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How should autonomous vehicles overtake other drivers?

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1 **Abstract**

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

19

20 **Keywords**

21 Autonomous vehicles, overtaking, trust, driving styles, driving simulator

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Highlights

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- **Introduction:** Autonomous vehicles are expected to become available soon, but much work has focused on holistic/a priori trust, with less research on acceptability of specific driving behaviours.
- **Method:** We conducted six experiments on the effects of pull-in distance, vehicle perspective, traffic context and level of immersion on evaluations of autonomous motorway overtakes.
- **Results:** Acceptability increased sharply and linearly with increasing pull-in distance up to approximately 28m, for both the perspectives of being overtaken and overtaking. There were smaller mediating effects of traffic context and level of immersion.
- **Results:** In the simulator-based experiments, participants showed a consistently higher probability of an orienting response to the sharpest pull-ins when being overtaken.
- **Conclusions:** Evaluations of autonomous overtaking behaviour appear ‘bi-linear’ over distance, with ratings plateauing above a given threshold, with some limited influence of traffic context.

1 Autonomous vehicles may arrive on the roads by approximately 2020 (“Driverless car
2 market watch”, n.d.), with one estimate claiming that 75% of all road vehicles will be
3 autonomous by 2040 (“Look Ma, No Hands!”, 05/09/2012). Despite this prediction, fully
4 autonomous vehicles will have to share the road with human-driven vehicles especially
5 during the transition period. Even when most vehicles are autonomous, some human driven
6 vehicles (e.g., motorcycles and ‘motor enthusiast’ vehicles) may remain on the roads. Hence,
7 safe and acceptable interactions between autonomous and human-driven vehicles will remain
8 vital. Furthermore, even if all vehicles become fully autonomous, their behaviour will still
9 need to be acceptable to their occupants. Accordingly, it is important to understand the
10 psychological factors that influence how autonomous vehicle behaviours are perceived.

11 Survey-based methods have identified factors such as gender (Hohenberger, Spörrle
12 & Welppe, 2016; Howard & Dai, 2014; Hulse, Xie & Galea, 2018; Schoettle & Sivak, 2014),
13 age (Bansal & Kockelman, 2018; Haboucha, Ishaq & Shiftan, 2017; Hohenberger et al.,
14 2016; Hulse et al., 2018; Kyriakidis, Happee & de Winter, 2015), personality (Kyriakidis, et
15 al., 2015; Choi & Ji, 2015), cultural differences (Haboucha et al., 2017; Kyriakidis et al.,
16 2015; Schoettle & Sivak, 2014) daily driving behaviours (Howard & Dai, 2014) and
17 experience (Bansal & Kockelman, 2018) as influencing acceptance and intentions to use
18 autonomous vehicles. A review of several surveys found that attitudes towards autonomous
19 vehicles were most positive for males, younger people, those living in urban environments,
20 drivers with previous experience of assistance systems and individuals who were more
21 familiar with the news on technological developments (Becker & Axhausen, 2017).

22 A review by Hoff and Bashir (2015) defined ‘trust’ as comprising three distinct
23 components: dispositional, situational and learned. The survey-based work above mainly
24 investigated how dispositional trust is influenced by various demographic factors, rather than
25 evaluations after interacting with and gaining experience with a system (situational and

1 learned trust). To examine the latter two aspects of Hoff and Bashir's (2015) taxonomy,
2 experimental designs in which participants interact with autonomous vehicles and/or in-
3 vehicle interfaces are required.

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

17 However, comparatively little work has examined evaluations of specific vehicle
18 behaviours between autonomous and human-driven vehicles. Drivers seem to be concerned
19 about human drivers taking advantage of autonomous vehicles (Tennant, Howard, Franks,
20 Bauer & Stares, 2016) and autonomous vehicles struggling with the 'informal' rules of
21 driver-driver interactions (Tennant et al., 2015). Hence, we need to determine the parameters
22 of behaviour for autonomous vehicles to be acceptable to their occupants and other road
23 users. In starting to address this issue, one simulator study found that participants preferred a
24 more cautious autonomous driving style than their own (Basu, Yang, Hungerman, Singhal &
25 Dragan, 2017). An on-road trial found that occupants gave higher trust ratings of an

1 autonomous vehicle when driving on an empty road than when overtaking a parked vehicle.
2 Higher ratings were also given when overtaking a parked vehicle with oncoming traffic
3 compared to when there was no oncoming traffic, potentially due to the vehicle slowing
4 down with no obvious justification in the latter case (Venturer Trial 2, 2017). A further
5 simulator study showed that participants preferred an autonomous vehicle to use larger lateral
6 distances and begin steering into the middle lane earlier than the driver's own behaviour
7 when overtaking bicycles and scooters (Abe, Sato & Itoh, 2018). Another simulator trial
8 found that participants were more likely to overtake (move to the fast lane) after two vehicles
9 had passed rather than pull into the gap between them, regardless of whether the second
10 vehicle was autonomous or human-driven, or the distinctiveness of the autonomous vehicle's
11 appearance (TRL PPR807, 2017).

12 However, neither the Venturer trial (2017) nor Abe et al. (2018) or TRL (2017)
13 examined the role of pull-in distance on ratings of autonomous overtaking behaviour, Abe et
14 al. (2018) did not examine trust in the context of an autonomous vehicle overtaking another
15 car, and TRL (2017) focused more on the behaviour of human drivers towards autonomous
16 vehicles rather than the evaluation of their behaviour. In addition, participants in both studies
17 were asked to rate their general level of trust in the vehicle, rather than evaluate a specific
18 vehicle behaviour or manoeuvre, and Abe et al. (2018) did not manipulate individual
19 parameters independently. However, we need data on what makes specific manoeuvres more
20 or less acceptable if autonomous vehicles / systems are to be programmed optimally. Thus,
21 we focused on peoples' ratings of acceptability of a specific manoeuvre as we systematically
22 varied a number of relevant parameters. We asked people to evaluate overtaking behaviours
23 as a function of: i) pull-in distance after the overtake, ii) occupant perspective: driving a
24 vehicle that is being overtaken or being in an autonomous vehicle that is overtaking another
25 vehicle, and iii) the effect of traffic context; whether ratings of an overtaking manoeuvre are

1 influenced if the overtaking vehicle is being followed by a third vehicle. Acceptability was
2 determined via a 15-item ‘Vehicle Character Questionnaire’ (VCQ) (Table 2). We present six
3 experiments; three simulator based (1a-c) and three video-based (2a-c) replications which
4 also allowed to us examine the potential influence of immersion on the results. We also
5 measured physiological responses; electrodermal activity (EDA, E1a-c) and heart rate (E1b-
6 c), and driver input data (E1a-c). These objective measures allowed us to determine, for
7 example, if attention was captured and potentially if someone was surprised, angered or
8 threatened by a manoeuvre (Boucsein, 2012; Frith & Allen, 1983; Critchley, 2002; Dewe,
9 Watson & Braithwaite, 2016). For an overview and summary of the main findings please see
10 Table 1.

11 **Experiments 1a – 1c: Evaluation of autonomous overtaking as a function of pull-in** 12 **distance, perspective and following distance of a third vehicle**

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

24 *Method*

25 *Participants*

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

5 *Driving simulator setup*

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

18 *Physiological measurements*

19 Electrodermal activity (EDA) was recorded via disposable EL507 electrodes attached
20 to the distal phalanges of the fingers of the non-dominant hand. Initial pilot work indicated
21 that this arrangement provided reliable measurements and was not intrusive to the driving
22 experience. Experiments 1b and 1c also recorded heart rate via Lead II ECG, with disposable
23 EL501 electrodes attached to the participant's right wrist and left ankle. Measurements were
24 recorded using a Biopac MP36R data acquisition unit and analysed with Acqknowledge v4.1.
25 ECG and EDA signals were sampled at 1000Hz. EDA measurements used a gain of x2000,

1 with low pass filters at 66.5 and 38.5Hz and band stop line frequency filter at 50Hz. ECG
2 measurements used the same filters but with a high-pass filter at 0.5Hz and a gain of x1000.
3 Relevant simulator events were automatically coded in the physiological data file.

4 *Simulator driver input*

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

10 *Design and procedure*

11 Experiment 1a used a fully within-subjects design. Participants first completed two
12 acclimatization trials (one driving the vehicle, one in an autonomous mode vehicle). They
13 then completed 18 test trials which were combinations of pull-in distance¹ (1m, 3m, 8m, 13m,
14 18m, 28m, 48m, 68m and 88m – selected using initial piloting) and perspective (being in the
15 autonomous overtaking vehicle vs. being in a non-autonomous vehicle that was being
16 overtaken). Trial order was randomized, and participants were given a break outside of the
17 simulator lab after the first 8 test trials. All 18 trials were randomized (such that participants
18 switched perspective more than once) in order to prevent participants losing interest in the
19 task (e.g., after prolonged periods of automated driving) and to reduce order effects especially
20 in respect to potential physiological habituation. After each trial, participants were presented
21 with the VCQ with each question presented sequentially on a touch-screen LCD panel
22 located in the center dashboard console and participants responded by touching an option on

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.

1 a 7-point Likert scale². For each trial, the average of the scores across all questions was
2 calculated to give a VCQ rating that ranged between 1 and 7. In the *being overtaken*
3 *condition*, participants drove at a specified speed in the left lane after which they were
4 overtaken by an autonomous vehicle which pulled in at varying distances. In the *overtaking*
5 *condition*, participants were placed within an autonomous vehicle which pulled out to
6 overtake a vehicle in the left-hand lane and pulled back into the left lane at varying distances
7 (*Figure 2*). After completing the final test trial, participants were screened for simulator
8 sickness, debriefed and thanked. The experiment lasted 60 to 90 min.

9 In Experiment 1b and 1c, participants experienced the same *being overtaken condition*
10 from Experiment 1a, except that a third vehicle followed behind the overtaking vehicle. In
11 Experiment 1b, the third vehicle followed 2 seconds (64.69m) behind and in Experiment 1c it
12 followed 0.5 seconds (16.17m) behind. These were selected based on guidelines
13 recommending 2 seconds as a safe following distance (“The Annotated Highway Code”,
14 n.d.). On each trial, the third vehicle remained at a fixed distance behind the overtaking
15 vehicle, pulled out to the middle lane at the same time, was yoked to the overtaking vehicle’s
16 speed, and remained in the middle lane after the pull-in. Each trial stopped ten seconds after
17 the following vehicle passed the participant, or ten seconds after the overtaking vehicle was
18 completely in the left lane after the pull-in, whichever came last.

19 **Results**

20 ***Vehicle character ratings***

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.

1 *Experiment 1a:* Mean VCQ ratings (Figure 3A) increased as a function of pull-in
 2 distance up to approx. 28m, plateaued and decreased slightly after approx. 48m. The effects
 3 of Vehicle perspective (*being overtaken* vs. *overtaking*) and Pull-in distance (1m to 88m) on
 4 VCQ ratings were analysed with a 2×9 within-subjects ANOVA (Greenhouse-Geisser
 5 corrections applied where necessary). There was a significant main effect of Pull-in distance,
 6 $F(4.367, 82.968) = 102.989, p < .001 (\eta^2 = .844)$. However, neither the main effect of
 7 perspective, $F(1, 19) = 3.12, p = .583 (\eta^2 = .016)$, nor the Perspective \times Pull-in distance
 8 interaction reached significance, $F(4.279, 81.306) = 1.985, p = .100 (\eta^2 = .095)$.

9 *Experiment 1b:* Mean VCQ ratings for Experiment 1b (Figure 3B) were analysed with
 10 a one-way repeated-measures ANOVA which revealed a significant main effect of Pull-in
 11 distance, $F(4.187, 79.550) = 58.47, p < .001 (\eta^2 = .755)$. To assess the influence of having a
 12 third vehicle follow the overtaking vehicle, we compared the VCQ ratings from the *being*
 13 *overtaken condition* of Experiment 1a with those of Experiment 1b with a mixed 2
 14 (Experiment: 1a, 1b) \times 9 (Pull-in-distance) ANOVA with Experiment as the between-
 15 subjects factor. This revealed a significant main effect of Pull-in distance $F(5.201, 197.642)$
 16 $= 145.556, p < .001 (\eta^2 = .789)$. However, neither the main effect of Experiment, $F(1, 38) =$
 17 $.006, p = .940 (\eta^2 = .000)$, nor the Experiment \times Pull-in distance approached significance, F
 18 $(5.201, 197.642) = 0.849, p = 0.521 (\eta^2 = .005)$.

19 *Experiment 1c:* Mean VCQ ratings for Experiment 1c are shown in Figure 3B. A
 20 One-way repeated-measures ANOVA revealed a significant main effect of Pull-in distance, F
 21 $(4.025, 76.468) = 34.33, p < .001 (\eta^2 = .644)$. To determine if evaluations were influenced by
 22 the closeness (2s vs. 0.5s) of a vehicle that followed the vehicle doing the overtaking, we
 23 compared VCQ ratings for Experiments 1b and 1c using a 2 (Experiment: 1b, 1c) \times 9 (Pull-in
 24 distance) mixed ANOVA with Experiment as the between-subjects factor. There was a main
 25 effect of Pull-in distance $F(5.086, 193.273) = 87.530, p < .001 (\eta^2 = .683)$ and a significant

1 Pull-in distance x Experiment interaction, $F(5.086, 193.273) = 2.602, p = .026 (\eta^2 = .020)$.
2 This mostly likely indicates that shorter pull-in distances were rated more positively in the
3 0.5s following condition than in the 2s following condition. The main effect of Experiment
4 did not approach significance, $F(1, 38) = .389, p = .537 (\eta^2 = .010)$.

5 *Electrodermal activity*

6 The probability of a skin conductance response (SCR) when the overtaking vehicle
7 pulled in was determined with Acqknowledge 4.1 using an automated analysis routine. The
8 minimum SCR size was set to $0.02\mu\text{s}$, only SCRs that began 0.5 to 7 seconds after the
9 overtaking vehicle crossed the centre line to enter the left lane were counted, SCRs had to
10 start and end within the driving scenario, and motion artefacts were excluded via a visual
11 analysis of the EDA signal. Mean probabilities are shown in Figure 4.

12 *Experiment 1a:* Data from 18 of participants from Experiment 1a were analysed (two
13 participants were excluded due to very little deflection in their EDA signal). The analyses for
14 Experiments 1b and 1c included all 20 participants. Cochran's Q test revealed a significant
15 effect of Pull-in distance on SCR probability for the *being overtaken condition*, $\chi^2(8) =$
16 $23.820, p = .002$, however, there was no reliable effect of pull-in distance in the *overtaking*
17 *condition*, $\chi^2(8) = 9.132, p = .33$. Exact McNemar tests for the *being overtaken condition*
18 revealed that SCR probability was higher in the 1m condition than all other conditions
19 between 8 and 28m, as well as the 88m ($p < .05$) and 68m conditions ($p < .01$). SCR
20 probability was significantly higher in the 3m condition than the 68m condition ($p < .05$).

21 *Experiment 1b:* A Cochran's Q test revealed a significant effect of pull-in distance on
22 SCR probability, $\chi^2(8) = 25.630, p < .001$. Exact McNemar tests showed that the probability
23 of an SCR was significantly higher in the 1m condition compared to the 13m condition ($p <$
24 $.05$) and all other conditions between 18 and 68m ($p < .01$). The probability of an SCR for a
25 3m pull-in was significantly higher than for the 18m pull-in ($p < .05$).

1 *Experiment 1c*: A Cochran's Q test revealed a significant main effect of pull-in
 2 distance on SCR probability, $\chi^2(8) = 33.6, p < .001$. Exact McNemar tests showed that SCR
 3 probability was significantly higher in the 1m condition than the 18 and 68m conditions ($p <$
 4 $.01$) and the 28 and 88m conditions ($p < .05$). SCR probability was significantly higher in the
 5 3m condition than in the 18 and 68m conditions ($p < .01$) and the 28 and 88m conditions ($p <$
 6 $.05$). The probability of an SCR was also significantly higher in the 8m condition than in the
 7 18, 28 and 68m conditions ($p < .05$).

8 ***EDA Frequency and Heart Rate Activity***

9 Experiments 1b and 1c included the rate of SCRs per minute and heart rate across the
 10 entire overtaking manoeuvre for each pull-in distance. The overall mean number of SCRs per
 11 minute was 2.84 ($SD = 2.81$). A 2 (Experiment: 1b, 1c) \times 9 (Pull-in distance) revealed no
 12 significant main effect of Experiment, $F(1, 37) = 1.018, p = .319 (\eta^2 = .027)$, no main effect
 13 of Pull-in distance, $F(5.647, 208.934) = 1.552, p = .167 (\eta^2 = .040)$, or their interaction, F
 14 $(5.647, 208.934) = .474, p = .817 (\eta^2 = .012)$. For heart rate (mean = 77.45 bpm, $SD = 12.16$),
 15 there was no main effect of Experiment, $F(1, 37) = .030, p = .864 (\eta^2 = .001)$, no main effect
 16 of Pull-in distance, $F(4.651, 172.105) = .915, p = .467 (\eta^2 = .024)$ and no interaction, F
 17 $(4.651, 172.105) = .493, p = .769 (\eta^2 = .013)$.

18 ***Simulator driver input***

19 We examined changes in the five dependent variables (gas, brake, steering, lane and
 20 speed) over a 4s window (binned into nine 0.5s intervals) for each of the nine pull-in
 21 distances using a series of one-way ANOVAs. Two windows were examined ranging from, -
 22 1 to 3s around: i) the overtaking vehicle passing, and ii) the overtaking vehicle pulling-in.
 23 Benjamini-Hochberg corrections (Benjamini & Hochberg, 1995) were applied for each
 24 resulting set of nine ANOVAs.

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

5 *Experiment 1b:* There was a significant change in lane gap over time when the
6 overtaking vehicle passed the participant, such that participants drifted to the right of the lane
7 in the 48m condition, $F(1.37, 26.03) = 7.92, p < .05$. There was a significant drop in gas
8 pedal input $F(2.11, 40.17) = 6.55, p < .05$, and a decrease in speed, $F(1.03, 19.60) = 8.07, p$
9 $< .05$, in the 1m condition after the pull-in. There was a significant increase in speed after the
10 pull-in in the 68m condition, $F(1.06, 20.15) = 8.33, p < .05$. No other effects were
11 significant.

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

13 **Experiments 2a-2c: Evaluation of overtaking using a video-based methodology**

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

18 ***Method***

19 *Participants*

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

22 *Measures and apparatus*

23 *Video stimuli:* Driver's eye videos of the driving scenarios from Experiments 1a-c were
24 made at 1080p resolution and 60 fps and presented on 57×35 cm LCD screens. A custom

1 HTML script presented the videos, questionnaire measures and recorded responses. All
 2 videos were between 24-44s in length encompassing 4s before the overtaking vehicle pulled
 3 into the middle lane, and 4s after the overtaking vehicle pulled into the left lane.

4 *Design and procedure*

5 In Experiment 2a participants saw 18 videos (2 levels of perspective \times 9 levels of
 6 pull-in distance), in a random order and provided VCQ ratings after each video. Experiment
 7 2b and 2c were similar except that participants viewed and rated 9 videos rather than 18.

8 **Results**

9 *Experiment 2a: Pull-in distance and Immersion*

10 We combined the VCQ data from Experiment 1a with that from Experiment 2a and
 11 analysed the resulting set with a 2 (Immersion: video vs. simulator) \times 2 (Vehicle perspective:
 12 overtaking vs. being overtaken) \times 9 (Pull-in distance) mixed ANOVA. Immersion was the
 13 between-subject factor. This revealed a main effect of Pull-in distance, $F(3.485, 167.284) =$
 14 $114.111, p < .001 (\eta^2 = .677)$. There was also a Pull-in Distance \times Immersion interaction, F
 15 $(3.485, 167.284) = 6.526, p < .001 (\eta^2 = .039)$, which was qualified by an Immersion \times Pull-
 16 in Distance \times Vehicle perspective 3-way interaction, $F(5.123, 245.896) = 2.851, p = .015 (\eta^2$
 17 $= .055)$. Ratings in the video condition were marginally higher than in the simulator
 18 conditions, $F(1, 48) = 3.632, p = .063 (\eta^2 = .070)$. The main effect of Vehicle perspective, F
 19 $(1, 48) = .632, p = .430 (\eta^2 = .012)$, and the remaining, Vehicle perspective \times Immersion, F
 20 $(1, 48) = 2.898, p = .095 (\eta^2 = .056)$ and Pull-in Distance \times Vehicle perspective interactions,
 21 $F(5.123, 245.896) = 1.103, p = .360 (\eta^2 = .021)$ were non-significant. As shown in *Figure 5*,
 22 in the *overtaking condition*, VCQ ratings increased with distance in a similar way for the
 23 simulator and video-based conditions. However, for the *being overtaken* condition, VCQ
 24 ratings were more positive at the shorter pull-in distances and plateaued at a lower overall
 25 level with the video-based methodology than with the simulator. Confirming this, we split the

1 data by perspective and conducted two separate mixed ANOVAs with the factors of
2 Immersion and Pull-in distance. For the *overtaking* condition there was a main effect of Pull-
3 in distance, $F(3.714, 178.280) = 72.929, p < .001 (\eta^2 = .593)$, however, neither the main
4 effect of Immersion, $F(1, 48) = .905, p = .346 (\eta^2 = .019)$, nor the Immersion \times Pull-in
5 interaction was significant, $F(3.714, 178.280) = 2.104, p = .087 (\eta^2 = .017)$. For the *being*
6 *overtaken* data, ratings were overall more positive in the video-based condition, $F(1, 48) =$
7 $6.520, p < .05 (\eta^2 = .120)$ and increased as pull-in distance increased, $F(4.604, 220.978) =$
8 $83.814, p < .001 (\eta^2 = .594)$. There was also a significant Immersion \times Pull-in distance
9 interaction, $F(4.604, 220.978) = 9.258, p < .001 (\eta^2 = .066)$.

10 *Experiment 2b: Being overtaken with a third vehicle following the overtaking vehicle with a*
11 *gap of 2 seconds.*

12 As in Experiment 2a, we combined the VCQ scores from Experiment 1b and 2b. A 2
13 (Immersion: video vs. simulator) \times 9 (Pull-in distance) mixed ANOVA revealed a main
14 effect of Pull-in distance, $F(4.513, 126.610) = 89.473, p < .001 (\eta^2 = .629)$, and an
15 Immersion \times Pull-in distance interaction, $F(4.513, 216.610) = 4.697, p < .001 (\eta^2 = .033)$.
16 The main effect of Immersion was not significant, $F(1, 48) = 2.957, p = .092 (\eta^2 = .058)$. As
17 shown in *Figure 6*, shorter pull-in distances were rated more positively and larger pull-in
18 distances more negatively using the less immersive video-based approach compared to data
19 collected in the driving simulator.

20 *Experiment 2c: Being overtaken with a third vehicle following the overtaking vehicle with a*
21 *gap of 0.5 seconds.*

22 The VCQ scores from Experiment 1c and 2c were combined and analysed using a 2
23 (Immersion: video vs. simulator) \times 9 (Pull-in distance) mixed ANOVA with immersion as
24 the between-subjects factor. This revealed a main effect of Pull-in distance, $F(4.523,$
25 $217.101) = 71.256, p < .001 (\eta^2 = .598)$. However, neither the main effect of Immersion, $F(1,$

1 48) = .031, $p = .862$ ($\eta^2 = .001$), nor the Immersion \times Pull-in Distance interaction, $F(4.523,$
 2 217.101) = 1.062, $p = .380$ ($\eta^2 = .009$) were significant. We also combined VCQ scores from
 3 Experiment 2b and Experiment 2c (*Figure 7*) to examine the influence of following distance
 4 on the effect of pull-in distance using only the video-based methodology, using a 2
 5 (Experiment: 2b and 2c) \times 9 (Pull-in distance) mixed ANOVA with Experiment as the
 6 between-subjects factor. This revealed a main effect of Pull-in distance, $F(4.317, 250.403) =$
 7 77.068, $p < .001$ ($\eta^2 = .569$), but neither the main effect of Experiment, $F(1, 58) = 2.11$, $p =$
 8 .152 ($\eta^2 = .035$), nor the Experiment \times Pull-in distance interaction, $F(4.317, 250.403) = .286$,
 9 $p = .899$ ($\eta^2 = .002$), reached significance.

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Discussion

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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 ~48m. 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. 28m 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 second gap rule used as a guide for car following ("The Annotated Highway Code", n.d.). The finding that distances as low as 28m (approximately a 1s 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, Bersch & Pfister, 2017; Siebert, Oehl & Pfister, 2014; Taib-Maimon & Shinar, 2001) that distances below the officially recommended following time of 2s are often used and rated as comfortable for drivers. The implication is

1 that the parameters of acceptable autonomous driving styles may diverge from formal
2 guidelines in some contexts.

3 The finding that drivers that were being overtaken (but not the driver/occupant of an
4 overtaking vehicle) were more likely to show an SCR to a pull-in manoeuvre for the shortest
5 distances provides additional, objective support to the questionnaire results. This orienting
6 response provides an objective measure of the effect of different manoeuvres and likely
7 reflects a combination of surprise, anger, threat and attention capture (Bouc sien, 2012;
8 Critchley, 2002; Dewe et al., 2016; Frith & Allen, 1983) by manoeuvres which were
9 subjectively rated as being the most unacceptable. The overall pattern of SCR probabilities as
10 a function of pull-in distance replicated across all three simulator experiments, suggesting
11 that an orienting response to a surprising overtake is a robust finding. Most of the significant
12 differences in SCR probability were between the two smallest pull-in distances and the larger
13 distances. Thus, although SCR probability appears to distinguish very unacceptable,
14 potentially threatening and surprising pull-ins from more acceptable pull-ins, it does not
15 provide fine-grained distinctions for larger pull-in distances. Furthermore, the maximum SCR
16 probability was 50% in Experiment 1a (being overtaken), and 55% in Experiment 1b and 1c.
17 Therefore, although the physiological data support the questionnaire findings and suggest that
18 the sharpest pull-ins were objectively surprising/threatening, it would not be feasible to use
19 the mere presence of an event-related SCR probability as a primary indicator of whether an
20 autonomous overtake is perceived as acceptable. Of note, there was little influence of pull-in
21 distance in the *overtaking conditions* suggesting that from a physiological response point of
22 view, overtaking with a short pull-in distance might be much less disruptive and attention
23 capturing than being overtaken in the same way. This difference likely reflects the difference
24 in visual distance information and sense of danger experienced by participants from the two
25 differing perspectives. We also observed evidence of a comparatively much smaller potential

1 reduction in ratings at the longer pull-in distances suggesting that excessively long pull-in
2 distances may result in negative vehicle character perceptions. This likely occurred because
3 remaining in an outside lane unnecessarily might be considered ‘lane hogging’.

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

13 Traffic context also seems to be important. In Experiment 1b, the overtaking vehicle
14 was followed by a third vehicle, at a relatively safe distance of 2s. In this condition, vehicle
15 character ratings did not differ from when there was no following vehicle. However, when a
16 third vehicle was following at a relatively unsafe distance³ (0.5s), participants were more
17 forgiving of a shorter pull-in distance than when the following vehicle was a safer distance.
18 The more positive evaluation of the 8m pull-in when the following vehicle was 0.5s behind at
19 least in the simulator experiments, suggests that previously unacceptable vehicle behaviours
20 may be viewed as appropriate in some driving contexts. Participants may have perceived the
21 overtaking vehicle as ‘getting out the way’ of following vehicle, and therefore rated the
22 shorter pull-in as more acceptable. However, it is important to note that the very shortest pull-
23 in distances (1 and 3m) were not rated more positively with a closer-following vehicle – so

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).

1 there are some limits to this. Of note, these were the distances that were most likely to
2 produce a physiological orienting/threat response. Furthermore, the effect of following
3 distance on evaluation of pull-in distance was much weaker than the overall effect of pull-in
4 distance on character evaluations. This suggests that there is a limit to the context-
5 dependency of evaluations of autonomous overtaking, with some behaviours remaining
6 unacceptable irrespective of traffic context, and the overall pattern of ratings over distance
7 remaining consistent. The implication for autonomous driving styles is that behaviour that is
8 unacceptable in one driving scenario may be rated more favourably in another, and
9 autonomous vehicles could therefore benefit from using information on traffic context to
10 perform more acceptable overtakes. Manufacturers may benefit from taking account of
11 possible contextual influences on acceptable behaviour and interactions with other road users
12 when developing autonomous vehicles.

13 This specific context effect was not, however, replicated in our video-based version of
14 the task – perhaps due to a lower level of immersion. The video-based approach also
15 produced some other differences. When viewed as a video on a relatively small computer
16 screen, participants rated manoeuvres at the small pull-in distance less negatively than
17 participants who experienced the same manoeuvre in the driving simulator. This difference
18 likely reflects the greater perception of direct threat perceived in the more immersive
19 simulator environment compared with that perceived by watching a video of the same
20 situation. Conversely, there was also some evidence that the video-based condition led to
21 more negative evaluations at one of the longer pull-in distances for the *being overtaken*
22 perspective. One possible account of this is that participants might have overestimated the
23 distance between themselves and the overtaking vehicle at the longer pull-in distances. This
24 might occur due to the relatively small size and low resolution of the monitor, perhaps
25 making a distant vehicle appear further away, compared to the much greater area and size of

1 the visuals presented in the driving simulator. It is not clear why there was no reliable
2 difference between the video and simulator-based ratings for Experiment 2c. However, there
3 was a trend for some of the longer distances to produce more negative evaluations in the
4 video condition consistent with the results of Experiment 2a and 2b. Although not the main
5 focus of this study, this suggests that lower levels of immersion can result in non-constant
6 (i.e. not just simply a positive bias) changes to valuations of road manoeuvres. This in turn
7 suggests that some of our driving simulator results, although indicative, may not fully reflect
8 what would happen in real-world driving conditions given that simulated environments may
9 not be as immersive as their real-world equivalents. Verifying our findings in real-world,
10 road-based conditions would therefore be a valuable goal for future research.

11

1 **Acknowledgements**

- 2 This work was supported by Jaguar Land Rover and the UK-EPSC grant EP/N012380/1 as
3 part of the jointly funded Towards Autonomy: Smart and Connected Control (TASCC)
4 Programme.

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- 23

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

5

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 ~28m; no effect of vehicle perspective
1b	Simulator	Pull-in distance, following distance/traffic context	Sharp increase in trust up to ~28m; no effect of presence of a following vehicle
1c	Simulator	Pull-in distance, following distance/traffic context	Sharp increase in trust up to ~28m; 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 ~28m; 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 ~28m; 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 ~28m; no difference in pattern of ratings when compared to simulator

6

7

1 Table 2. Full VCQ questionnaire.

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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

4

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

7

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

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Experiment	Number of participants (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 M=25.15 SD=4.34	20	10 months – 19 years 13 UK
1b	20 (10F)	18 RH	18 – 35 years M=21.65 SD=3.4	20	6 months – 12 years 9 UK
1c	20 (11F)	18 RH	18 – 28 years M=20.85 SD=2.20	20	4 months – 7 years 8 UK
2a	30(20F)	25 RH	20 – 61 years M=25.76 SD=7.76	20	1 – 27 years 4 UK
2b	30(18F)	28 RH	18 – 36 years M=22.34 SD=4.30	22	1 – 15 years 2 UK
2c	30(23F)	26 RH	18 – 50 years M=23.03 SD=6.10	20	6 months – 20 years 7 UK

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(A)



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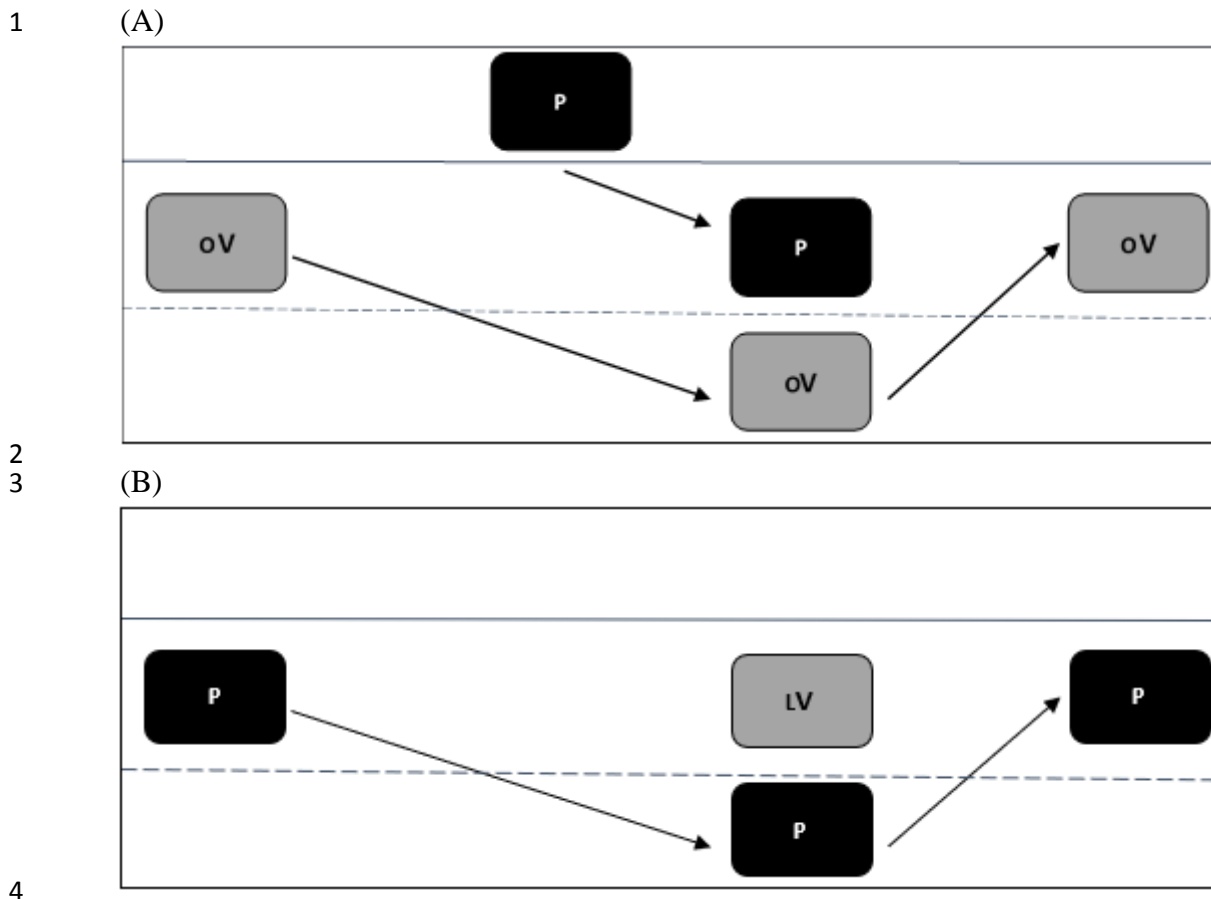
(B)



4

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

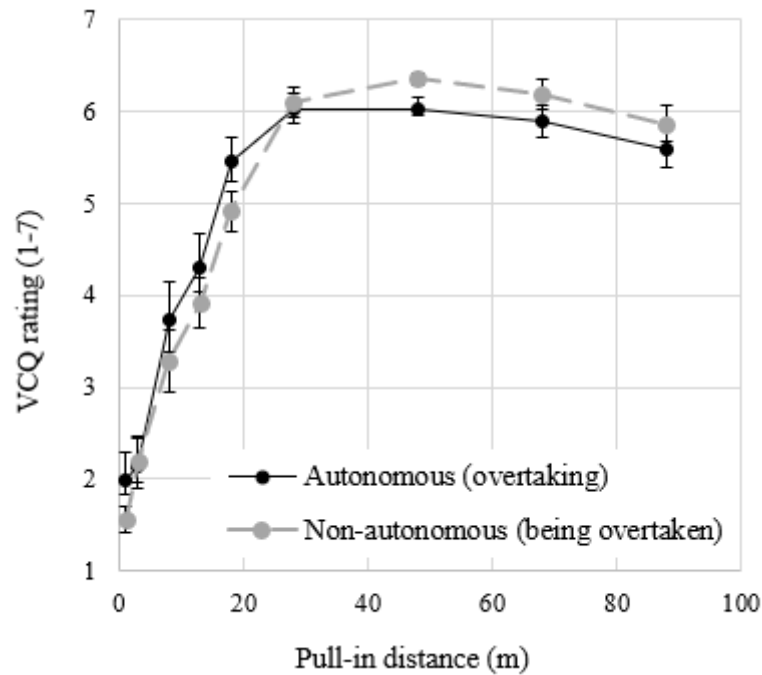
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5 *Figure 2: Overview of a single trial. (A) In each being overtaken condition trial, the*
 6 *participant (P) moved from the hard shoulder to the left lane and accelerated to 96 km/h while*
 7 *being followed at a distance of 50m by the overtaking vehicle (OV). Three seconds after the*
 8 *participant exceeded 90 km/h, the overtaking vehicle accelerated to 16 km/h above the*
 9 *participant's speed and moved to the middle lane, pulling back into the left lane at the set*
 10 *pull-in distance. (B) In each overtaking condition trial, the participant's vehicle (P)*
 11 *accelerated from zero to 96 km/h over ten seconds, followed the lead vehicle (LV) at a*
 12 *distance of 50m for ten seconds, moved to the middle lane and accelerated to 112 km/h, then*
 13 *pulled back into the left lane at the set pull-in distance. For both perspectives, the trial was*
 14 *stopped ten seconds after the overtaking vehicle was completely in the left lane.*
 15

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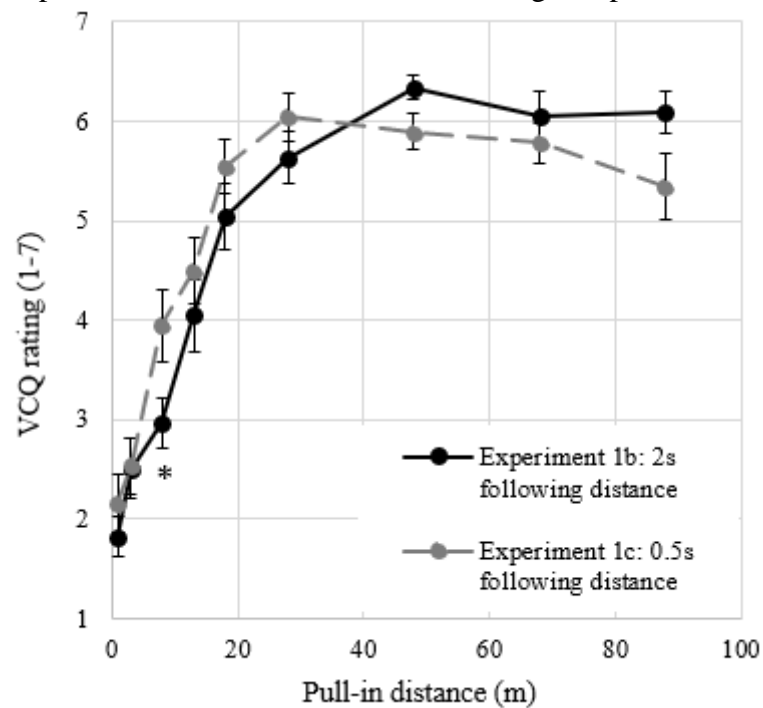
A) Experiment 1a: Effect of perspective and pull-in distance



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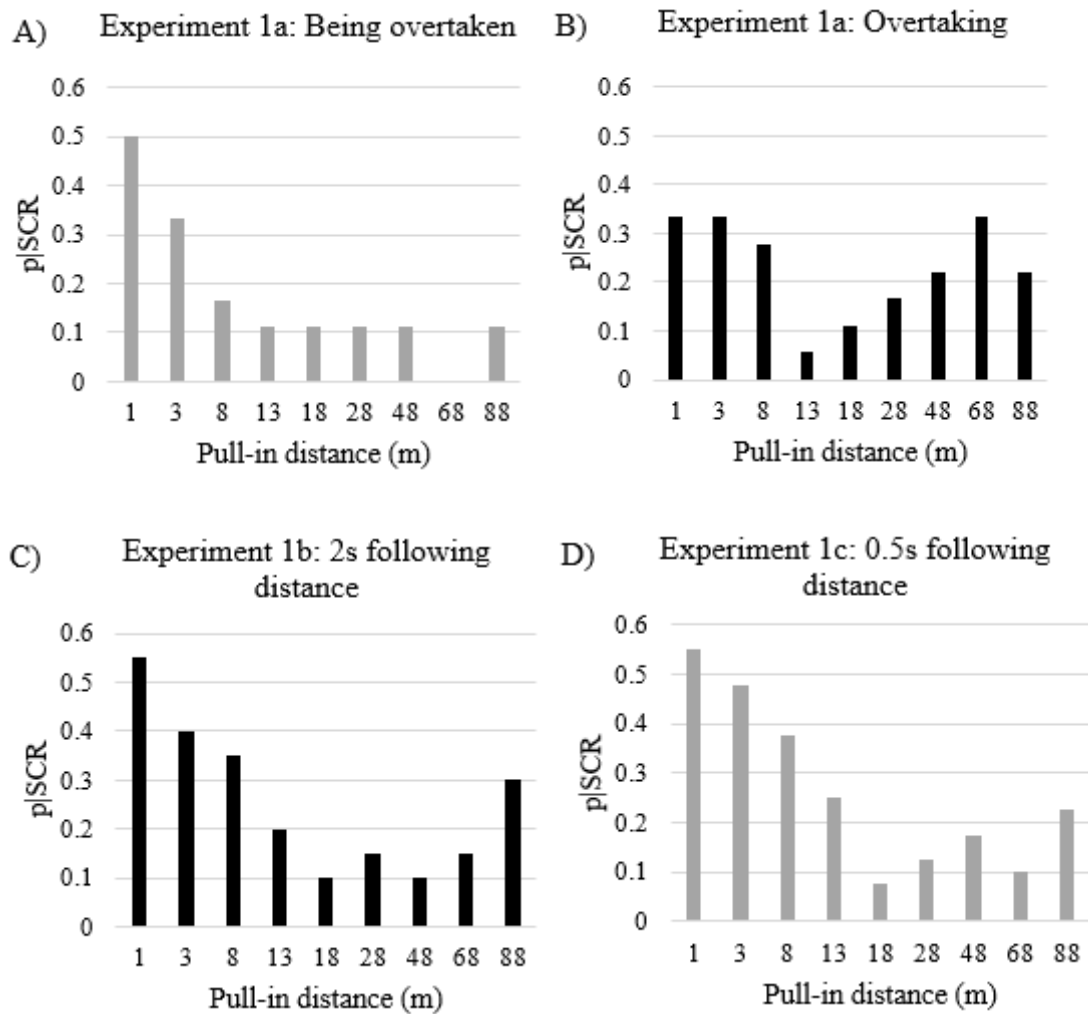
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B) Experiment 1b and 1c: Effect of following and pull-in distance



4

5 *Figure 3: Mean VCQ ratings as a function of pull-in distance and perspective in Experiment*
 6 *1a (Panel A) and ratings as a function of pull-in distance and following distance for*
 7 *Experiment 1b and 1c (Panel B). Error bars correspond to ± 1 SE. Asterisks below data points*
 8 *(Panel B) indicate a significant difference between the same pull-in distance across*
 9 *Experiment 1b and 1c ($p < .05$, two-tailed).*



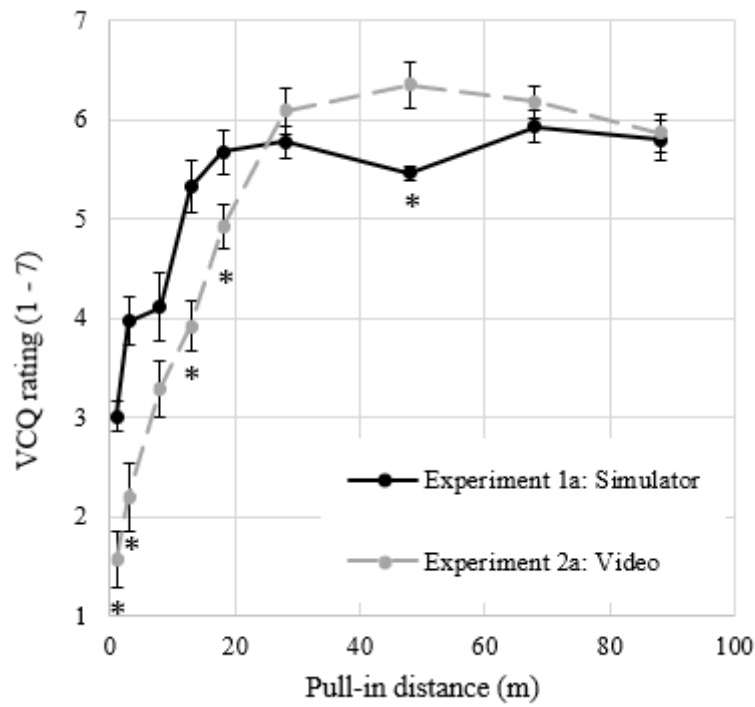
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3 *Figure 4: Probability of an SCR in response to overtakes as a function of pull-in distance in*
 4 *Experiment 1a (Panel A: Overtaking; Panel B: Being overtaken), Experiment 1b (Panel C)*
 5 *and Experiment 1c (Panel D).*

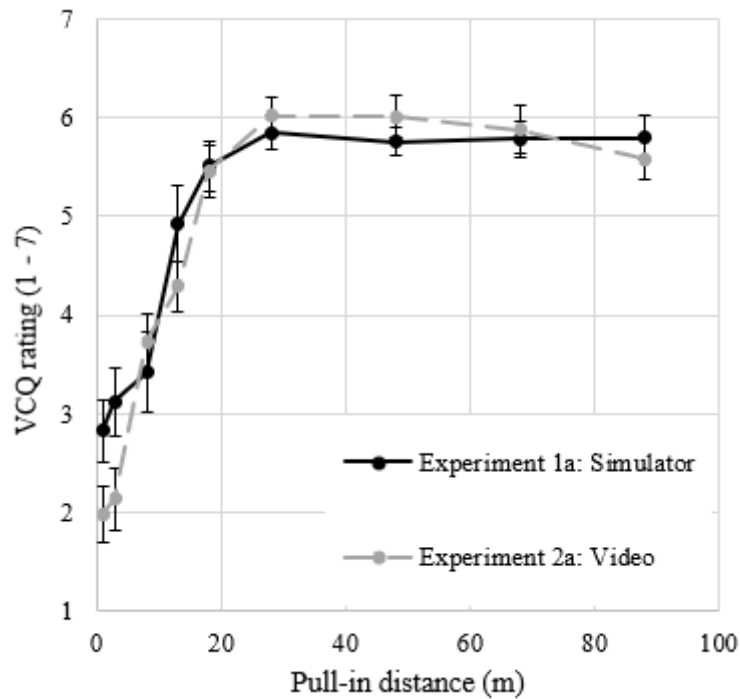
6

1 A) Experiment 1a and 2a: Effect of immersion and pull-in distance for being overtaken



2 B) Experiment 1a and 2a: Effects of immersion and pull-in distance for overtaking

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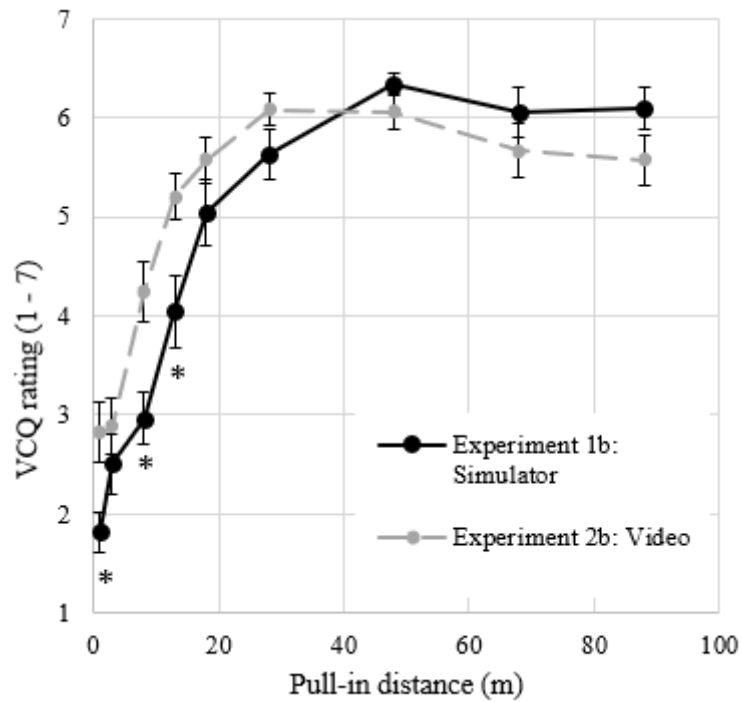
4

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

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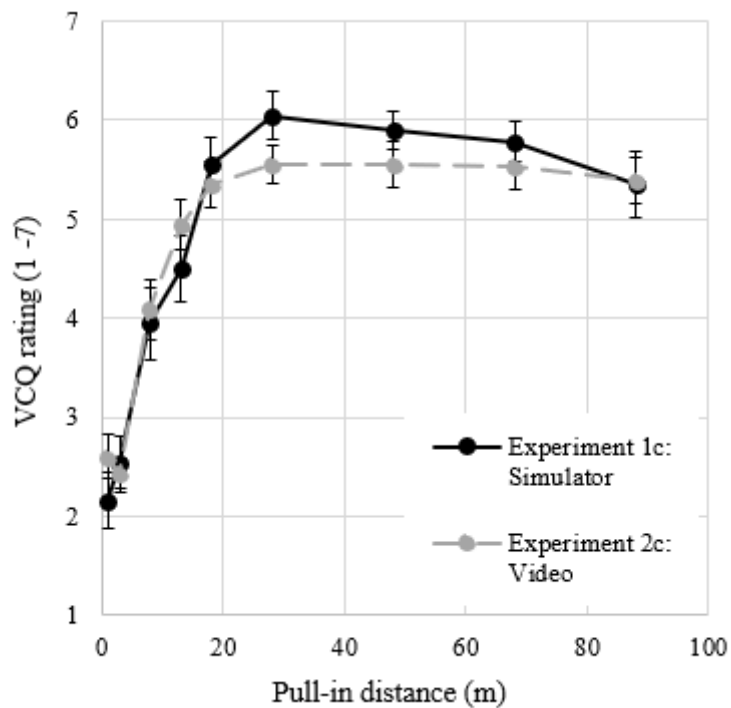
A) Experiment 1b and 2b: Effect of immersion and pull-in distance



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B) Experiment 1c and 2c: Effect of immersion and pull-in distance



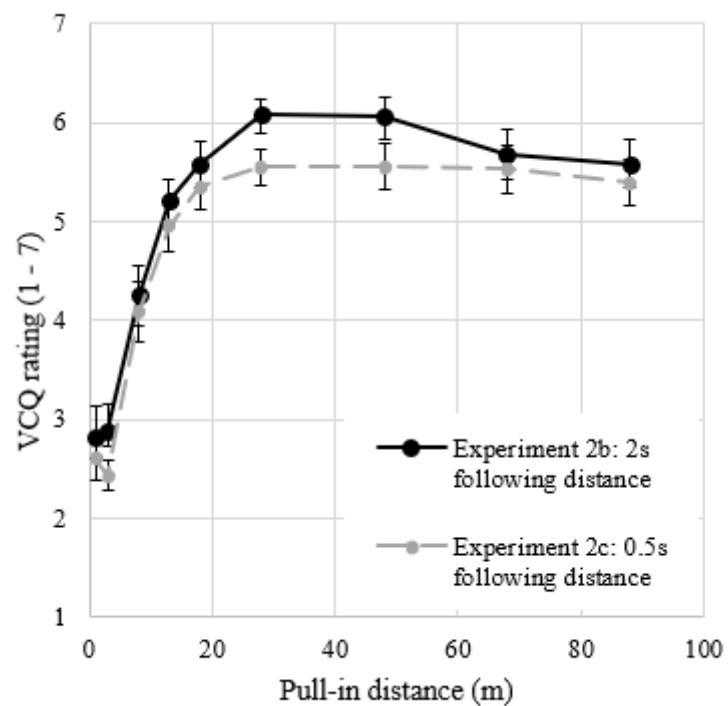
4

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

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Experiment 2b and 2c: Effect of following and pull-in distance



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

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