 2006). Beyond the aspects named above, culture not only has an influence on driving behaviour and road safety, but also on the perception of automated driving (Edelmann, Stümper, & Petzoldt, 2021; Tolbert & Nojoumian, 2023). However, no comparison was made between the UK and Germany here.

The aim of the study was to investigate whether differences between the two countries exist in the evaluation of implicit means of communication on motorways. Even though some of the studies mentioned above suggest that differences may be found, due to the high similarity in the Hofstede dimensions and the geographical and cultural proximity, we hypothesise no differences in the results of the two samples.

1.2. Hypotheses

The following hypotheses were derived from the literature, whereby hypotheses H1 & H2 were adapted from the German to the UK study (cf. Ehrhardt et al., 2023):

H1a.	Drivers on the slip road perceive a deceleration of the vehicle in the nearside lane as more cooperative and less critical than acceleration and maintaining speed.
H1b.	Drivers in the nearside lane of the motorway perceive deceleration of the merging vehicle on the slip road as more cooperative and less critical than acceleration and maintaining speed.
H2a.	There is no significant difference in the cooperation partners' perceptions of cooperation and criticality between manual and automated vehicles with identical behaviour.
H2b.	There is no significant difference in the distance behaviour towards manual and automated vehicles with identical behaviour.
H3.	There are no differences in the result profiles between the German and UK samples.

2. Material and methods

The current study is a replication of the study previously published in Ehrhardt et al., 2023 in which a German sample of drivers were recruited. An ethics approval for both studies was obtained from the Ethics Council of the Karlsruhe Institute of Technology. The results from the original study are used to assess the effect of cultural differences on the dependent variables. In the following section, the methodology of data collection in the UK is described, differences to the methodology in Germany are discussed in 2.6.

2.1. Participants

Participants were recruited via the institute's own database, and through various local Facebook groups. Inclusion criteria were possession of a UK driving licence, fluency in English and an age range of 20–40 years. The last condition was chosen to match the German sample. A power analysis performed with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) based on the effect sizes of the original study resulted in a target sample size of 28 participants.

Data from 27 participants in the UK sample were included in the analysis. Four participants were female (15 %) and 19 were male (85 %). The original study from Germany included 32 participants, of whom ten (31 %) were female (Ehrhardt et al., 2023).

Descriptive statistics of both samples can be found in Table 1. Sample differences were calculated using a t-Test.

2.2. Setting

Data from the UK sample was collected in the University of Leeds Driving Simulator (UoLDS). The simulator consists of a Jaguar S-Type in a spherical projection dome with a projection angle of 300° (see Fig. 1). In addition, the wing mirrors are equipped with screens. Furthermore, the simulator has a motion system with eight degrees of freedom. However, this was not used in the study to ensure compatibility with the study using the German sample. At the KIT in Germany, on the other hand, a static driving simulator based on a VW Golf 6 automatic was used, which features a modernised digital speedometer display. A curved screen and three projectors provide a 180-degree field of vision, while the view to the rear is made possible by displays in the mirrors (see Fig. 1). For a more detailed description of the setup in Germany, please see Ehrhardt et al., 2023.

Each test run consisted of two individual scenarios. The first began on the slip lane of a motorway junction, from where the participants merged into the traffic on the three-lane motorway. The first cooperation situation with a drone car took place during the merging situation. The "drone car" is the vehicle whose behaviour and appearance were manipulated for the purpose of the study and with which the participants interacted at the slip roads. After approximately 2 km (1.2 miles) on the motorway, the participants passed an exit slip road and then 1.3 km (0.8 miles) later reached a second entry slip road on which a drone car was located. The second cooperation took place as the second drone car drove along the slip road onto the motorway. The participants were instructed to stay in the nearside lane of the motorway to ensure the interaction. Additionally, traffic adapted to the speed of the participants prevented them from changing to the adjacent lane. Shortly after this situation, the scenario ended with a grey screen. For an overview of the test track, see Fig. 2. As there were 2x3x2 independent variables overall (see 2.3), each participant completed 12 scenarios over six runs.

2.3. Independent variables

To test the hypotheses, three independent variables were manipulated: the participants perspective, the behaviour of the cooperation partner and the presence of labelling of the automated vehicle with a status eHMI. In addition, the study was conducted with samples from two countries (Germany and the UK) to investigate the cultural influence on behaviour assessment, resulting in a 2x3x2x2-Design.

2.3.1. Perspective

Motorway slip roads are experienced by drivers from two perspectives: firstly, they use them to join the flowing traffic on the motorway themselves. Secondly, on a longer journey on the motorway, drivers pass many other slip roads on which there may be other vehicles that want to merge into the driver's lane. Their expectations and motivation may differ in these two situations. In this study, each participant first merged from the slip road onto the motorway while interacting with an approaching car in the left lane. After a stretch on the motorway, they passed another slip road, from which a car drove onto the participant's lane. Thus, both perspectives on a motorway slip road were covered: their own slip road as well as the slip road of another vehicle while driving in the left lane of the motorway (in the German sample, the participants were on the right lane, of course, due to right-hand traffic). Because of the layout of the test track, this independent variable was not randomised; the participants experienced the two perspectives alternately, starting with their own slip road.

2.3.2. Behaviour

Three longitudinal communication behaviours emerge from the literature, which are associated with different behavioural intentions and were perceived as different desirable in previous studies. We therefore manipulated the behaviour of the vehicles with which the test subjects interacted at the slip roads in three ways: the vehicles accelerated, maintained the participants speed, or decelerated. In each of the three conditions, the drone car initially matched its speed to that of the participants so that they travelled side by side for a certain distance until a decision point. From the decision point, the behaviour varied as shown in Table 2. The decision point was at the end of the right (offside) lane of the two-lane slip road, at the first position where the lane change becomes possible. The three behaviour patterns were completely randomised between participants.

2.3.3. eHMI

In addition to the behaviour of the drone cars, their appearance was also manipulated: An external status HMI (eHMI) was added in the form of a surrounding turquoise light band (see Fig. 3). Previous studies suggest that these status eHMI do not influence the

Table 1
Means and standard deviations of demographic data for both samples.

Variable	UK Sample ($N = 27$)		German Sample ($N = 32$)		Differences
	M	*SD*	*M*	*SD*	*p*
Age	26.07	5.42	25.44	3.72	0.600
Driving licence possession (in years)	6.74	4.97	7.15	3.58	0.715

Note. M and *SD* represent mean and standard deviation, respectively.

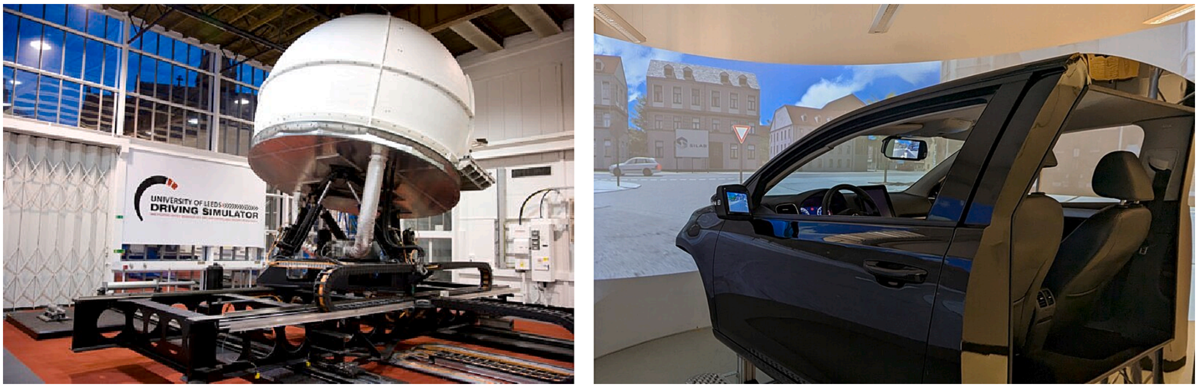

Fig. 1. University of Leeds Driving Simulator (UoLDS; left) and KIT Driving Simulator (right).

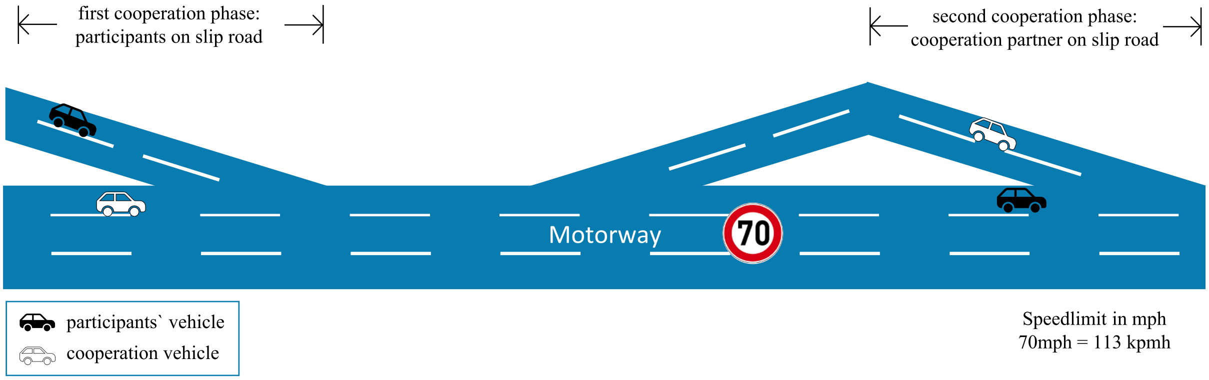

Fig. 2. Overview of the test track.

Table 2
Behaviour of the drone cars on the nearside lane of the motorway and the slip road, respectively.

	Participant on slip road	Participant on nearside lane, passing a slip road
Accelerating	Accelerate to 130 km/h (approx. 80 mph)	Accelerate to 130 km/h, then join the nearside lane of the motorway at the end of the slip road
Maintaining Speed	Maintain participants's speed (speed at the decision point)	Maintain the participants's speed (speed at the decision point), then join the nearside lane of the motorway at the end of the slip road
Decelerating	Decelerate to 50 km/h (approx. 31 mph)	Decelerating to 50 km/h, then join the nearside lane of the motorway at the end of the slip road

Fig. 3. Drone car on the nearside lane of the motorway with eHMI.

participants evaluation of and behaviour towards the labelled vehicles (Ehrhardt, Graeber, et al., 2023; Fuest et al., 2020; GATEway Project, 2017; Stange et al., 2022). Confirmation of these results is important both for the political decision for or against mandatory labelling and for the question of whether the results of research on human interaction behaviour can be used in the development of automated vehicles. Following Maurer, Gerdes, Lenz, and Winner (2015), this light band was to indicate that the vehicle was in automated driving mode. Vehicles without eHMI were equivalent to human drivers. The participants were instructed about the meaning of the eHMI before the start of the study and were shown sample images of vehicles with and without status eHMI. They were instructed that these labelled vehicles are not controlled by humans, but entirely by an automated system. The display of the eHMI was randomised, with either the first half (1–6) or the second half (7–12) of the scenarios being run with eHMI.

2.4. Dependent variables

To measure the evaluation of the drone cars' behaviour, two subjective and one objective dependent variable were captured. After each scenario, the participants were asked to rate the criticality of the situation on an eleven-point Likert scale from (0) "not at all critical" to (10) "extremely critical", based on Neukum and Krueger (2003). The rating is divided into five categories. A rating of (0) corresponds to the category "nothing noticed", (1–3) falls into the category "noticeable", (4–6) describes impaired driving, (7–9) classifies the situation as dangerous and a rating of (10) describes the vehicle as no longer controllable. They were also asked to rate the cooperativeness of the interaction partner. This was done on a seven-point Likert scale from (1) "very uncooperative" to (7) "very cooperative" as defined by Imbsweiler (2019). The participants completed the rating verbally via radio while they continued driving. The scales were presented to the participants during the pre-questionnaire and the experimenter repeated the respective scale each time the rating was requested.

As an objective measure, the time headway (THW) was analysed. THW was calculated by dividing the distance between the two vehicles at the time of the lane change by the participant's speed (Maurer et al., 2015). It allows a statement about the safety distance maintained in relation to the speed driven.

2.5. Collection of descriptive data

In addition to age, sex and driving experience (possession of a driving licence in years), technical affinity, the attitude towards automated driving and the driving style were measured in a pre-questionnaire before the test drive. To capture technical affinity, the validated "TA-EG" questionnaire (Karrer, Glaser, Clemens, & Bruder, 2009) was adapted to reflect the affinity for assistance systems in motor vehicles. The number of items was reduced by selecting two questions from the four item categories (enthusiasm, complexity, positive attitude, negative attitude) to facilitate adaptation to the narrower topic of "driver assistance systems". The internal consistency of the shortened questionnaire is satisfying, with Cronbach's alpha = 0.70.

Agreement on these questions is asked on a seven-level Likert scale from (1) "strongly disagree" to (7) "strongly agree". The attitude towards automated driving was recorded with the item "What is your general attitude towards automated driving?" The 7-point Likert scale ranged from (1) "very negative" to (7) "very positive". Driving style was collected in the self-report, whereby the participants were asked to rate their own driving style on a scale from (1) "very calm" to (7) "very sporty".

After driving in the driving simulator, the participants were given a short post-questionnaire. They were asked which of the three behaviours they would prefer in the two perspectives by choosing one of the three behaviours as the one they would like to see most in the other vehicle.

2.6. Procedure

Upon arrival, the participants were informed about the procedure and purpose of the study and gave their informed consent for data collection. Subsequently, the demographic data was collected, and the participants were instructed about the function of the eHMI. In addition, the scales for evaluating the driving situations were presented. In the simulator, the participants first drove a familiarisation phase during which the experimenter sat in the vehicle with them to answer any questions that arose. This phase was approx. 10 min long. The experimenter then left the simulator dome, allowing the participant to drive in isolation, although they were in contact with the experimenter by radio, when required. These were used to query the rating after each interaction situation. After the experiment, participants answered the follow-up questionnaire and received £10.

2.7. Intercultural aspects and disparities in study execution

Probably the most significant difference between the two data collections is that Germany has right-hand traffic, whereas the UK has left-hand traffic. For this reason alone, the simulated test tracks differed. In addition, routes were created in the respective simulations according to the valid road layout specifications. Also, different speed limits applied to take account of country-specific circumstances: In the German study, a speed limit of 130 km/h (approx. 81 mph) applied, in the UK study a speed limit of 70 mph (approx. 113 km/h). In addition to the country-specific differences in road traffic, there are also variations due to the technical realisation of the two driving simulators, but care was taken to achieve the greatest possible similarity in the simulation. Due to a technical limitation, the circuit realised in the German study could not be implemented in the UK simulator, so the circuit was divided into six individual scenarios. A final country-specific difference can be found in the wording of the questions. These were translated with great care, but a slightly different understanding of the questions cannot be ruled out.

2.8. Data analysis

Due to the confounding of the variable "country" described in 2.7, the data are not analysed in a joint analysis, but separately and the results of the two analyses are contrasted. We present the results of two separate two-factor MANOVAs for the two perspectives, each compared to the results of the German sample.

3. Results

Besides gender (see 2.1), the UK sample differed from the German sample in technical affinity and the attitude towards automated driving: Both variables had significantly lower values in the British sample (see Table 3). Sample differences were calculated using a t-Test. However, there is no significant gender difference in the attitude towards automated driving ($t\,(57) = 0.13$, $p = .894$, $d = 0.04$) or technical affinity ($t\,(57) = 1.31$, $p = .197$, $d = 0.40$). The self-reported driving style did not differ significantly between the samples. There is also no significant gender effect ($t\,(57) = 2.00$, $p = .051$, $d = 0.61$).

3.1. First-person perspective of the slip road

3.1.1. Subjective Measures: Perceived criticality & perceived cooperation

The influence of the behaviour of the vehicle on the nearside lane while the test persons were driving on the slip road and the influence of the presence of a status eHMI on the evaluation by the participants was investigated using a two-factor MANOVA (see Table 4). There is neither a significant effect of the two predictors "eHMI" and "behaviour" on the dependent variables "perceived criticality" and "perceived cooperation", nor is the interaction of the predictors significant. However, a significant difference emerges in the post hoc tests: "Maintaining Speed" was rated as significantly less cooperative than the other two behaviours. The criticality rating, though, does not differ significantly. This result differs from the results of the German sample, for which accelerating of the cooperation partner was rated as significantly more critical than decelerating, while maintaining speed was rated similar to decelerating (see Fig. 4). In addition, deceleration was assessed as significantly more cooperative than the other two behaviours (see Fig. 5). In both samples, there are no significant differences between the two eHMI conditions for the three behaviours investigated.

3.1.2. Objective Measure: Time headway

The eHMI has no significant influence on the time headway (THW) during the participants first-person perspective of the slip road (see Fig. 6). This applies to both the UK sample ($t\,(24) = -1.09$, $p = .285$) and the German sample ($t\,(31) = 0.13$, $p = .894$). The THW also does not differ significantly between the two countries ($t_{automated}\,(56) = -1.93$, $p = .059$; $t_{manual}\,(55) = -1.01$, $p = .319$). One accident (THW = 0) was recorded during the study in the UK, however, when interacting with a vehicle with eHMI that showed the "acceleration" behaviour. No accidents were recorded in the German study. Both samples have a reduced number of degrees of freedom for analysing the THW, as the THW could only be calculated if the ego vehicle and the drone car were directly in front of or behind each other after the lane change.

3.1.3. Position of the participant

The position of the participants after the lane change (in front of or behind the drone car) is shown in Fig. 7. In the German sample, the results are unambiguous: the participants always merged behind accelerating drone cars and in front of decelerating drone cars. If the drone car maintained its speed, the participants merged in front of the drone more often than behind it. There are no relevant differences due to the eHMI. In the UK sample, on the other hand, some participants merged in front of the accelerating drone and behind the decelerating drone car. In addition, more participants in the UK than in the German sample decided to merge behind a drone that maintained its speed. A noticeable eHMI-related difference can be observed for this behaviour in the UK sample: If the vehicle was marked as automated, the participants drove in front of the drone vehicle more often.

3.2. Slip road of the cooperation partner

3.2.1. Subjective Measures: Perceived criticality and perceived cooperation

The second analysis regards the other perspective on motorway slip roads, where the participants are in the nearside lane of the motorway while a drone car is next to them on the slip road. The eHMI has no significant effect on perceived criticality, but it does

Table 3
Means and standard deviations of demographic data for both samples.

Variable	UK Sample (N = 27)		German Sample (N = 32)		Differences	Effect Size
	M	*SD*	*M*	*SD*	*p*	*d*
Technical Affinity	4.46	0.94	5.06	1.04	**0.036**	0.56
Attitude towards automated driving	4.30	1.46	5.28	1.22	**0.007**	0.74
Driving style	3.19	0.96	3.44	1.34	0.418	0.73

Note. M and *SD* represent mean and standard deviation, respectively. Technical affinity, attitude towards automated driving and driving style were measured on 7-point-likert scales from 1 to 7.

Table 4
Two-factor MANOVA with repeated measures with perceived criticality and perceived cooperation as the criteria for the first-person perspective on the slip road in the UK sample.

	Sum of Squares	*df*	df_{error}	Mean Square	*F*	*p*	partial η^2
	Perceived criticality						
Main Effects							
eHMI	0.22	1	26	0.22	0.02	0.879	0.001
behaviour	16.09	2	52	8.04	1.78	0.179	0.064
eHMI × behaviour	3.59	2	52	1.80	0.55	0.580	0.021
Post Hoc Tests							
Accelerating × Decelerating	1.82	1	26	1.82	0.31	0.585	0.012
Decelerating × Maintaining Speed	15.57	1	26	15.57	5.11	0.096	0.164
Maintaining Speed × Accelerating	6.75	1	26	6.75	1.48	0.472	0.048
	Perceived cooperation						
Main Effects							
eHMI	2.47	1	26	2.47	0.71	0.406	0.027
behaviour	25.15	2	52	12.57	2.54	0.089	0.089
eHMI × behaviour	1.86	2	52	0.93	0.33	0.723	0.012
Post Hoc Tests							
Accelerating × Decelerating	4.90	1	26	4.90	0.88	0.526	0.033
Decelerating × Maintaining Speed	25.04	1	26	25.04	7.40	**0.033**	0.222
Maintaining Speed × Accelerating	7.79	1	26	7.79	1.31	0.526	0.048

Note. p-Values of the post hoc tests are corrected for alpha-Error by Bonferroni-Holm correction (Holm, 1979).

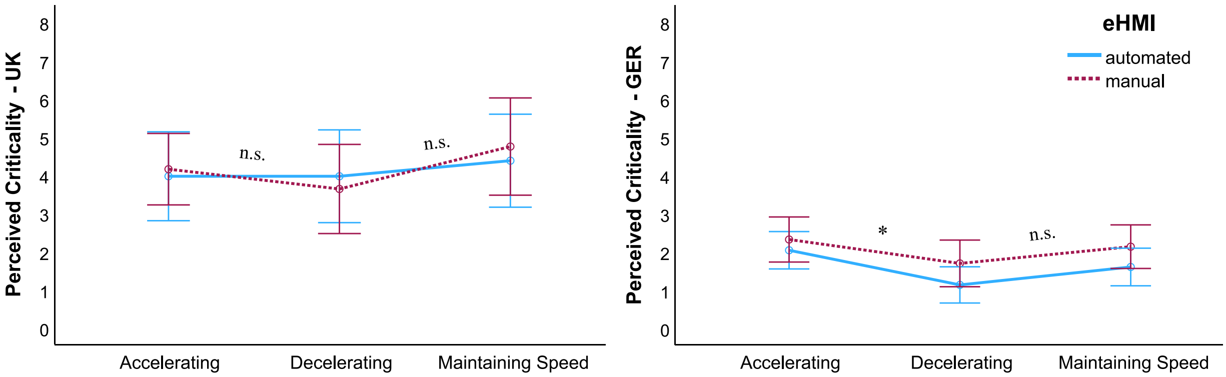

Fig. 4. Influence of the behaviour of the cooperation partner, who is driving on the motorway, on perceived criticality for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. * p <.05, n.s. = not significant.

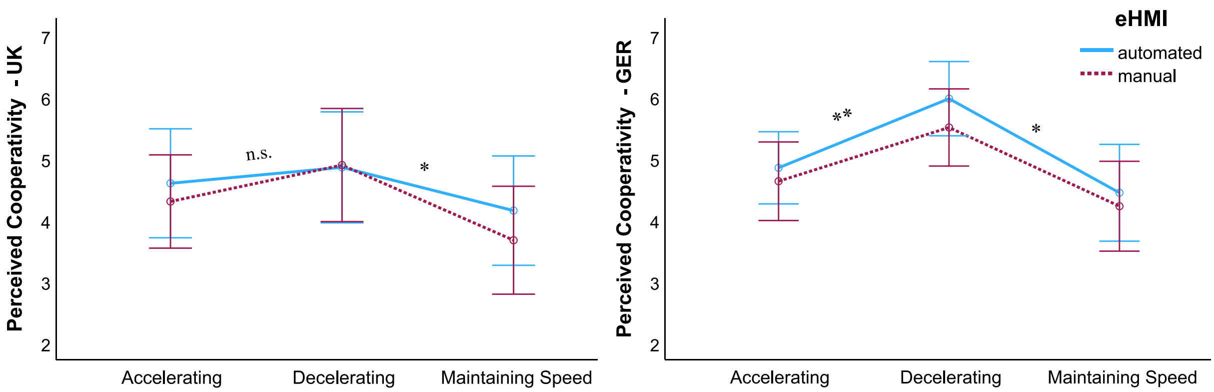

Fig. 5. Influence of the behaviour of the cooperation partner, who is driving on the motorway, on perceived cooperativity for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p <.001, * p <.05, n.s. = not significant.

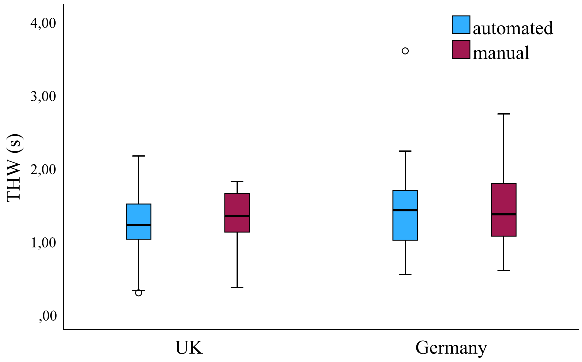

Fig. 6. Time Headway (THW) for the first-person perspective on the slip road, divided after the eHMI condition.

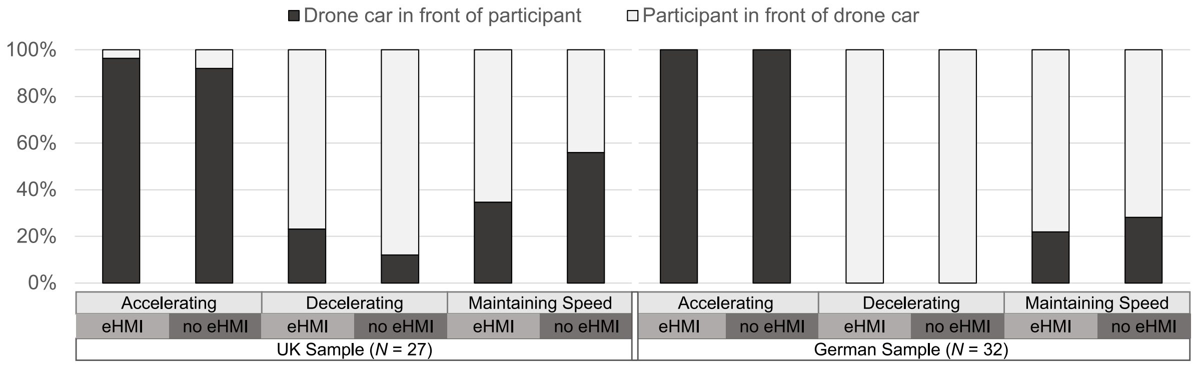

Fig. 7. Position of the participant after the lane change for the first-person perspective on the slip road for both samples.

influence perceived cooperativity (see Table 5). Vehicles with eHMI are rated as significantly more cooperative under identical behaviour. Post-hoc tests show that this significant main effect can only be attributed to the "maintaining speed" condition ($t\,(26) = 1.84$, $p = .039$). The difference is not significant for the other two behavioural patterns. The main effect of behaviour is significant for both dependent variables. The post-hoc tests show that this is the result of the behavioural pattern "decelerating" being rated as significantly less critical and significantly more cooperative than the other two behaviours. There is no significant difference between maintaining speed and accelerating. The results for this perspective are in line with the results from the German sample (see Figs. 8 &

Table 5
Two-factor MANOVA with repeated measures with perceived criticality and perceived cooperation as the criteria for the slip road of the cooperation partner in the UK sample.

	Sum of Squares	*df*	df_{error}	Mean Square	*F*	*p*	partial η^2
	Perceived criticality						
Main Effects							
eHMI	5.93	1	26	5.93	2.00	0.169	0.071
behaviour	419.27	2	52	209.64	35.20	**<0.001**	0.575
eHMI × behaviour	2.83	2	52	1.41	0.36	0.699	0.014
Post Hoc Tests							
Accelerating × Decelerating	240.01	1	26	240.01	48.10	**<0.001**	0.649
Decelerating × Maintaining Speed	374.08	1	26	374.08	76.48	**<0.001**	0.746
Maintaining Speed × Accelerating	14.82	1	26	14.82	1.86	0.185	0.067
	Perceived cooperation						
Main Effects							
eHMI	8.00	1	26	8.00	4.95	**0.035**	0.160
behaviour	268.15	2	52	134.57	42.88	**<0.001**	0.623
eHMI × behaviour	0.93	2	52	0.46	0.27	0.767	0.010
Post Hoc Tests							
Accelerating × Decelerating	222.45	1	26	222.45	95.92	**<0.001**	0.787
Decelerating × Maintaining Speed	178.90	1	26	178.90	43.33	**<0.001**	0.625
Maintaining Speed × Accelerating	2.37	1	26	2.27	0.80	0.380	0.030

Note. p-Values of the post hoc tests are corrected for alpha-Error by Bonferroni-Holm correction (Holm, 1979).

9).

3.2.2. Objective Measure: Time headway

While the eHMI has no influence on the THW in both samples in the first-person perspective, there is a significant difference in this perspective, but only for the German sample ($t\,(19) = 3.46$, $p = .003$; see Fig. 10). In the UK sample, there is again no difference in the THW towards vehicles with and without eHMI ($t\,(12) = 0.72$, $p = .484$). On the other hand, three accidents (THW = 0) were recorded in the UK sample, all of which occurred when vehicles on the slip road maintained their speed. One of the vehicles involved in the accident was equipped with an eHMI, the other two were manual vehicles.

The THW of the two countries differed significantly, both in the interaction with automated ($t\,(39) = 21.79$, $p < .001$) and with manual vehicles ($t\,(18) = 15.42$, $p < .001$). The safety distances in the UK sample were higher in both cases. The lower degrees of freedom again result from both vehicles not always travelling directly in front of or behind each other after the lane change. In most cases, this was because the participants were driving too close in front of or behind another vehicle so that the vehicle on the slip road was unable to merge there. In other cases, the participants managed to change lanes despite another vehicle blocking their path to clear the way for the vehicle on the slip road.

3.2.3. Position of the participant

Fig. 11 shows the position of the participant after the lane change (either in front or behind the drone car) for the two samples. As with the first-person perspective of the slip road, the picture of the position of the participants after the slip road is less ambiguous in the German sample. The participants always allowed accelerating drone cars to merge in front of them on the slip road, while decelerating drone cars changed lanes behind their own vehicle. If the drone car maintained its speed, most of the participants in the German sample accelerated so that the drone car could merge in behind them. The eHMI has no influence on the sequence. The picture in the UK sample is more ambiguous: firstly, individual participants managed to drive faster than the accelerating drone car on the slip road, so that the drone car merged behind them. Secondly, when the drone car decelerated, around a third of the participants in the UK decelerated so sharply that the drone car ultimately merged in front of them. If the drone car maintained its speed on the slip road, UK participants allowed the vehicle to merge in front of them significantly more often than in the German sample. If they were labelled with an eHMI, this happened more frequently than if they did not have an eHMI.

3.3. Preferred behaviour

In the follow-up survey, the participants were asked which of the three behaviours they would prefer in the two scenarios. The results are shown in Fig. 12. Whereas in the UK, the preferred behaviour for the vehicle in the target lane is to slow down or maintain speed, in Germany it is expected that the cooperation vehicle will accelerate or maintain speed. The results of the two samples also differ for the second perspective: in the UK, the vehicle on the slip road is expected to accelerate, followed in second place by decelerating. In Germany, on the other hand, decelerating is clearly the preferred behaviour.

4. Discussion

4.1. Evaluation of longitudinal driving dynamic behaviours

The first aim of the study was to find out how implicit communication through three longitudinal driving dynamic behaviours is evaluated by other drivers. No clear picture emerges for the first-person perspective on the slip road. The ratings of the three behaviours did not differ significantly in the UK sample, which is contrary to our first hypothesis. There are various possible reasons for

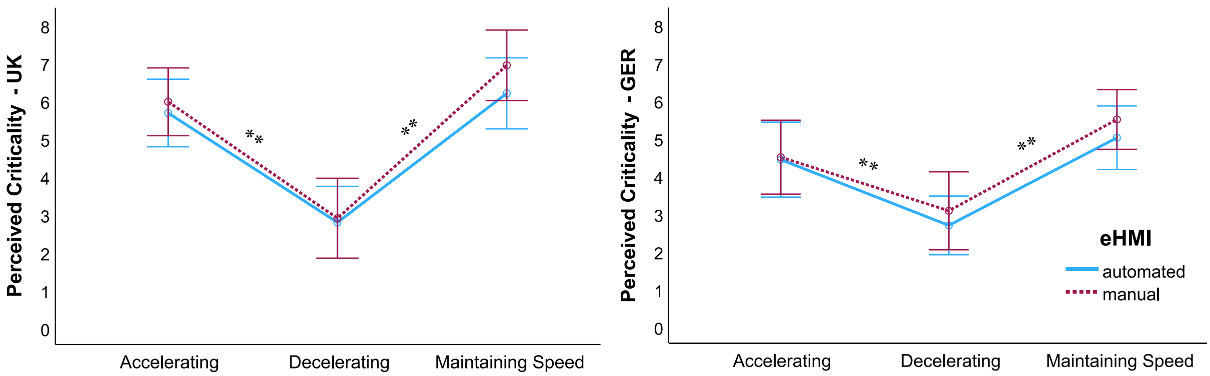

Fig. 8. Influence of the behaviour of the cooperation partner, who is driving on the slip road, on perceived criticality for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p <.001.

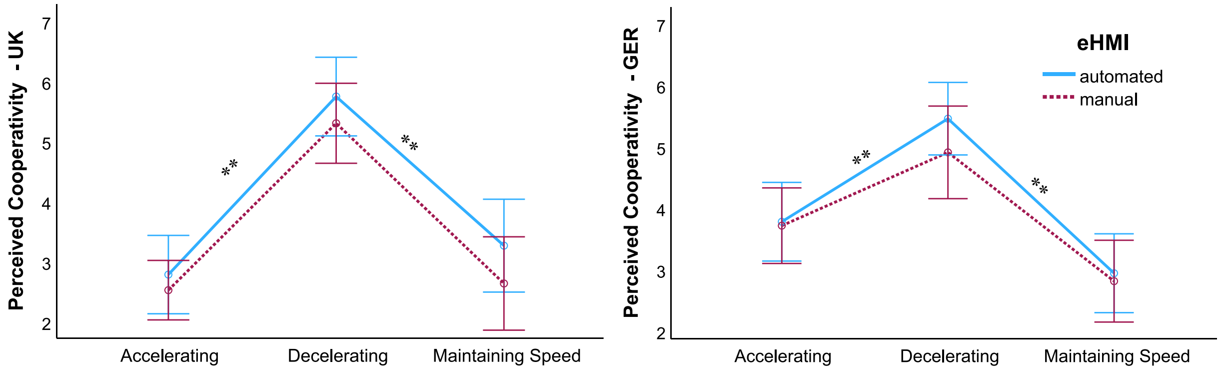

Fig. 9. Influence of the behaviour of the cooperation partner, who is driving on the slip road, on perceived cooperativity for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p <.001.

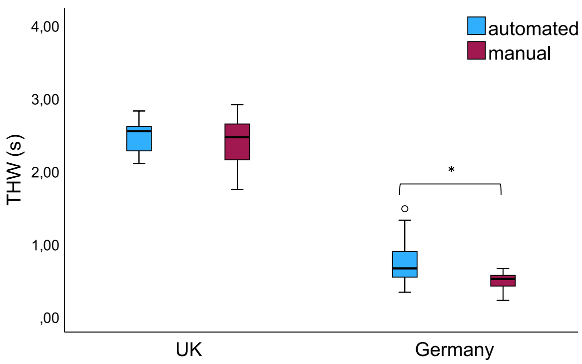

Fig. 10. Time Headway (THW) for the slip road of the cooperation partner, divided after the eHMI condition.

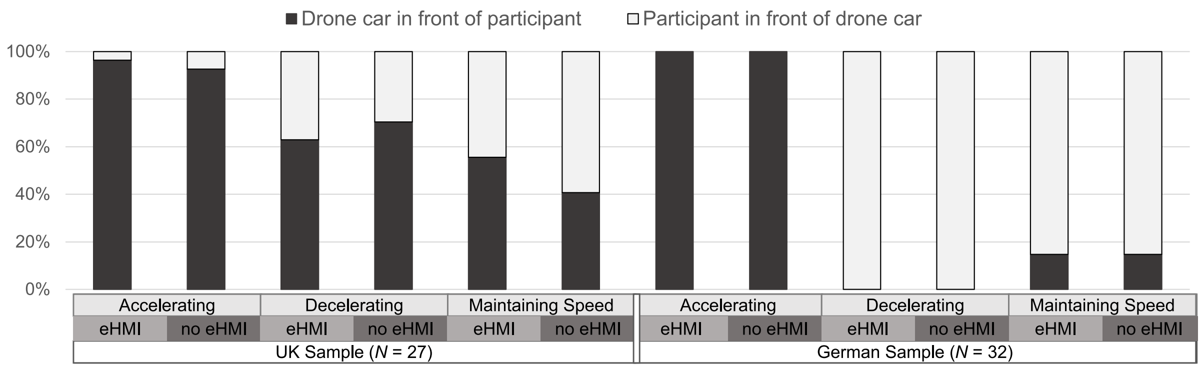

Fig. 11. Position of the participant after the lane change for the slip road of the cooperation partner for both samples.

this. Firstly, it is possible that there is no preference for one of the behaviours in the UK. The follow-up survey shows, however, that maintaining speed or braking is clearly favoured over accelerating. Another reason may lie in the road layout and the implementation of the study. In line with the usual UK slip road layout, the slip road had two lanes. To ensure that the drone car drove at the same speed as the test person for a while, as in the German study, the vehicle only indicated the differences in behaviour towards the end of the right lane of the slip road. Some participants tried to force a lane change from right-hand lane of the slip road to the motorway, even if the drone car blocked their way. Therefore, they only experienced the behavioural variation to a limited extent. This can also be seen in the position of the participants after the lane change: in the UK sample, a few participants got in front of accelerating and behind braking drone cars, which did not occur in the German sample. This shows above all that it is very important to take the different road layouts into account when designing automated driving functions.

For the slip road of the cooperation partner, on the other hand, a clear result emerged: Deceleration of the drone car and pulling in

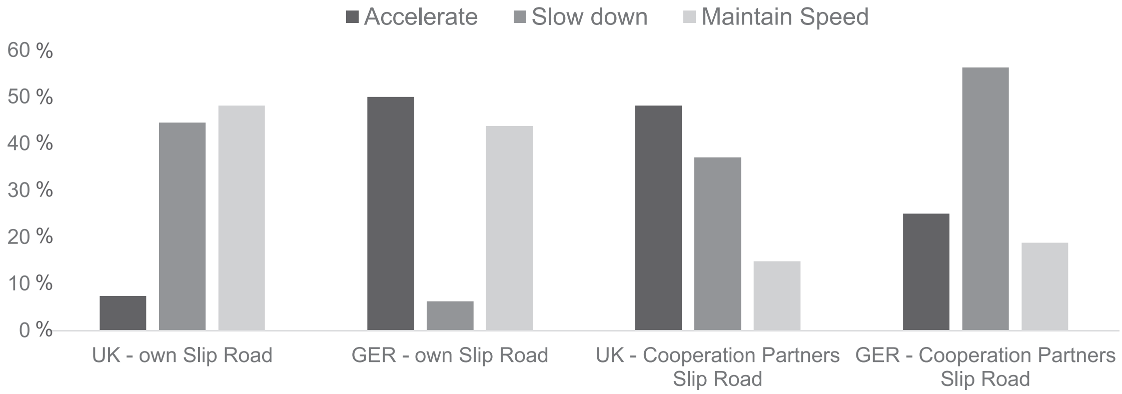

Fig. 12. Preferred behaviour of the cooperation partner, as indicated in the post questionnaire.

behind the participants vehicle is viewed most cooperatively and least critically. This is in line with our hypothesis, and applies to both the UK and the German sample (Ehrhardt et al., 2023). These results match the findings of Kauffmann et al. (2018) and Imbsweiler (2019), in which braking was perceived as particularly cooperative, while accelerating and maintaining speed were perceived as aggressive and uncooperative.

In the follow-up questionnaire, however, the participants partially contradicted the results. If the participants were on the slip road themselves, the follow-up questionnaire revealed that UK participants preferred the vehicles in the target lane to maintain their speed. However, this behaviour was rated as the least cooperative in the study. Decelerating, which was favoured by vehicles on the slip road in the driving simulator, only came second in the ranking after accelerating. However, this may only be because vehicles on the acceleration lane are always expected to accelerate first, while braking is only appropriate in some situations. This primarily shows that mere questioning is often not sufficient, but that the situation in question must be experienced.

4.2. *Influence of the status eHMI*

Our second aim was to find out whether the implicit communication of vehicles labelled as automated is evaluated differently than when subjects assume they are interacting with a human. For the first-person perspective of the slip road, the eHMI has no significant influence on the behavioural assessment and also not on the safety distance (THW). This applies to both countries. The results for the first-person perspective of the slip road are therefore in line with the results from previous studies (Ehrhardt, Graeber, et al., 2023; Fuest et al., 2020; GATEway Project, 2017; Stange et al., 2022). In the UK sample, however, decelerating vehicles on the slip road are perceived as significantly more cooperative with identical behaviour if they are labelled as automated. This is remarkable, as it contradicts earlier findings and also our hypothesis. This effect does not exist in Germany, too. We suspect that this difference is due to a difference in the two samples: the attitude towards automated driving in the UK sample was more negative than in the German sample. UK participants may therefore have been positively surprised by the cooperative driving behaviour of the vehicles labelled as automated and rated them more positively.

However, there is also a different sex distribution in the two samples. We did not find any difference in attitudes towards autonomous driving between the genders in our samples. Previous studies have found a more critical attitude towards automated driving among women though (Hőgye-Nagy, Kovács, & Kurucz, 2023; Hulse, Xie, & Galea, 2018). Another study shows that the gender gap in the willingness to use, buy or activate an automated driving function is culturally influenced (Torrao, Lehtonen, & Innamaa, 2024). However, they categorise both the UK and Germany in the group with a significant gender gap.

As hypothesised, UK drivers did not keep a different safety distance from vehicles with eHMI. The descriptive evaluation shows the effect of the eHMI on the position of the participants after the lane change: the participants more frequently merged in front of vehicles with an eHMI in the "maintaining speed" behaviour pattern than when no eHMI was present. This effect can also be seen in the German sample, but to a lesser extent. If the drone car decelerates, the eHMI increases the probability that the participants will still change lanes behind the drone car. If the drone car was on the slip road, a drone car with eHMI that maintained its speed was more likely enabled to change lanes in front of the participants. If it decelerated, the participants were less likely to brake hard enough to stay behind the drone car. From this perspective, the eHMI had no influence for the German sample. This result of the UK sample is also inconsistent with the cited literature, which assumes no influence of an eHMI on the behaviour of other drivers (Fuest et al., 2020; GATEway Project, 2017).

4.3. *Intercultural aspects*

The third aim was to find out whether the answers to the two previous questions (evaluation of the means of communication and influence of eHMI) differ between the UK and Germany, and whether the results of the first study can be generalised across different countries.

Since differences were found in the result profiles of the two samples, full applicability of the findings between the countries is not possible. At the same time, major similarities were found in the results. These are congruent with assertions of the Culture Factor Group (2023), according to which the two countries show no relevant differences in four of the six Hofstede dimensions. The countries achieve different scores in the dimensions “uncertainty avoidance” and “indulgence”. The lower values for “uncertainty avoidance” in the UK provide a possible explanation for several of the differences found: In addition to the differences in road layout, this uncertainty avoidance may also play a role in the fact that there is no preference for one type of behaviour in the first-person perspective of the slip road in the UK sample. While “deceleration” is preferred in Germany, which is a clear behaviour pattern, different behaviour patterns and thus “uncertainty” appear to be accepted in the UK.

Another difference between the two samples lies in the position of the participant after lane change: remarkably, some participants in the UK sample remained behind braking drone cars, which did not occur in the German sample. Özkan et al. (2006) attested UK drivers a very low score for aggressive offences on the road, i.e. a rather passive behaviour, which may explain this result. At the same time, however, Özkans study also provides a clue to the explanation for the fact that some UK drivers got in front of accelerating drone cars (which did not occur in the German sample) by reporting that UK drivers are more likely than other countries to be guilty of “speeding on the motorway” and “pulling out and forcing your way out”. However, future research should analyse the general differences in driving behaviour between the two countries in more detail.

Only minor differences were found in the evaluation of automated vehicles. Our results thus differ from those of Edelmann et al. (2021), in which culture had a major influence on the perception of automated driving. However, their results related to China, Germany, Japan and the United States, i.e. countries with greater cultural differences. Future research could consider whether there are clusters in the perception of automated driving (e.g. Europe) or whether the perception must be considered at country level.

4.4. Limitations

Even though great care was taken in the planning and execution of the study, it is still subject to some limitations: The biggest is likely the use of two different driving simulators, which was unavoidable due to the data collection in two countries. Although the track design and the execution were standardised as far as possible (for more details see 2.7), differences in vehicle control and perception of the environment cannot be ruled out. In addition, translated questionnaires have the inherent problem of slight differences in understanding the wording. Furthermore, both samples are not representative of the population in terms of age and gender. In particular, the unbalanced sex distribution in both samples is a limitation (as discussed in further detail in 4) and should be addressed in detail in future studies.

5. Conclusion

The study showed that there is a clear behavioural preference towards vehicles on motorway slip roads, namely, to decelerate and pull in behind the vehicle in the target lane. This was seen as the most cooperative and least critical type of behaviour in both countries. For the first-person perspective on the slip road, results are ambiguous, with only a slight preference for “decelerating”. The eHMI has only a small influence on the behavioural assessment in the UK; vehicles with eHMI are rated as more cooperative when decelerating on the slip road. In Germany, a greater safety distance was maintained from vehicles with eHMI on the slip road; in the UK there were no differences in this respect.

Even if the results barely differ between the countries in many important aspects, there are still certain cultural influences on the assessment of behaviour. For this reason, it is important to consider the cultural aspect in the development of automated driving functions. At the same time, the differences appear to be small enough to allow cross-regional traffic to function across national borders without having to change the driving behaviour of the vehicles. It can also be assumed that previous research results can be generalised to a certain extent beyond the country in which they were collected, even if future research must provide further data.

CRediT authorship contribution statement

Sofie Ehrhardt: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Natasha Merat:** Writing – review & editing, Resources, Project administration. **Michael Daly:** Writing – review & editing, Software. **Albert Solernou Crusat:** Software. **Barbara Deml:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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