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# How should autonomous vehicles overtake other drivers?

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ABSTRACT

Previous research examining trust of autonomous vehicles has largely focused on holistic trust, with little work on evaluation of specific behaviours and interactions with human-controlled vehicles. Six experiments examined the influence of pull-in distance, vehicle perspective (overtaking/being overtaken), following distance and immersion on self-reported evaluations of, and physiological responses to, autonomous motorway overtakes. We found that: (i) overtake manoeuvres were viewed more positively as pull-in distance increased before reaching a plateau at approximately 28 m, (ii) physiological-based orienting responses occurred for the smallest pull-in distances, (iii) participants being overtaken were more forgiving of a sharper pull-in if the overtaking vehicle was followed closely by another vehicle, and (iv) for two of three cross-experiment comparisons participants were more forgiving of smaller pull-in distances with lower immersion levels. Overall, the results suggest that the acceptability of an overtake manoeuvre increases linearly with pull-in distance up to a set point for both overtaking and being overtaken manoeuvres, with some influence of traffic context and levels of immersion. We discuss the findings in terms of implications for the development of assisted and fully autonomous vehicle systems that perform in a way that will be acceptable to both the vehicle occupants and other road users.



## 1. Introduction

Autonomous vehicles may arrive on the roads by approximately 2020 (‘‘Driverless car market watch”, n.d.), with one estimate claiming that 75% of all road vehicles will be autonomous by 2040 (Ma, 2012). Despite this prediction, fully autonomous vehicles will have to share the road with human-driven vehicles especially during the transition period. Even when most vehicles are autonomous, some human driven vehicles (e.g., motorcycles and ‘motor enthusiast’ vehicles) may remain on the roads. Hence, safe and acceptable interactions between autonomous and human-driven vehicles will remain vital. Furthermore, even if all vehicles become fully autonomous, their behaviour will still need to be acceptable to their occupants. Accordingly, it is important to understand the psychological factors that influence how autonomous vehicle behaviours are perceived.

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Survey-based methods have identified factors such as gender (Hohenberger, Spörrle, & Welpe, 2016; Howard & Dai, 2014; Hulse, Xie, & Galea, 2018; Schoettle & Sivak, 2014), age (Bansal & Kockelman, 2018; Haboucha, Ishaq, & Shiftan, 2017; Hohenberger et al., 2016; Hulse et al., 2018; Kyriakidis, Happee, & de Winter, 2015), personality (Choi & Ji, 2015; Kyriakidis et al., 2015), cultural differences (Haboucha et al., 2017; Kyriakidis et al., 2015; Schoettle & Sivak, 2014) daily driving behaviours (Howard & Dai, 2014) and experience (Bansal & Kockelman, 2018) as influencing acceptance and intentions to use autonomous vehicles. A review of several surveys found that attitudes towards autonomous vehicles were most positive for males, younger people, those living in urban environments, drivers with previous experience of assistance systems and individuals who were more familiar with the news on technological developments (Becker & Axhausen, 2017).

A review by Hoff and Bashir (2015) defined 'trust' as comprising three distinct components: dispositional, situational and learned. The survey-based work above mainly investigated how dispositional trust is influenced by various demographic factors, rather than evaluations after interacting with and gaining experience with a system (situational and learned trust). To examine the latter two aspects of Hoff and Bashir (2015) taxonomy, experimental designs in which participants interact with autonomous vehicles and/or in-vehicle interfaces are required.

Previous experimental work has focused on judgements relating to the overall trust of a vehicle, based on features of the vehicle itself or information provided about the vehicle/by an in-vehicle interface. For example, simulator-based work found higher trust for autonomous vehicles and driving agents that possess more anthropomorphised features (Lee, Kim, Lee, & Shin, 2015; Waytz, Heafner, & Epley, 2014). Providing feedback on an autonomous vehicle's level of uncertainty influenced trust (Beller, Heesen, & Vollrath, 2013; Helldin, Falkman, Riveiro, & Davidsson, 2013), experience with an autonomous vehicle led to increased positivity of initial attitudes (Hartwich, Witzlack, Beggiato, & Krems, 2018), and drivers paid less attention to non-driving tasks in an automated vehicle when given information on the vehicle's limitations (Körber, Baseler, & Bengler, 2018). With respect to takeover activity, Payre, Cestac and Delhomme (2016) found higher trust was associated with slower manual control recovery, but this effect disappeared when participants were given more elaborate practise with the vehicle.

However, comparatively little work has examined evaluations of specific vehicle behaviours between autonomous and human-driven vehicles. Drivers seem to be concerned about human drivers taking advantage of autonomous vehicles (Tennant, Howard, Franks, Bauer, & Stares, 2016) and autonomous vehicles struggling with the 'informal' rules of driver-driver interactions (Tennant et al., 2015). Hence, we need to determine the parameters of behaviour for autonomous vehicles to be acceptable to their occupants and other road users. In starting to address this issue, one simulator study found that participants preferred a more cautious autonomous driving style than their own (Basu, Yang, Hungerman, Singhal, & Dragan, 2017). An on-road trial found that occupants gave higher trust ratings of an autonomous vehicle when driving on an empty road than when overtaking a parked vehicle. Higher ratings were also given when overtaking a parked vehicle with oncoming traffic compared to when there was no oncoming traffic, potentially due to the vehicle slowing down with no obvious justification in the latter case (Trial, 2017). A further simulator study showed that participants preferred an autonomous vehicle to use larger lateral distances and begin steering into the middle lane earlier than the driver's own behaviour when overtaking bicycles and scooters (Abe, Sato, & Itoh, 2018). Another simulator trial found that participants were more likely to overtake (move to the fast lane) after two vehicles had passed rather than pull into the gap between them, regardless of whether the second vehicle was autonomous or human-driven, or the distinctiveness of the autonomous vehicle's appearance (TRL PPR807, 2017).

However, neither the Trial (2017) nor Abe et al. (2018) or TRL (2017) examined the role of pull-in distance on ratings of autonomous overtaking behaviour, Abe et al. (2018) did not examine trust in the context of an autonomous vehicle overtaking another car, and TRL (2017) focused more on the behaviour of human drivers towards autonomous vehicles rather than the evaluation of their behaviour. In addition, participants in both studies were asked to rate their general level of trust in the vehicle, rather than evaluate a specific vehicle behaviour or manoeuvre, and Abe et al. (2018) did not manipulate individual parameters independently. However, we need data on what makes specific manoeuvres more or less acceptable if autonomous vehicles/systems are to be programmed optimally. Thus, we focused on peoples' ratings of acceptability of a specific manoeuvre as we systematically varied a number of relevant parameters. We asked people to evaluate overtaking behaviours as a function of: (i) pull-in distance after the overtake, (ii) occupant perspective: driving a vehicle that is being overtaken or being in an autonomous vehicle that is overtaking another vehicle, and (iii) the effect of traffic context; whether ratings of an overtaking manoeuvre are influenced if the overtaking vehicle is being followed by a third vehicle. Acceptability was determined via a 15-item 'Vehicle Character Questionnaire' (VCQ) (Table 2). We present six experiments; three simulator based (1a–c) and three video-based (2a–c) replications which also allowed to us examine the potential influence of immersion on the results. We also measured physiological responses; electrodermal activity (EDA, E1a–c) and heart rate (E1b-c), and driver input data (E1a–c). These objective measures allowed us to determine, for example, if attention was captured and potentially if someone was surprised, angered or threatened by a manoeuvre (Boucsien, 2012; Critchley, 2002; Dewe, Watson, & Braithwaite, 2016; Frith & Allen, 1983). For an overview and summary of the main findings please see Table 1.

**Table 1**
An overview and summary of the methodologies, key variables and central findings of all six experiments presented in this article. In order to obtain a full understanding of the results, the table must be read alongside the detailed coverage of the methodology and results in the main body of this article.

| Experiment | Methodology | Key independent variables | Key results |
|---|---|---|---|
| 1a | Simulator | Pull-in distance, vehicle perspective | Sharp increase in trust with increasing pull-in distance up to ∼28 m; no effect of vehicle perspective |
| 1b | Simulator | Pull-in distance, following distance/traffic context | Sharp increase in trust up to ∼28 m; no effect of presence of a following vehicle |
| 1c | Simulator | Pull-in distance, following distance/traffic context | Sharp increase in trust up to ∼28 m; drivers more forgiving of sharper pull-ins with a closer following third vehicle |
| 2a | Video | Pull-in distance, vehicle perspective, immersion level | Sharp increase in trust up to ∼28 m; drivers more forgiving of sharper pull-ins on video compared to when in the simulator |
| 2b | Video | Pull-in distance, following distance/traffic context, immersion level | Sharp increase in trust up to ∼28 m; drivers more forgiving of sharper pull-ins on video compared to when in the simulator |
| 2c | Video | Pull-in distance, following distance/traffic context, immersion level | Sharp increase in trust up to ∼28 m; no difference in pattern of ratings when compared to simulator |

**Table 2**
Full VCQ questionnaire.

| Question number | Question text |
|---|---|
| 1 | With 1 being "unpleasant", and 7 being "pleasant", please rate the driving scenario you have just experienced |
| 2 | With 1 being "incompetent", and 7 being "competent", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 3 | With 1 being "erratic", and 7 being "predictable", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 4 | With 1 being "rude", and 7 being "polite", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 5 | With 1 being "untrustworthy", and 7 being "trustworthy", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 6 | With 1 being "unhelpful", and 7 being "helpful", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 7 | With 1 being "aggressive", and 7 being "timid", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 8 | With 1 being "selfish", and 7 being "considerate", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 9 | With 1 being "unjustified", and 7 being "justified", please rate the extent to which [the overtaking vehicle/your vehicle]'s behaviour was justified in the driving scenario you have just experienced |
| 10 | With 1 being "uncooperative", and 7 being "cooperative", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 11 | With 1 being "reckless", and 7 being "safe", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 12 | With 1 being "unacceptable", and 7 being "unacceptable", please rate the behaviour of [the overtaking vehicle/your vehicle] in the driving scenario you have just experienced |
| 13 | Would you be more or less likely to purchase a vehicle that behaves like [the one/your vehicle] in the driving scenario you have just experienced? 1 = highly unlikely, 7 = highly likely |
| 14 | Would you be happy to be driven by a vehicle that behaves like [the one/your vehicle] in the driving scenario you have just experienced? 1 = highly unlikely, 7 = highly likely |
| 15 | Would you use a system in your own car that behaved like [the vehicle/your vehicle] in the driving scenario you have just experienced? 1 = highly unlikely, 7 = highly likely |

VCQ scores ranged from 1 to 7, with lower scores being more negative and higher scores being more positive.

## 2. Experiments 1a–1c: Evaluation of autonomous overtaking as a function of pull-in distance, perspective and following distance of a third vehicle

Experiment 1a examined the acceptability of overtaking manoeuvres as a function of pull-in distance from two perspectives (being overtaken while driving vs. overtaking as a passenger in an autonomous vehicle). In the *being overtaken condition*, participants drove in the left lane of a three-lane motorway and a second vehicle overtook in the middle lane and then and pulled back into the driver's lane. The distance between the two vehicles when the pull-in manoeuvre commenced varied between 1 m and 88 m. In the *overtaking condition*, participants were placed in an autonomous vehicle which overtook another vehicle and then pulled back into the left lane at different pull-in distances. In Experiments 1b and 1c we presented participants with the same *being overtaken condition* except that a third vehicle was present which followed the overtaking vehicle at either a relatively safe following distance of 2 s (Experiment 1b) or at a relatively unsafe distance of 0.5 s (Experiment 1c).

## 2.1. Method

### 2.1.1. Participants

There were 20 participants in each Experiment (Table 3). Each held a driving licence and was screened for motion sickness, migraine, photosensitivity, heart conditions, vertigo, postural instability and current pregnancy and completed the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Each was paid was £5.

### 2.1.2. Driving simulator setup

The simulator consisted of a fixed-base setup, with the front half of Jaguar XJ 2009 used for the cabin (Fig. 1) running SCANeR Studio 1.4. There were three projection screens in front of the vehicle (SXGA+ resolution, ~135° horizontal visual angle) and three rear screens reflected in the left, rear and right mirrors. Sound was provided by a 5.1ch surround system. Driver input was via the vehicle's original pedals and steering wheel (with force feedback). Additional tactile feedback was provided by a shaker located under the driver's seat. A dashboard LCD panel displayed vehicle speed (mph), engine RPM and gear. The vehicle used an automatic transmission with no gear changing or turn signal input required from the participant. An additional LCD panel located within the centre console was used to administer the questionnaire measures. The environment was a 9.02 km UK motorway, with three lanes and hard shoulder on the left, the equivalent lanes in the opposite direction and a 2 m central reservation in between with road lamps every 40 m.

### 2.1.3. Physiological measurements

Electrodermal activity (EDA) was recorded via disposable EL507 electrodes attached to the distal phalanges of the fingers of the non-dominant hand. Initial pilot work indicated that this arrangement provided reliable measurements and was not intrusive to the driving experience. Experiments 1b and 1c also recorded heart rate via Lead II ECG, with disposable EL501 electrodes attached to the participant's right wrist and left ankle. Measurements were recorded using a Biopac MP36R data acquisition unit and analysed with Acqknowledge v4.1. ECG and EDA signals were sampled at 1000 Hz. EDA measurements used a gain of x2000, with low pass filters at 66.5 and 38.5 Hz and band stop line frequency filter at 50 Hz. ECG measurements used the same filters but with a high-pass filter at 0.5 Hz and a gain of x1000. Relevant simulator events were automatically coded in the physiological data file.

### 2.1.4. Simulator driver input

We examined gas pedal position (0–1), brake pedal force (Newtons), steering wheel angle (radians), lane gap (distance from the centre of the current lane in metres) and speed (mph) over a four-second window from: (i) one second before the start of the pull-in to three seconds after the pull-in, and (ii) one second before to three seconds after the overtaking vehicle passed the participants' vehicle. All data were from the 'being overtaken' conditions.

### 2.1.5. Design and procedure

Experiment 1a used a fully within-subjects design. Participants first completed two acclimatization trials (one driving the vehicle, one in an autonomous mode vehicle). They then completed 18 test trials which were combinations of pull-in distance[1] (1 m, 3 m, 8 m, 13 m, 18 m, 28 m, 48 m, 68 m and 88 m – selected using initial piloting) and perspective (being in the autonomous overtaking vehicle vs. being in a non-autonomous vehicle that was being overtaken). Trial order was randomized, and participants were given a break outside of the simulator lab after the first 8 test trials. All 18 trials were randomized (such that participants switched perspective more than once) in order to prevent participants losing interest in the task (e.g., after prolonged periods of automated driving) and to reduce order effects especially in respect to potential physiological habitation. After each trial, participants were presented with the VCQ with each question presented sequentially on a touch-screen LCD panel located in the center dashboard console and participants responded by touching an option on a 7-point Likert scale[2]. For each trial, the average of the scores across all questions was calculated to give a VCQ rating that ranged between 1 and 7. In the *being overtaken condition*, participants drove at a specified speed in the left lane after which they were overtaken by an autonomous vehicle which pulled in at varying distances. In the *overtaking condition*, participants were placed within an autonomous vehicle which pulled out to overtake a vehicle in the left-hand lane and pulled back into the left lane at varying distances (Fig. 2). After completing the final test trial, participants were screened for simulator sickness, debriefed and thanked. The experiment lasted 60 to 90 min.

In Experiment 1b and 1c, participants experienced the same *being overtaken condition* from Experiment 1a, except that a third vehicle followed behind the overtaking vehicle. In Experiment 1b, the third vehicle followed 2 s (64.69 m) behind and in Experiment 1c it followed 0.5 s (16.17 m) behind. These were selected based on guidelines recommending 2 s as a safe

[1] Measurements correspond to the distance between the front bumper of the lead vehicle and the rear bumper of the overtaking vehicle at the commencement of the pull-in to the left lane.

[2] Each point of the 7-point scale was represented by a grey dot with a white number inside. When participants pressed a dot to respond, the dot turned red to indicate that their response had been received. When the next question was presented, the dot participants had pressed in the previous question remained red until they responded to the next question. This meant that their response to the previous question was visible in the same way as a previous response on a paper-based questionnaire would be. We do not believe that this had any influence on the results but we have included this methodological detail for completeness.

**Table 3**
Participant details (F = Female, RH = right handed).

| Experiment | Number of participant (number females) | Handedness | Age range, mean and standard deviation | Participants with driving license | Driving license duration and type |
|---|---|---|---|---|---|
| 1a | 20 (12F) | 16 RH | 21–37 years<br>M = 25.15<br>SD = 4.34 | 20 | 10 months–19 years<br>13 UK |
| 1b | 20 (10F) | 18 RH | 18–35 years<br>M = 21.65<br>SD = 3.4 | 20 | 6 months–12 years<br>9 UK |
| 1c | 20 (11F) | 18 RH | 18–28 years<br>M = 20.85<br>SD = 2.20 | 20 | 4 months–7 years<br>8 UK |
| 2a | 30(20F) | 25 RH | 20–61 years<br>M = 25.76<br>SD = 7.76 | 20 | 1–27 years<br>4 UK |
| 2b | 30(18F) | 28 RH | 18–36 years<br>M = 22.34<br>SD = 4.30 | 22 | 1–15 years<br>2 UK |
| 2c | 30(23F) | 26 RH | 18–50 years<br>M = 23.03<br>SD = 6.10 | 20 | 6 months–20 years<br>7 UK |

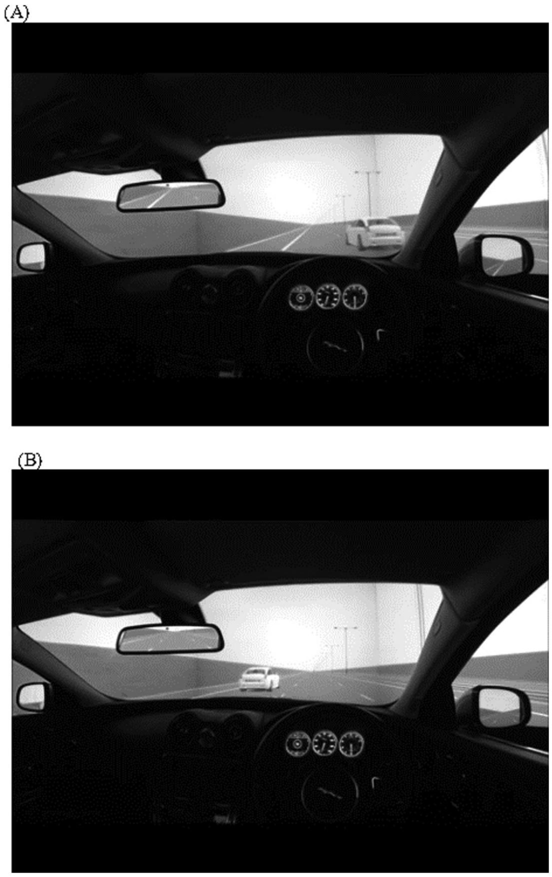


**Fig. 1.** Participants views of the overtaking scenario in the University of Warwick Psychology/WMG fixed-base driving simulator, showing the inside of the cabin, mirrors, steering wheel and visual panels. Panel (A) shows the perspective of a driver being overtaken. Panel (B) shows the perspective of an occupant of an autonomous vehicle performing an overtake.

following distance ("The Annotated Highway Code", n.d.). On each trial, the third vehicle remained at a fixed distance behind the overtaking vehicle, pulled out to the middle lane at the same time, was yoked to the overtaking vehicle's speed, and remained in the middle lane after the pull-in. Each trial stopped ten seconds after the following vehicle passed the participant, or ten seconds after the overtaking vehicle was completely in the left lane after the pull-in, whichever came last.

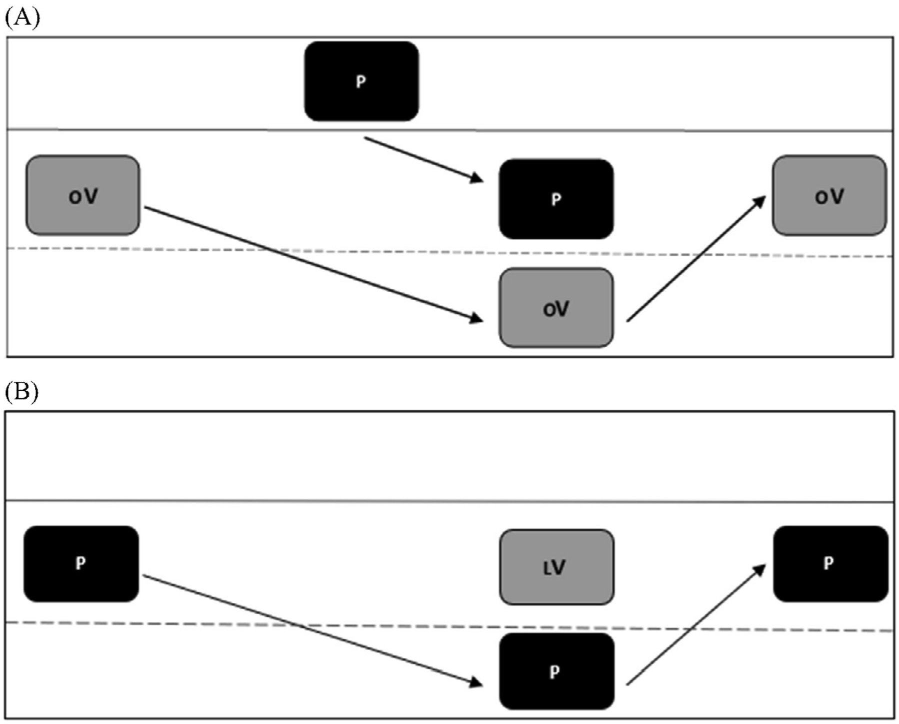


**Fig. 2.** Overview of a single trial. (A) In each *being overtaken condition* trial, the participant (P) moved from the hard shoulder to the left lane and accelerated to 96 km/h while being followed at a distance of 50 m by the overtaking vehicle (OV). Three seconds after the participant exceeded 90 km/h, the overtaking vehicle accelerated to 16 km/h above the participant's speed and moved to the middle lane, pulling back into the left lane at the set pull-in distance. (B) In each *overtaking condition* trial, the participant's vehicle (P) accelerated from zero to 96 km/h over ten seconds, followed the lead vehicle (LV) at a distance of 50 m for ten seconds, moved to the middle lane and accelerated to 112 km/h, then pulled back into the left lane at the set pull-in distance. For both perspectives, the trial was stopped ten seconds after the overtaking vehicle was completely in the left lane.

### 2.2. Results

#### 2.2.1. Vehicle character ratings

*Experiment 1a:* Mean VCQ ratings (Fig. 3A) increased as a function of pull-in distance up to approx. 28 m, plateaued and decreased slightly after approx. 48 m. The effects of Vehicle perspective (*being overtaken* vs. *overtaking*) and Pull-in distance (1–88 m) on VCQ ratings were analysed with a 2 × 9 within-subjects ANOVA (Greenhouse-Geisser corrections applied where necessary). There was a significant main effect of Pull-in distance, $F$ (4.367, 82.968) = 102.989, $p < .001$ ($\eta^2 = 0.844$). However, neither the main effect of perspective, $F$ (1, 19) = 3.12, $p = .583$ ($\eta^2 = 0.016$), nor the Perspective × Pull-in distance interaction reached significance, $F$ (4.279, 81.306) = 1.985, $p = .100$ ($\eta^2 = 0.095$).

*Experiment 1b:* Mean VCQ ratings for Experiment 1b (Fig. 3B) were analysed with a one-way repeated-measures ANOVA which revealed a significant main effect of Pull-in distance, $F$ (4.187, 79.550) = 58.47, $p < .001$ ($\eta^2 = 0.755$). To assess the influence of having a third vehicle follow the overtaking vehicle, we compared the VCQ ratings from the *being overtaken condition* of Experiment 1a with those of Experiment 1b with a mixed 2 (Experiment: 1a, 1b) × 9 (Pull-in-distance) ANOVA with Experiment as the between-subjects factor. This revealed a significant main effect of Pull-in distance $F$ (5.201, 197.642) = 145.556, $p < .001$ ($\eta^2 = 0.789$). However, neither the main effect of Experiment, $F$ (1, 38) = 0.006, $p = .940$ ($\eta^2 = 0.000$), nor the Experiment × Pull-in distance approached significance, $F$ (5.201, 197.642) = 0.849, $p = 0.521$ ($\eta^2 = 0.005$).

*Experiment 1c:* Mean VCQ ratings for Experiment 1c are shown in Fig. 3B. A One-way repeated-measures ANOVA revealed a significant main effect of Pull-in distance, F (4.025, 76.468) = 34.33, $p < .001$ ($\eta^2 = 0.644$). To determine if evaluations were influenced by the closeness (2 s vs. 0.5 s) of a vehicle that followed the vehicle doing the overtaking, we compared VCQ ratings for Experiments 1b and 1c using a 2 (Experiment: 1b, 1c) × 9 (Pull-in distance) mixed ANOVA with Experiment as the between-subjects factor. There was a main effect of Pull-in distance $F$ (5.086, 193.273) = 87.530, $p < .001$ ($\eta^2 = 0.683$) and a significant Pull-in distance × Experiment interaction, $F$ (5.086, 193.273) = 2.602, $p = .026$ ($\eta^2 = 0.020$). This mostly likely indicates that shorter pull-in distances were rated more positively in the 0.5 s following condition than in the 2 s following condition. The main effect of Experiment did not approach significance, $F$ (1, 38) = 0.389, $p = .537$ ($\eta^2 = 0.010$).

#### 2.2.2. Electrodermal activity

The probability of a skin conductance response (SCR) when the overtaking vehicle pulled in was determined with Acqknowledge 4.1 using an automated analysis routine. The minimum SCR size was set to 0.02 µs, only SCRs that began

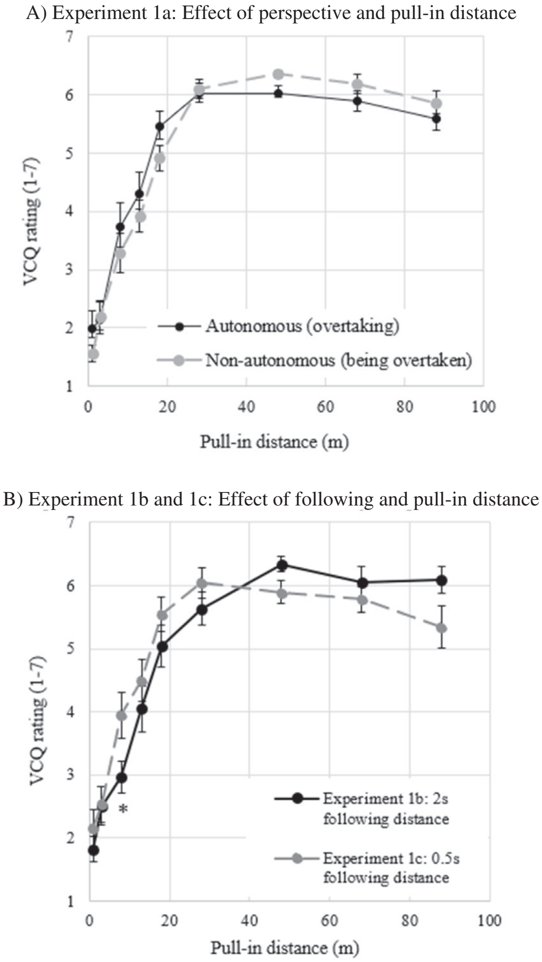


**Fig. 3.** Mean VCQ ratings as a function of pull-in distance and perspective in Experiment 1a (Panel A) and ratings as a function of pull-in distance and following distance for Experiment 1b and 1c (Panel B). Error bars correspond to ±1SE. Asterisks below data points (Panel B) indicate a significant difference between the same pull-in distance across Experiment 1b and 1c ($p < .05$, two-tailed).

0.5–7 s after the overtaking vehicle crossed the centre line to enter the left lane were counted, SCRs had to start and end within the driving scenario, and motion artefacts were excluded via a visual analysis of the EDA signal. Mean probabilities are shown in Fig. 4.

*Experiment 1a:* Data from 18 of participants from Experiment 1a were analysed (two participants were excluded due to very little deflection in their EDA signal). The analyses for Experiments 1b and 1c included all 20 participants. Cochran's Q test revealed a significant effect of Pull-in distance on SCR probability for the *being overtaken condition*, $\chi^2$ (8) = 23.820, $p = .002$, however, there was no reliable effect of pull-in distance in the *overtaking condition*, $\chi^2$ (8) = 9.132, $p = .33$. Exact McNemar tests for the *being overtaken condition* revealed that SCR probability was higher in the 1 m condition than all other conditions between 8 and 28 m, as well as the 88 m ($p < .05$) and 68 m conditions ($p < .01$). SCR probability was significantly higher in the 3 m condition than the 68 m condition ($p < .05$).

*Experiment 1b:* A Cochran's Q test revealed a significant effect of pull-in distance on SCR probability, $\chi^2$ (8) = 25.630, $p < .001$. Exact McNemar tests showed that the probability of an SCR was significantly higher in the 1 m condition compared to the 13 m condition ($p < .05$) and all other conditions between 18 and 68 m ($p < .01$). The probability of an SCR for a 3 m pull-in was significantly higher than for the 18 m pull-in ($p < .05$).

*Experiment 1c:* A Cochran's Q test revealed a significant main effect of pull-in distance on SCR probability, $\chi^2$ (8) = 33.6, $p < .001$. Exact McNemar tests showed that SCR probability was significantly higher in the 1 m condition than the 18 and 68 m conditions ($p < .01$) and the 28 and 88 m conditions ($p < .05$). SCR probability was significantly higher in the 3 m condition than in the 18 and 68 m conditions ($p < .01$) and the 28 and 88 m conditions ($p < .05$). The probability of an SCR was also significantly higher in the 8 m condition than in the 18, 28 and 68 m conditions ($p < .05$).

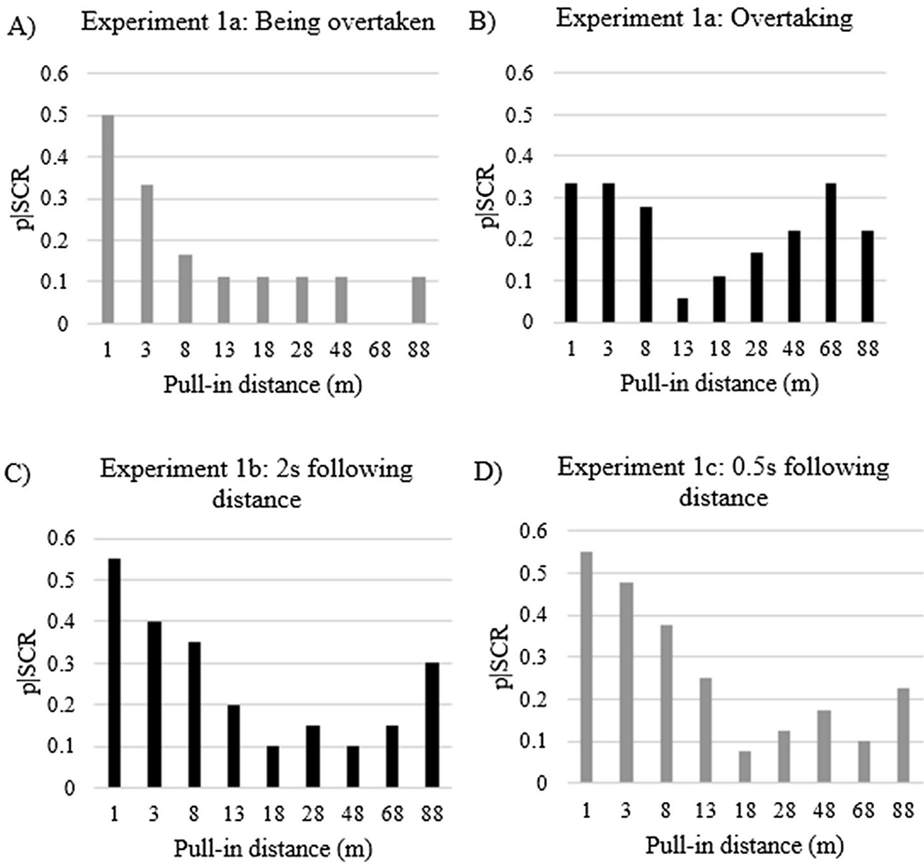


**Fig. 4.** Probability of an SCR in response to overtakes as a function of pull-in distance in Experiment 1a (Panel A: *Overtaking*; Panel B: *Being overtaken*), Experiment1b (Panel C) and Experiment 1c (Panel D).

### 2.2.3. EDA frequency and heart rate activity

Experiments 1b and 1c included the rate of SCRs per minute and heart rate across the entire overtaking manoeuvre for each pull-in distance. The overall mean number of SCRs per minute was 2.84 (*SD* = 2.81). A 2 (Experiment: 1b, 1c) $\times$ 9 (Pull-in distance) revealed no significant main effect of Experiment, $F(1, 37) = 1.018$, $p = .319$ ($\eta^2 = 0.027$), no main effect of Pull-in distance, $F$ (5.647, 208.934) = 1.552, $p = .167$ ($\eta^2 = 0.040$), or their interaction, $F$ (5.647, 208.934) = 0.474, $p = .817$ ($\eta^2 = 0.012$). For heart rate (mean = 77.45 bpm, *SD* = 12.16), there was no main effect of Experiment, $F$ (1, 37) = 0.030, $p = .864$ ($\eta^2 = 0.001$), no main effect of Pull-in distance, $F$ (4.651, 172.105) = 0.915, $p = .467$ ($\eta^2 = 0.024$) and no interaction, $F$ (4.651, 172.105) = 0.493, $p = .769$ ($\eta^2 = 0.013$).

### 2.2.4. Simulator driver input

We examined changes in the five dependent variables (gas, brake, steering, lane and speed) over a 4 s window (binned into nine 0.5 s intervals) for each of the nine pull-in distances using a series of one-way ANOVAs. Two windows were examined ranging from, −1 to 3 s around: (i) the overtaking vehicle passing, and (ii) the overtaking vehicle pulling-in. Benjamini-Hochberg corrections (Benjamini & Hochberg, 1995) were applied for each resulting set of nine ANOVAs.

*Experiment 1a:* There was a significant change in lane gap over time when the overtaking vehicle passed the participant, such that participants drifted towards the left of the lane in the 28 m condition, $F(1.84, 34.88) = 7.09$, $p < .05$. There were no other significant effects.

*Experiment 1b:* There was a significant change in lane gap over time when the overtaking vehicle passed the participant, such that participants drifted to the right of the lane in the 48 m condition, $F(1.37, 26.03) = 7.92$, $p < .05$. There was a significant drop in gas pedal input $F(2.11, 40.17) = 6.55$, $p < .05$, and a decrease in speed, $F(1.03, 19.60) = 8.07$, $p < .05$, in the 1 m condition after the pull-in. There was a significant increase in speed after the pull-in in the 68 m condition, $F(1.06, 20.15) = 8.33$, $p < .05$. No other effects were significant.

*Experiment 1c:* No significant effects were found for any of the behavioural variables.

## 3. Experiments 2a–2c: Evaluation of overtaking using a video-based methodology

Experiments 2a–c replicated Experiments 1a–c using a video-based methodology. This allowed us to: (i) test the robustness of the findings and provide a replication of the basic effects, and (ii) examine the potential influence of the level of immersion (presumed to be higher in the simulator) in terms of perceiving and reporting vehicle character.

### 3.1. Method

#### 3.1.1. Participants

Thirty participants completed each experiment (Table 3) and were paid £3. Participants were tested in groups of up to 24 in a large computer laboratory in sessions lasting 30–45 m.

#### 3.1.2. Measures and apparatus

*Video stimuli:* Driver's eye videos of the driving scenarios from Experiments 1a–c were made at 1080p resolution and 60 fps and presented on 57 × 35 cm LCD screens. A custom HTML script presented the videos, questionnaire measures and recorded responses. All videos were between 24 and 44 s in length encompassing 4 s before the overtaking vehicle pulled into the middle lane, and 4 s after the overtaking vehicle pulled into the left lane.

#### 3.1.3. Design and procedure

In Experiment 2a participants saw 18 videos (2 levels of perspective × 9 levels of pull-in distance), in a random order and provided VCQ ratings after each video. Experiment 2b and 2c were similar except that participants viewed and rated 9 videos rather than 18.

### 3.2. Results

#### 3.2.1. Experiment 2a: Pull-in distance and immersion

We combined the VCQ data from Experiment 1a with that from Experiment 2a and analysed the resulting set with a 2 (Immersion: video vs. simulator) × 2 (Vehicle perspective: overtaking vs. being overtaken) × 9 (Pull-in distance) mixed ANOVA. Immersion was the between-subject factor. This revealed a main effect of Pull-in distance, $F$ (3.485, 167.284) = 114.111, $p < .001$ ($\eta^2 = 0.677$). There was also a Pull-in Distance × Immersion interaction, $F$ (3.485, 167.284) = 6.526, $p < .001$ ($\eta^2 = 0.039$), which was qualified by an Immersion × Pull-in Distance × Vehicle perspective 3-way interaction, $F$ (5.123, 245.896) = 2.851, $p = .015$ ($\eta^2 = 0.055$). Ratings in the video condition were marginally higher than in the simulator conditions, $F$ (1, 48) = 3.632, $p = .063$ ($\eta^2 = 0.070$). The main effect of Vehicle perspective, $F$ (1, 48) = 0.632, $p = .430$ ($\eta^2 = 0.012$), and the remaining, Vehicle perspective × Immersion, $F$ (1, 48) = 2.898, $p = .095$ ($\eta^2 = 0.056$) and Pull-in Distance × Vehicle perspective interactions, $F$ (5.123, 245.896) = 1.103, $p = .360$ ($\eta^2 = 0.021$) were non-significant. As shown in Fig. 5, in the *overtaking condition*, VCQ ratings increased with distance in a similar way for the simulator and video-based conditions. However, for the *being overtaken* condition, VCQ ratings were more positive at the shorter pull-in distances and plateaued at a lower overall level with the video-based methodology than with the simulator. Confirming this, we split the data by perspective and conducted two separate mixed ANOVAs with the factors of Immersion and Pull-in distance. For the *overtaking* condition there was a main effect of Pull-in distance, $F$ (3.714, 178.280) = 72.929, $p < .001$ ($\eta^2 = 0.593$), however, neither the main effect of Immersion, $F$ (1, 48) = 0.905, $p = .346$ ($\eta^2 = 0.019$), nor the Immersion × Pull-in interaction was significant, $F$ (3.714, 178.280) = 2.104, $p = .087$ ($\eta^2 = 0.017$). For the *being overtaken* data, ratings were overall more positive in the video-based condition, $F$ (1, 48) = 6.520, $p < .05$ ($\eta^2 = 0.120$) and increased as pull-in distance increased, $F$ (4.604, 220.978) = 83.814, $p < .001$ ($\eta^2 = 0.594$). There was also a significant Immersion × Pull-in distance interaction, $F$ (4.604, 220.978) = 9.258, $p < .001$ ($\eta^2 = 0.066$).

#### 3.2.2. Experiment 2b: Being overtaken with a third vehicle following the overtaking vehicle with a gap of 2 s

As in Experiment 2a, we combined the VCQ scores from Experiment 1b and 2b. A 2 (Immersion: video vs. simulator) × 9 (Pull-in distance) mixed ANOVA revealed a main effect of Pull-in distance, $F$ (4.513, 126.610) = 89.473, $p < .001$ ($\eta^2 = 0.629$), and an Immersion × Pull-in distance interaction, $F$ (4.513, 216.610) = 4.697, $p < .001$ ($\eta^2 = 0.033$). The main effect of Immersion was not significant, $F$ (1, 48) = 2.957, $p = .092$ ($\eta^2 = 0.058$). As shown in Fig. 6, shorter pull-in distances were rated more positively and larger pull-in distances more negatively using the less immersive video-based approach compared to data collected in the driving simulator.

#### 3.2.3. Experiment 2c: Being overtaken with a third vehicle following the overtaking vehicle with a gap of 0.5 s

The VCQ scores from Experiment 1c and 2c were combined and analysed using a 2 (Immersion: video vs. simulator) × 9 (Pull-in distance) mixed ANOVA with immersion as the between-subjects factor. This revealed a main effect of Pull-in distance, $F$ (4.523, 217.101) = 71.256, $p < .001$ ($\eta^2 = 0.598$). However, neither the main effect of Immersion, $F$ (1, 48) = 0.031, $p = .862$ ($\eta^2 = 0.001$), nor the Immersion × Pull-in Distance interaction, $F$ (4.523, 217.101) = 1.062, $p = .380$ ($\eta^2 = 0.009$) were significant. We also combined VCQ scores from Experiment 2b and Experiment 2c (Fig. 7) to examine the influence of following distance on the effect of pull-in distance using only the video-based methodology, using a 2 (Experiment: 2b and

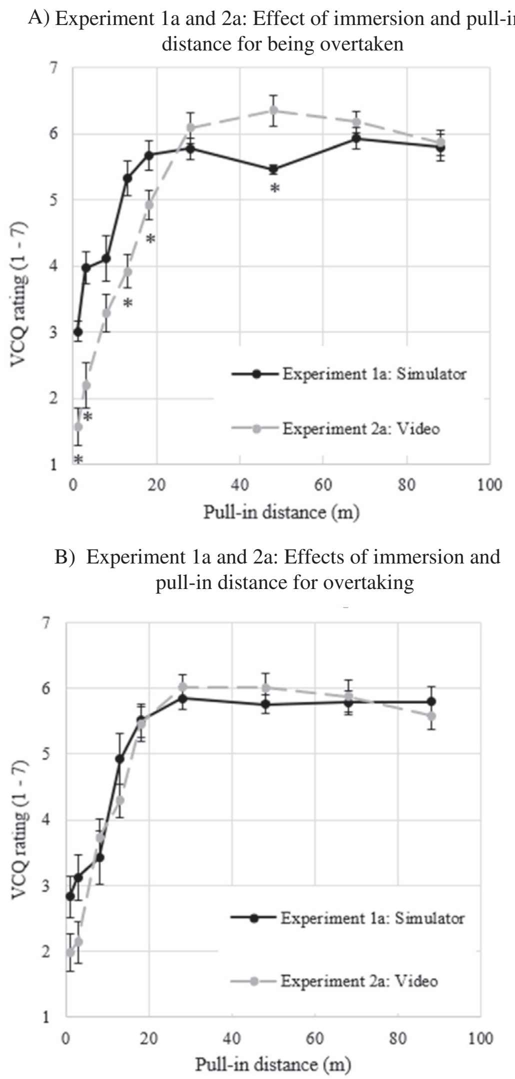


**Fig. 5.** Influence of pull-in distance and immersion for Experiments 1a and 1b, for the *being overtaken* (Panel A) and *overtaking* (Panel B) conditions. Asterisks below data points (Panel B) indicate significant differences between the same pull-in distances across as a function of immersion ($p < .05$, two-tailed).

2c) × 9 (Pull-in distance) mixed ANOVA with Experiment as the between-subjects factor. This revealed a main effect of Pull-in distance, $F$ (4.317, 250.403) = 77.068, $p < .001$ ($\eta^2 = 0.569$), but neither the main effect of Experiment, $F$ (1, 58) = 2.11, $p = .152$ ($\eta^2 = 0.035$), nor the Experiment × Pull-in distance interaction, $F$ (4.317, 250.403) = 0.286, $p = .899$ ($\eta^2 = 0.002$), reached significance.

## 4. Discussion

All six experiments revealed that vehicle character ratings became more positive as pull-in distance increased, before levelling off and beginning a downward trend after ~48 m. The pattern of ratings was similar when the driver was overtaking or being overtaken (suggesting that the type of vehicles involved in a manoeuvre may not influence the acceptability of that manoeuvre, as in TRL PPR807, 2017). The results suggest that there is a threshold of approx. 28 m for what is accepted to be a reasonable pull-in distance. Of note, most of the pull-in distances used were below the recommended 2 s gap rule used as a guide for car following ("The Annotated Highway Code", n.d.). The finding that distances as low as 28 m (approximately a 1 s gap at 96kmh or 60mph) were rated very positively is consistent with findings in the car following literature (Hutchinson, 2008; Nowakowski, O'Connell, Shladover, & Cody, 2010; Siebert, Oehl, & Pfister, 2014; Siebert, Oehl, Bersch, & Pfister, 2017; Taib-Maimon & Shinar, 2001) that distances below the officially recommended following time of 2 s are often used and rated as comfortable for drivers. The implication is that the parameters of acceptable autonomous driving styles may diverge from formal guidelines in some contexts.

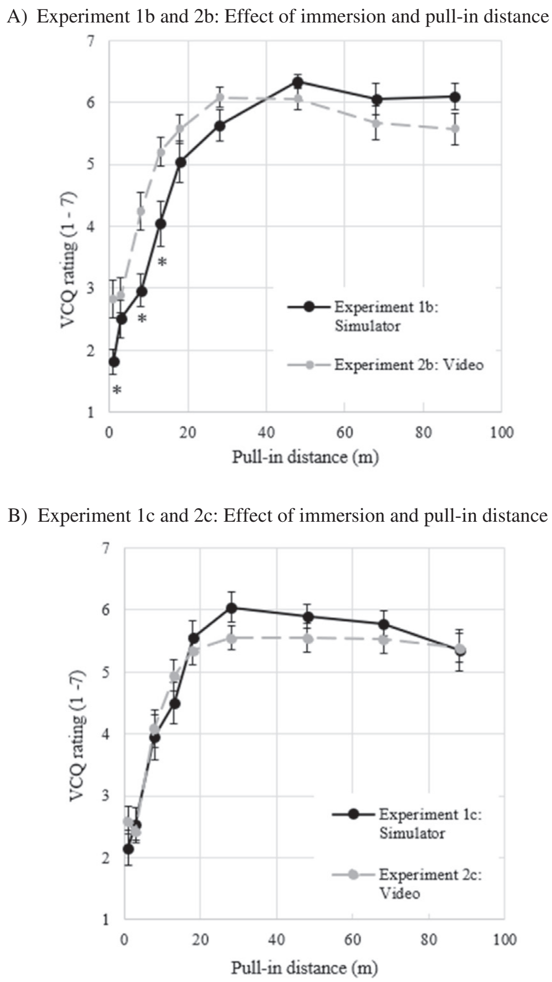


**Fig. 6.** Influence of pull-in distance and immersion for Experiment 1b 2b (Panel A) and Experiment 1c and 2c (Panel B). Asterisks below data points (Panel A) indicate significant differences between the same pull-in distances as a function of immersion. ($p < .05$, two-tailed).

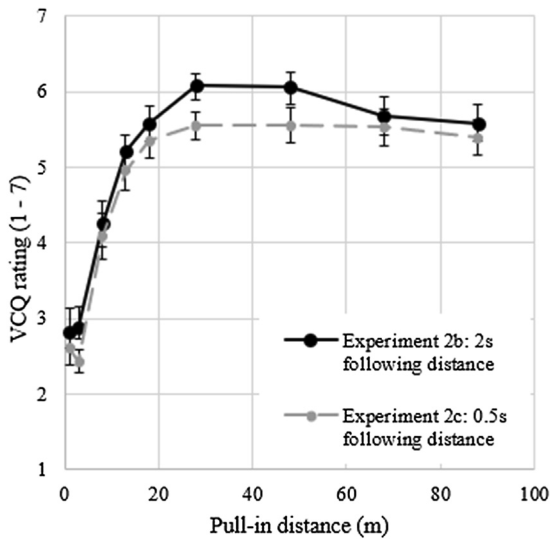


**Fig. 7.** Influence of following (2 s vs 0.5 s) and pull-in distance on VCQ ratings in the low immersion video-based methodology (Experiment 2b and 2c).

The finding that drivers that were being overtaken (but not the driver/occupant of an overtaking vehicle) were more likely to show an SCR to a pull-in manoeuvre for the shortest distances provides additional, objective support to the questionnaire results. This orienting response provides an objective measure of the effect of different manoeuvres and likely reflects a combination of surprise, anger, threat and attention capture (Boucsien, 2012; Critchley, 2002; Dewe et al., 2016; Frith & Allen, 1983) by manoeuvres which were subjectively rated as being the most unacceptable. The overall pattern of SCR probabilities as a function of pull-in distance replicated across all three simulator experiments, suggesting that an orienting response to a surprising overtake is a robust finding. Most of the significant differences in SCR probability were between the two smallest pull-in distances and the larger distances. Thus, although SCR probability appears to distinguish very unacceptable, potentially threatening and surprising pull-ins from more acceptable pull-ins, it does not provide fine-grained distinctions for larger pull-in distances. Furthermore, the maximum SCR probability was 50% in Experiment 1a (being overtaken), and 55% in Experiment 1b and 1c. Therefore, although the physiological data support the questionnaire findings and suggest that the sharpest pull-ins were objectively surprising/threatening, it would not be feasible to use the mere presence of an event-related SCR probability as a primary indicator of whether an autonomous overtake is perceived as acceptable. Of note, there was little influence of pull-in distance in the *overtaking conditions* suggesting that from a physiological response point of view, overtaking with a short pull-in distance might be much less disruptive and attention capturing than being overtaken in the same way. This difference likely reflects the difference in visual distance information and sense of danger experienced by participants from the two differing perspectives. We also observed evidence of a comparatively much smaller potential reduction in ratings at the longer pull-in distances suggesting that excessively long pull-in distances may result in negative vehicle character perceptions. This likely occurred because remaining in an outside lane unnecessarily might be considered 'lane hogging'.

The simulated driver input data showed that participants took pressure off of the gas pedal and reduced speed after a sharp pull-in and increased speed after a longer pull-in in one simulator experiment and drifted to the left of the lane after a moderate pull-in in another experiment. There were no substantial changes in brake pedal force or steering wheel angle in any of the simulator experiments. There was a general trend for participants to reduce gas pedal force and/or speed over time in response to very sharp pull-ins. Overall, these data provide some, albeit weak, evidence, that participants being overtaken at very small pull-in distances did try to slow down, supporting the finding that these distances were perceived as unsafe.

Traffic context also seems to be important. In Experiment 1b, the overtaking vehicle was followed by a third vehicle, at a relatively safe distance of 2 s. In this condition, vehicle character ratings did not differ from when there was no following vehicle. However, when a third vehicle was following at a relatively unsafe distance[3] (0.5 s), participants were more forgiving of a shorter pull-in distance than when the following vehicle was a safer distance. The more positive evaluation of the 8 m pull-in when the following vehicle was 0.5 s behind at least in the simulator experiments, suggests that previously unacceptable vehicle behaviours may be viewed as appropriate in some driving contexts. Participants may have perceived the overtaking vehicle as 'getting out the way' of following vehicle, and therefore rated the shorter pull-in as more acceptable. However, it is important to note that the very shortest pull-in distances (1 and 3 m) were not rated more positively with a closer-following vehicle – so there are some limits to this. Of note, these were the distances that were most likely to produce a physiological orienting/threat response. Furthermore, the effect of following distance on evaluation of pull-in distance was much weaker than the overall effect of pull-in distance on character evaluations. This suggests that there is a limit to the context-dependency of evaluations of autonomous overtaking, with some behaviours remaining unacceptable irrespective of traffic context, and the overall pattern of ratings over distance remaining consistent. The implication for autonomous driving styles is that behaviour that is unacceptable in one driving scenario may be rated more favourably in another, and autonomous vehicles could therefore benefit from using information on traffic context to perform more acceptable overtakes. Manufacturers may benefit from taking account of possible contextual influences on acceptable behaviour and interactions with other road users when developing autonomous vehicles.

This specific context effect was not, however, replicated in our video-based version of the task – perhaps due to a lower level of immersion. The video-based approach also produced some other differences. When viewed as a video on a relatively small computer screen, participants rated manoeuvres at the small pull-in distance less negatively than participants who experienced the same manoeuvre in the driving simulator. This difference likely reflects the greater perception of direct threat perceived in the more immersive simulator environment compared with that perceived by watching a video of the same situation. Conversely, there was also some evidence that the video-based condition led to more negative evaluations at one of the longer pull-in distances for the *being overtaken* perspective. One possible account of this is that participants might have overestimated the distance between themselves and the overtaking vehicle at the longer pull-in distances. This might occur due to the relatively small size and low resolution of the monitor, perhaps making a distant vehicle appear further away, compared to the much greater area and size of the visuals presented in the driving simulator. It is not clear why there was no reliable difference between the video and simulator-based ratings for Experiment 2c. However, there was a trend for some of the longer distances to produce more negative evaluations in the video condition consistent with the results of Experiment 2a and 2b. Although not the main focus of this study, this suggests that lower levels of immersion can result in non-constant (i.e. not just simply a positive bias) changes to valuations of road manoeuvres. This in turn

[3] Please note however, that distances of approximately 0.5s are commonly used and rated as acceptable (Hutchinson, 2008; Nowakowski et al., 2010; Siebert et al., 2017; Siebert et al., 2014; Taib-Maimon & Shinar, 2001).

suggests that some of our driving simulator results, although indicative, may not fully reflect what would happen in real-world driving conditions given that simulated environments may not be as immersive as their real-world equivalents. Verifying our findings in real-world, road-based conditions would therefore be a valuable goal for future research.

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