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Rear-view perception in driving: Distance information is privileged in the selection of safe gaps

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A R T I C L E I N F O

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A B S T R A C T

Selecting a safe gap before merging into the traffic is a crucial driving skill that relies on images provided by rear-view mirrors or, recently, camera-monitor systems. When using these visual aids, some drivers select dangerously small gaps to cut in front of faster vehicles. They may do so because they base their decision either on information about distance or object size, or on miscalculated information about time-to-passage (TTP). Previous experiments have been unable to compare the role of TTP, speed, and distance information for drivers' gap selection, as they did not investigate them in the same experimental regime. The present experiments seek to determine the perceptual variables that guide drivers' rearward gap selection. Using short videos of an approaching vehicle filmed from three different camera heights (low, conventional, high), a total of 61 subjects either made gap safety decisions (Experiment I), or estimated the TTP, speed, and distance of an approaching vehicle (Experiment II). An effect of camera height was found for gap selection, TTP, and distance estimation, but not for speed estimation. For the high camera position, smaller gaps were selected as safe, TTP estimates were longer, and the distance to the approaching vehicle was perceived as farther. An opposite pattern was found for the low camera. Regression analyses suggested that distance is an important player. The subjects strongly relied on distance information when estimating TTP, and perceived distance dominated subjects' gap selection. Thus, drivers seem to employ distance-based strategies when selecting safe gaps in rear-view mirrors or monitors.

1. Introduction

When a car is stopped at the roadside and the driver wants to merge into the traffic, he/she often has to decide whether or not it is safe to pull out in front of a vehicle approaching from behind. For an ideal observer, the best strategy for a lane-change decision would be to consider the time available to make the lane change (i.e., the gap duration) and to compare this to the time required to make the lane change. If the available time is shorter than the required time, then the driver should not change the lane, because it would increase the risk of a collision and would force the following car to perform a potentially dangerous action, such as initiaingt an emergency braking maneuver. Note that the time available to make the lane change is correlated with but not identical to other variables, such as the distance to or the velocity of an approaching vehicle. However, factors such as the velocity or size of an approaching vehicle affect the size of selected gaps (Alexander et al., 2002; Lobjois & Cavallo, 2007; Oxley et al., 2005; Petzoldt, 2014; Robbins et al., 2018). To select safe gaps, drivers might therefore either prioritize distance information (Lobjois & Cavallo, 2007; Oxley

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et al., 2005), or they might rely on inaccurate time judgements (e. g. Dommes & Cavallo, 2011; Keshavarz et al., 2017; Petzoldt, 2014; Wilmut & Purcell, 2021). Note that by using terms like strategy or information use, we do not wish to imply that the underlying perceptual processes are necessarily deliberate or conscious. To the contrary, the information processing of the visual system may only be cognitively penetrable to a very small degree by the actor.

The purpose of the current study is to determine which perceptual variables guide gap selection. When entering traffic, gap selection is based mostly on the visual information available in the rear-view mirrors. This information can be altered by changes in the type or position of the mirrors. Especially in camera-monitor systems (CMS), which are increasingly replacing conventional rear-view mirrors (Terzis, 2016), the position of the side-mounted rear-view camera could deviate strongly from the conventional mirror position. It was frequently observed that the eye-height can affect distance perception (e. g. Bernhard & Hecht, 2020; Leyrer et al., 2015; Ooi et al., 2001). In the present experiments, we have varied the camera height and investigated whether camera-height effects surface in gap selection and its underlying perceptual variables. Based on the observed differences, we then examined which variables might have guided the selection of safe gaps.

1.1. On the relationship between time-to-passage and gap selection

A perceptual quantity closely related to gap selection is the perception of time-to-contact (TTC), that is the time until an object arrives at the observer's position (Cohen et al., 1955; Kadali & Vedagiri, 2013; Petzoldt, 2016). For a stationary observer and constant approach speed, TTC is determined physically by the ratio of the approaching object's distance at a given point of time and its velocity. Usually, the physical distance to and the velocity of an approaching object are not directly available but need to be estimated by our perceptual system. With respect to frontal approaches, Hoyle (1957) and Lee (1976) showed TTC to be approximately specified by the optical variable tau (τ), which is the ratio of an object's instantaneous angular size (ϕ) and its instantaneous temporal derivative ($\dot{\phi}$). Moreover, for passing trajectories, which is referred to as time-to-passage (TTP), a similar τ-variable can be specified as $\tau_{TTP} = \theta / \dot{\theta}$, where θ is the angle between the longitudinal axis of the observer and the line drawn from the observer to the object approaching on a passing trajectory (see Fig. 1), and $\dot{\theta}$ the change rate of this angle (Calabro et al., 2011; Kaiser & Mowafy, 1993). For simplicity, we use TTP in the following to denote TTC and TTP, whichever may be appropriate. However, please note that even if TTP can be derived mathematically by the previously mentioned equations, this does not mean that observers actually perform these arithmetic operations to estimate TTP. In contrast, we take the perception of TTP to be rather intuitive.

The size of selected gaps, if estimated by τ-variables, should be invariant to changes in the approaching object's characteristics, such as size or texture, or its surround. However, TTP estimation and likewise gap selection is affected by factors such as vehicle size, velocity, or distracting traffic (Baurès et al., 2014; DeLucia, 1991, 2013; Hecht & Savelsbergh, 2004; Lobjois & Cavallo, 2007; Oberfeld & Hecht, 2008; Petzoldt, 2014, 2016; Yannis et al., 2013). For instance, smaller temporal gaps are accepted when a vehicle approaches with greater speed and is thus observed from a larger distance (Alexander et al., 2002; Beggiato et al., 2017; Kadali & Vedagiri, 2013; Petzoldt et al., 2017; Yannis et al., 2013). This has also been observed in rear-view mirrors and CMS (Flannagan & Mefford, 2005; Hahnel & Hecht, 2012; Schmidt et al., 2016; Smith et al., 2016). Based on these results, some researchers promoted that observers may rely mostly on distance, and not on TTP, to select safe gaps (Lobjois & Cavallo, 2007; Oxley et al., 2005). This does not correspond to the general assumption that gap selection is based on TTP, which is perceived inaccurately (e. g. DeLucia et al., 2016; Dommes & Cavallo, 2011; Keshavarz et al., 2017; Petzoldt, 2014).

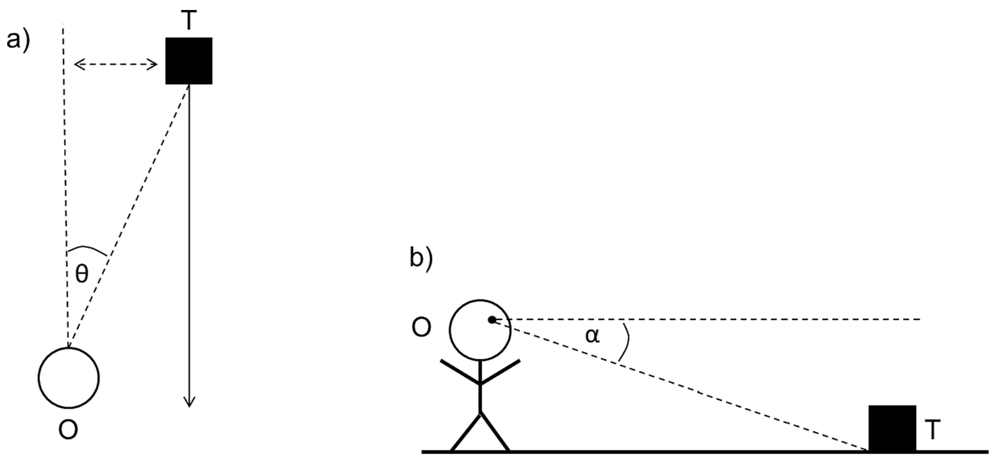

Fig. 1. Illustration of the visual angle θ used to calculate τ_{TTP} (Kaiser & Mowafy, 1993; panel a) and the angular declination below the horizon α (Ooi et al., 2001; panel b). An observer (O) observes a target (T) either approaching on a passing trajectory (solid arrow in panel a) or resting on the ground plane (panel b). θ denotes the angle between the longitudinal axis of the observer and the line drawn from the observer to the object (dotted lines in panel a). α denotes the angle between the line drawn from the observer's eye to the horizon and the line between the eye and the contact point between a target and the ground plane (dotted lines in panel b).

1.2. Distance cues and the effect of perspective

Depth cues associated with an object's distance could affect gap selection directly, and they could affect gap selection indirectly through the estimated TTP. Indeed, relative size, height in the field, and occlusion influence TTP estimation (DeLucia, Kaiser et al., 2003), and an object's inverse angular size and the distance from the observer is factored into the estimation of TTP (DeLucia et al., 2016; Keshavarz et al., 2017; Landwehr et al., 2013; Law et al., 1993; Liu et al., 2008). The integration of depth cues also suggests perspective to affect TTP estimation. This has been demonstrated for object-object collisions (Hecht et al., 2015; Landwehr et al., 2014; Steward et al., 1993). The effect of eye height on TTP estimation in observer-object collisions could be related to the angular declination below the horizon, also referred to as vertical gaze angle (Gardner & Mon-Williams, 2001; Ooi et al., 2001; Sedgwick, 1986). This is the angle between the line drawn from the observer's eye to the horizon and the line between the eye and the contact point between a target and the ground plane (Ooi et al., 2001; Proffitt, 2006; see Fig. 1). If this angle is used as a heuristic for distance estimation, the distance should appear larger from low and shorter from high viewpoints – exactly what was observed in many experiments (Daum & Hecht, 2009; Leyrer et al., 2015; Li & Durgin, 2012; Messing & Durgin, 2005; Ooi et al., 2001).

We found evidence for a camera-height effect on distance estimation in CMS (Bernhard & Hecht, 2020). As suggested by the declination angle, placing the camera farther down elongated the perceived distance, whereas placing it farther up shortened it. Fig. 2 depicts the declination angles calculated from a geometric representation of the scenario used in the current experiments, as a function of simulated distance and the three camera heights used in the following experiments. Based on these angles, we expect distance to appear shorter (longer) for the high (low) camera, compared to the conventional camera height. We chose these camera heights for different reasons. These heights are comparable with the heights used in the aforementioned experiment (Bernhard & Hecht, 2020). Even if a height of 190 cm is not feasible for sedans or most SUVs, it is feasible for larger vehicles, such as transportation vehicles or light trucks. Changing the camera height on large trucks has been considered before (Fornell Fagerström & Gardlund, 2012), with heights of up to 4 m. Therefore, the considered heights still represent realistic heights for different vehicles. Finally, a wider range of camera heights was needed to increase the angular differences between the three heights and to disentangle the declination angle from other perceptual variables, such as the angular object size. Note that the effect of camera height is expected to decrease for smaller ranges more feasible for sedans, as has been observed earlier (Bernhard et al., 2021).

1.3. Research scope and hypotheses

Before drivers pull out in front of an approaching vehicle, they have to assess the safety of the rearward gap. Ideally, this safety assessment and consequently the selection of a gap should depend solely on the TTP of an approaching vehicle. The presented experiments investigate whether and how TTP and other perceptual variables are actually factored into gap selection decisions. If distance information forms the basis for rearward gap selection, as proposed earlier (Lobjois et al., 2013; Oxley et al., 2005), a camera-height effect consistent with the effect on distance estimation (see above) should surface in gap selection. We investigated this in Experiment I and accordingly hypothesized to observe larger (smaller) gaps as result of shorter (longer) perceived distance in the high (low) camera position. Moreover, we hypothesized the variation in selected gap sizes to increase for the low camera position and to decrease for the high position. A similar effect has been observed in one of our earlier experiments (Bernhard et al., 2021).

Experiment II focussed on the perceptual variables underlying gap selection and therefore examined the camera-height effect with respect to TTP, speed, and distance estimation. We expected effects of camera height on TTP and distance estimation that follow the effects on gap selection in Experiment I, assuming that the perceived distance could influence TTP estimates and gap selection. To shed

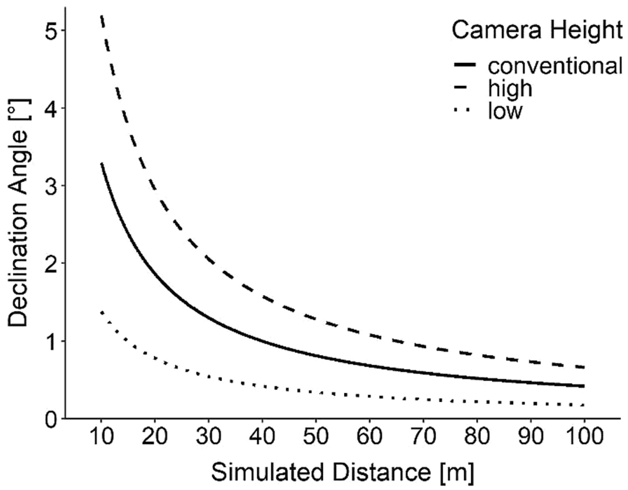

Fig. 2. Declination angles as a function of the camera heights and distances simulated in Experiments I and II. The cameras are placed 50 cm (low), 120 cm (conventional), and 190 cm (high) above the ground.

more light on the relationship between these variables, we used multiple regression analyses to evaluate the relative importance of the simulated distance and, in particular, the declination angle in the estimation of TTP. Finally, logistic regression analyses were used to quantify the relative importance of perceived TTP, perceived speed, and perceived distance in gap selection. This analysis evaluates whether the perceived TTP or the perceived distance is more important for the selection of safe gaps (Dommes & Cavallo, 2011; Lobjois et al., 2013; Oxley et al., 2005; Petzoldt, 2014).

2. Experiment I: Gap selection

2.1. Methods

2.1.1. Sample description

An a-priori power analysis was employed to determine the required sample size. We aimed at a power of 1-β = 0.95 for the main effect of camera height. The effect size and correction factor for the degrees of freedom ($\eta^2_p = .29$, $\tilde{\varepsilon} = 0.63$) were based on a previous CMS experiment (Bernhard & Hecht, 2020). The power analysis was conducted in G*Power (Faul et al., 2007) and resulted in a recommended sample size of $N = 30$ subjects. Accordingly, 30 subjects ($n = 15$ female) volunteered in our experiment. The subjects, psychology students recruited via an e-mail distribution list, received partial course credit for their participation. In accordance with the Declaration of Helsinki, all subjects gave their written informed consent and were debriefed after the experiment. Their age ranged from 18 to 39 years ($M = 25.72$ years, $SD = 4.67$ years). All subjects had owned a valid driving license for a mean time period of 7.93 years ($SD = 4.46$ years, range 1 to 21 years). 80% stated to drive no more than 10.000 km per year, the remaining 20% stated to drive up to 20.000 km or more per year. All subjects had normal or corrected-to-normal visual acuity, as confirmed by the Freiburg Visual Acuity Test (FrACT; Bach, 1996). They were naïve regarding the hypotheses of the experiment and had not participated in a similar experiment before.

2.1.2. Apparatus and stimuli

The subjects sat in a small lab chamber in front of a 24-inch Ultra HD monitor with a native resolution of 3840 × 2160 pixels. The subject's bridge of the nose was aligned to the center of the display at a distance of 40 cm using a chin rest. Both eyes and the display center were at a height of 120 cm. On the monitor, 1.5 s-long videos were presented as experimental stimuli with 1280 × 690 pixels resolution, resulting in a diagonal size of 7″ and a horizontal visual angle of 24.68°. The subject's vehicle was parked on the right roadside in the simulated environment. The videos depicted a yellow target vehicle (L: 4.939 m, W: 1.886 m, H: 1.467 m) on the right lane of a two-lane road (in Germany, one drives on the right side of the road). The target vehicle approached the subject's vehicle from behind with constant velocity on a passing trajectory. The back portion of the ego-vehicle was visible in the video. Moreover, the visual scene depicted in the monitor was mirrored horizontally, similar to existing camera-monitor systems. Otherwise, the scene showed an urban environment and provided a large range of visual depth cues (see Fig. 3).

To create the videos, 45 video frames were rendered separately using Autodesk 3ds Max 2018, with a virtual camera mounted on the simulated ego vehicle either in the position of a conventional side-mounted mirror 120 cm above the ground, or 70 cm higher or lower. The virtual camera depicted the simulated scene with a horizontal visual angle of 39.6°, which is comparable to the image of aspherical curved mirrors (Bach et al., 2006). The 45 frames were then combined to videos with a frame rate of 30 Hz using Adobe Premiere. Example videos can be found in the supplemental material. Furthermore, Fig. 3 exemplarily depicts three final video frames.

2.1.3. Experimental task and design

We employed a forced choice paradigm following the method of constant stimuli. The subject's task was to observe the approaching vehicle. After 1.5 s, the video ended and a response screen appeared. It depicted the statement *I could have driven into the adjacent lane without causing a crash.* Subjects responded by pressing the left (*No*) or right (*Yes*) button on a keypad placed in front of them. As shown in Table 1, the simulated TTP varied in eight steps and the target vehicle approached with two different velocities, resulting in 14 different simulated final distances at the end of the video. The camera height (low, conventional, high), with the respective heights of 0.5 m, 1.2 m, and 1.9 m represented the third within-subjects factor. The factors were fully crossed, resulting in 8 × 2 × 3 = 48 factor level combinations (i. e. videos). The videos were presented ten times each block-wise, resulting in 480 experimental trials in ten blocks. In each block, all videos were presented once. The order of the videos within each block was randomized per subject.

Fig. 3. Final frames of the videos used in the experiments. The vehicle is at a simulated distance of 10 m and a simulated TTP of 1 s. The camera is placed 0.5 m (left), 1.2 m (middle) or 1.9 m (right) above the ground. All videos were 1.5 s long.

Table 1
Target velocities as well as simulated TTP and distances presented in Experiment I and II.

Velocity [km/h]	36								54							
Simulated TTP [s]	1.0	2.0	3.0	3.5	4.0	4.5	5.5	6.5	1.0	2.0	3.0	3.5	4.0	4.5	5.5	6.5
Simulated final distance [m]	10	20	30	35	40	45	55	65	15	30	45	52.5	60	67.5	82.5	97.5

2.1.4. Procedure

The procedure of the trials was first outlined. Six training trials were then presented to familiarize the subject with the task. The training trials were identical to the test trials, expect that the vehicle approached with a constant speed of 45 km/h and disappeared at a TTP of 0.5 or 7 s. The training trials were presented at all three camera heights. The subjects received no feedback about the accuracy of their decision throughout the experiment. Fig. 4 depicts an example trial. After the subjects had completed all 480 experimental trials, they filled out a short questionnaire on demographic information and received a debriefing. The whole experiment lasted approximately 60 min.

2.1.5. Data preparation and analysis strategy

First, the probability of a *Yes* response (i. e. gap selected, p_{Yes}) was calculated for each simulated TTP across the ten presentation times. Then, a cumulative-normal psychometric function (PMF) was fitted to p_{Yes} for each combination of subject, velocity, and camera height. The PMFs were fitted using generalized linear models (GLM, McCullagh & Nelder, 1989) with probit link functions and a Maximum Likelihood approach. This resulted in 180 PMFs. Next, we estimated our two dependent variables, that is the *gap selected with a probability of 50%* ($GS_{50\%}$) and the *difference limen* (DL), from the PMFs. $GS_{50\%}$ was defined as the 50% point of the PMFs, that is the temporal gap size (TTP) into which subjects deemed it safe to drive in 50% of the ten presentations. The DL was defined as half the difference between the TTP corresponding to the 75% and 25% points on the PMF. Thus, DL represented the change in TTP necessary to alter the perceived safety of a rearward gap. Fig. 5 depicts an example PMF.

The residuals of both dependent variables approximated a normal distribution and no extreme outliers were observed. Therefore, for each variable, a univariate repeated-measures analysis of variance (rmANOVA) was conducted with the within-subjects factors camera height and velocity. Note that we also checked for gender effects and for systematic changes of the subjects' responses over the trials. However, no systematic effects were observed. Consequently, these variables were not included in the further analysis. Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) of the degrees of freedom was applied if sphericity was violated. Effect sizes (η^2_p) and, if applicable, the correction value $\hat{\varepsilon}$ will be reported. If significant, the main effect of camera height was further analyzed by means of planned contrasts, which compared the low and high to the conventional camera height using paired-sample *t*-tests. From these comparisons, *p*-values and, if significant, Cohen's d_z will be reported. Finally, to link our gap sizes to safety, we estimated the longest time gaps that would have resulted in a collision, assuming the approaching vehicle did not brake (TTP_{crit}), for both approach velocities. Note that even if the approaching vehicle prevented a collision by braking hard, this could still result in a critical situation. Details on the estimation are provided in Appendix A. Note that the critical gaps are approximations and not definite thresholds. Figures show 95% within-subjects confidence intervals (CI), which were calculated following the approach of Cousineau (2005) and the corrections proposed by Morey (2008) and Baguley (2012). For these CIs, non-overlapping intervals between means indicate a significant difference. We performed the analyses in R 4.0.2 and interpreted all results using a significance level of $\alpha = 0.05$.

2.2. Results and discussion

In order to evaluate the goodness-of-fit of our PMFs, the area under the Receiver Operating Characteristic curve (Swets, 1986) was calculated. The area under the curve (AUC) describes to what extent the predicted probabilities of the logistic regression models are concordant with the observed outcome, with a value of 0.5 corresponding to chance performance and a value of 1.0 to perfect performance (Dittrich & Oberfeld, 2009; Hosmer & Lemeshow, 2000). The predictive power of the models was high, with AUC ranging

Fig. 4. Screenshots from an example trial, camera at conventional height.

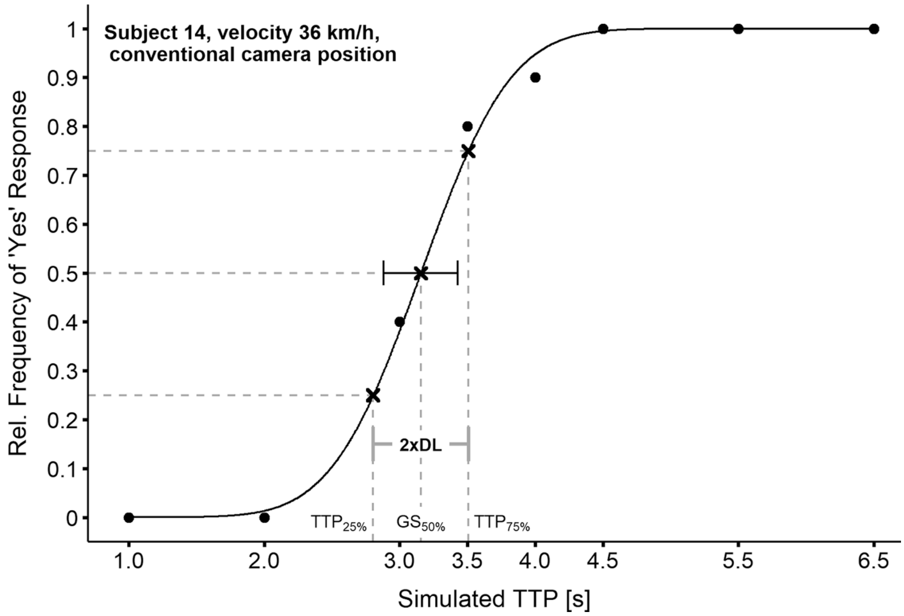

Fig. 5. Example of a fitted psychometric function (black line) with empirical data points (black circles), and the 25%, 50%, and 75% points (black crosses and dashed lines). The error bar shows the bootstrapped 95% confidence interval of the $GS_{50\%}$, based on 1000 random samples. $GS_{50\%}$ = gap selected with a probability of 50%. DL = difference limen. $TTP_{25\%}$ = TTP corresponding to the 25% point of the PMF. $TTP_{75\%}$ = TTP corresponding to the 75% point of the PMF.

from 76.00% to 99.64% (M = 93.04%, SD = 5.05%).

On average, the $GS_{50\%}$ had a size of 3.44 s ($SD_{GS50\%}$ = 0.86 s) and the DL a size of 0.65 s (SD_{DL} = 0.30 s) for the conventional camera height, which represented the baseline in our analyses. More detailed descriptive statistics are provided in the supplementary material. The rmANOVA on $GS_{50\%}$ revealed a significant main effect of camera height, $F_{(2,58)} = 57.79, p < .001, \eta^2_p = .67, \hat{\varepsilon} = 0.76$, and velocity, $F_{(1,29)} = 99.89, p < .001, \eta^2_p = .78$. This main effect is shown in Fig. 6 (black line). On average, the $GS_{50\%}$ increased for the low camera by around 500 ms and decreased for the high camera by around 200 ms, relative to the conventional camera height. Both differences were significant (conventional-low: $p < .001$, $d_z = 1.56$; conventional-high: $p < .001$, $d_z = 1.36$). Regarding the velocity, the mean $GS_{50\%}$ was larger for 36 km/h ($M_{36km/h}$ = 3.98 s, $SD_{36km/h}$ = 0.97 s) and smaller for 54 km/h ($M_{54km/h}$ = 3.09 s, $SD_{54km/h}$ = 0.76 s). Finally, the interaction effect between the two factors was significant but weak ($F_{(2,58)} = 5.57, p = .008, \eta^2_p = .16, \hat{\varepsilon} = 0.90$). This effect is depicted in Fig. 6 (grey lines). Apparently, the difference between the low and conventional height was slightly larger for 36 km/h

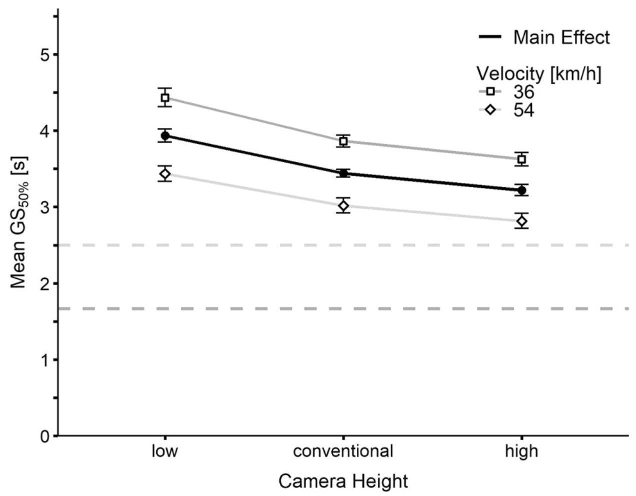

Fig. 6. Mean $GS_{50\%}$ as a function of camera height and velocity. The black line shows the main effect of camera height, averaged across velocity. The grey dashed lines show approximate estimates of the critical time gaps (TTP_{crit}) that would have resulted in a collision, assuming the approaching vehicle did not brake, based on an acceleration of 3.0 m/s^2 (Burg & Moser, 2009). Dark grey dashed line: TTP_{crit} = 1.67 s. Light grey dashed line: TTP_{crit} = 2.50 s. Error bars show 95% within-subjects confidence intervals. N = 30.

than for 54 km/h.

The second rmANOVA analyzed the effects of camera height and velocity on the DL. However, neither the main effects nor the camera height × velocity interaction were significant ($p > .14$).

$GS_{50\%}$ was smaller for the faster approaching vehicle, which has been found earlier in gap selection research (e. g. Alexander et al., 2002; Beggiato et al., 2017; Lobjois & Cavallo, 2007; Petzoldt, 2014). Consequently, subjects might have relied on the simulated final distance, or final object size, which was perfectly correlated with the final distance, in addition to TTP. However, the main effect of camera height on $GS_{50\%}$ contradicts the camera-height effects observed in distance estimation (Bernhard & Hecht, 2020; Leyrer et al., 2015; Ooi et al., 2001). In these studies, the distance was perceived as shorter in the high camera position, but in the present experiment the selected gaps were smaller in the high camera position. How can we explain this unexpected result? Other factors could have affected subjects' gap selections. For example, subjects might have felt more self-confident or safer in the high viewpoint condition and thus selected smaller gaps, despite a shorter perceived final distance. A higher feeling of confidence while driving in a higher viewpoint has been observed earlier (Rudin-Brown, 2004; Thomas & Walton, 2008). Alternatively, subjects might have perceived TTP and / or distance as longer or the velocity of the approaching vehicle as slower in the high camera condition. Experiment II thus investigated these perceptual variables and their association with gap selection in greater detail.

3. Experiment II: Estimation of TTP, speed, and distance

3.1. Methods

3.1.1. Sample description

The sample size in Experiment 2 was comparable to Experiment 1. $N = 31$ subjects ($n = 16$ female) volunteered. The subjects were recruited via an e-mail distribution list or by personal reference and received partial course credit or payment for their participation. The age ranged from 18 to 63 years ($M = 32.71$ years, $SD = 11.68$ years). All subjects had owned a valid driving license for a mean time period of 15.24 years ($SD = 11.65$ years, range 1 to 45 years). 71% stated they would drive no more than 10.000 km per year, whereas eight subjects would drive up to 20.000 km or more. All subjects had normal or corrected-to-normal visual acuity, as confirmed by means of a Landolt ring optotype chart. They were naïve regarding the hypotheses of the experiment and had not participated in Experiment I or a similar experiment before. In accordance with the Declaration of Helsinki, all subjects gave their written informed consent and were debriefed after the experiment.

3.1.2. Experimental task and design

The set-up was identical to Experiment I. However, subjects participated in three different tasks. In the **TTP estimation task** using a prediction motion paradigm (Schiff & Detwiler, 1979), subjects watched the same 1.5 s long videos as in Experiment I and estimated the TTP after the video had disappeared. In the **speed estimation task**, subjects verbally estimated the speed of the approaching vehicle in km/h. Finally, in the **distance estimation** task, the final video frames were presented for 1.5 s and subjects verbally estimated the distance between themselves and the rearward vehicle in meters and centimeters. In the latter two tasks, the subjects' estimates were recorded by the examiner. The three estimates and their respective variance represented the dependent variables in Experiment 2. The independent variables were identical to Experiment I. Therefore, in each task, 8 (simulated TTP) × 3 (camera height) × 2 (velocity) = 48 factor level combinations (i. e., videos) were presented 5 times, resulting in 240 trials per task and a total of 720 trials. Within each task, the videos were presented in five blocks and their order was randomized within each block. Moreover, the experiment was split into two sessions. In order to prevent prior knowledge about the presented speed or distance to influence the estimation of TTP, the prediction motion task was always conducted in the first session. The second session followed the first with a minimum and maximum time interval of 1 day and 1 month, respectively. In this session, the speed and distance estimation tasks were conducted. The order of the tasks was counterbalanced across subjects.

3.1.3. Procedure

In the first session, subjects received detailed information about the experiment, gave their written informed consent and completed the visual acuity test. Then, the TTP-estimation task was outlined to them. They were instructed to press a button on the keyboard when they thought that the front bumper of the approaching vehicle would have touched the rear bumper of their ego vehicle, had the object continued to move with the same velocity after it was no longer visible. Subjects again completed six training trials, using the same videos as in Experiment I. The 240 test trials followed, divided into five blocks. The subjects were able to take breaks after completing a test block. At the end of the first session, subjects filled out a short questionnaire on demographic information. In the second session, the distance and speed estimation tasks were collected in counterbalanced order. In each task, six training trials preceded the 240 test trials. Feedback about the accuracy of the subjects' estimation was provided after the first training trial in the distance estimation task, but not in the following trials or in the speed task. Between the two tasks, a break of at least 15 min was administered. After the final task, subjects received a debriefing. The second session lasted approximately 1.5 h and the whole experiment around 2.5 h.

3.1.4. Data preparation and analysis strategy

In a first part of the analysis, the mean estimates and their variation were analyzed. Beforehand, two subjects in the speed estimation and one subject in the distance estimation task were excluded from the analyses due to data entry errors. The raw estimates of each task were scanned for outliers using the Tukey heuristic (Jones, 2019), separately for each subject and factor level combination.

281 TTP estimates (3.78%), 468 speed estimates (6.72%), and 399 distance estimates (5.36%) were removed. The mean estimates and their standard deviation across the 5 trials collected in each combination of subject and factor level combination were calculated. The coefficient of variation (CV), that is the standard deviation proportional to the mean estimate ($CV = SD/M * 100$), was then calculated as a metric of estimation variation. The distribution of the mean estimates and of their CVs approximated normality. Therefore, rmANOVAs and subsequent tests were conducted separately for each experimental task, following the strategy outlined in Experiment I. Gender effects and changes of responses over time were again checked before the analysis, but no systematic effects were observed.

In the second part of the analysis, we used regression analyses to quantify the relative importance of distance cues in the estimation of TTP, and the relative importance of the perceived TTP, perceived speed, and perceived distance in the safety decisions of Experiment I. A similar approach had been used earlier when investigating the relative importance of visual and auditory cues (DeLucia et al., 2016; Keshavarz et al., 2017). In a first step, multiple linear regression models were fitted with the raw TTP estimates as criterion, separately for each subject. An intercept term and five predictors were included: a) the final simulated distance to the approaching vehicle (D_{final}); b) the simulated TTP, which was perfectly correlated with the corresponding τ-variable (see introduction; Kaiser & Mowafy, 1993); c) the inverse of the declination angle (Ooi et al., 2001) on the final video frame (α_{final}^{-1}); d) the logarithm of the inverse final rate of change in the declination angle ($\ln(\dot{\alpha}_{final}^{-1})$). Note that D_{final} models the numerous monocular depth cues available in the simulated environment. α_{final}^{-1} and $\ln(\dot{\alpha}_{final}^{-1})$ provided viewpoint-dependent heuristic cues for judging TTP and were thus included. The inverse and logarithmized values were used to establish a positive linear relationship with the estimated TTP. The τ-variable calculated from these two quantities was perfectly correlated with TTP and was thus not included as predictor.

All four predictors were *z*-standardized and entered the analysis simultaneously. Data points were defined as outliers if their externally studentized residual exceeded a value of $t_{1-\alpha/2,\ N-k-2}$ with $\alpha = 0.05$, $N = 240$ (the number of trials in the experiment) and $k = 4$ (the number of predictors in the model). Across subjects, 0.42% − 7.08% ($M = 5.20\%$, $SD = 1.51\%$) of the data points were excluded. All predictors were linearly related to the criterion and no systematic deviations from normality or homoscedasticity of the residuals was observed. As shown in Table 2, the predictors were correlated. In this case, the relative importance of a single predictor cannot be derived from the size of its squared standardized regression coefficient (Tonidandel & LeBreton, 2011). Therefore, in a second step, we applied a dominance analysis approach (Azen & Budescu, 2003; Budescu, 1993) and calculated normalized General Dominance Weights (GDWs). These normalized GDWs sum up to one and represent the proportion of R^2 explained by a specific predictor in a given model. They therefore represent a measure of relative importance for a specific predictor. Differences in the normalized GDWs were tested by means of paired-samples two-tailed *t*-tests. More detailed information about the dominance analysis approach is provided in Appendix B.

In a final step, a similar approach was used to test whether the gap selection in Experiment I was affected more strongly by the perceived TTP, as indicated earlier (e. g. Dommes & Cavallo, 2011; Petzoldt, 2014), or by the perceived distance (Lobjois & Cavallo, 2007; Oxley et al., 2005). To do so, we calculated the median estimated TTP ($\widehat{TTP}_{med}$), median estimated distance ($\widehat{D}_{med}$), and the inverse of the median estimated speed ($\widehat{V}_{med}^{-1}$) across the subjects of Experiment II and included these as predictors in individual multiple logistic regression models with the binary safety decisions from Experiment I (gap not safe vs. gap safe) as criterion. The inverse values of the estimated speed were used to establish a positive relationship with the gap decisions. The three predictors were *z*-standardized and entered the analysis simultaneously. As measure of predictive power, we again report the area under the Receiver Operating Characteristic curve (AUC, see Section 2.2; Hosmer & Lemeshow, 2000; Swets, 1986). The two predictors $\widehat{TTP}_{med}$ and $\widehat{D}_{med}$ were correlated ($r = 0.92$). Therefore, dominance analysis was again applied in order to quantify the relative importance of $\widehat{TTP}_{med}$, $\widehat{D}_{med}$, and $\widehat{V}_{med}^{-1}$. In this analysis, the R^2 proposed by McFadden (1974) was used as measure for the variance accounted-for, as recommended earlier (Azen & Traxel, 2009). All results were interpreted using a significance level of $\alpha = 0.05$.

3.2. Results and discussion

3.2.1. Analysis of mean estimates and estimation variance

We first present descriptive statistics on the estimates at the conventional camera height, which represented the baseline for the analysis. To do this, we calculated the signed estimation error for each condition by subtracting the simulated values from the estimated values. We also calculated the relative signed error for each condition by dividing the error by the simulated values. Subjects estimated the TTP of the approaching vehicle as slightly shorter than the simulated values on average ($M_{error} = -0.23$ s, $SD_{error} = 1.89$ s). Similar patterns were observed for the speed ($M_{error} = -12.77$ km/h, $SD_{error} = 12.53$ km/h) and distance ($M_{error} = -0.86$ m, $SD_{error} = 14.58$ m) estimates on average. With respect to the relative signed error, TTP was underestimated by 2.3%, speed by 27.28%, and

Table 2
Pairwise Pearson correlation coefficients between the four z-standardized predictors.

	1	2	3
1. TTP			
2. D_{final}	0.90		
3. α_{final}^{-1}	0.54	0.60	
4. $\ln(\dot{\alpha}_{final}^{-1})$	0.84	0.82	0.83

Note. Correlations calculated across all 240 trials.

distance by 4.72%. More descriptive statistics can be found in the supplementary material.

The first two rmANOVAs included the within-subjects factors simulated TTP, velocity, and camera height as well as either the TTP estimates or CV as dependent variable. The results are shown in Table 3 and the main effect of camera height is displayed in Fig. 7, panel a. TTP estimates were shorter at the low camera position, compared to the conventional position ($p < .001$, $d_z = 0.93$), and longer at the high camera position ($p < .001$, $d_z = 0.79$). The effect of camera height increased with the simulated TTP (Fig. 7, panel b). The effect of camera height was also larger for the higher target velocity (Fig. 7, panel a). The velocity of the target vehicle had a significant effect on the TTP estimates. The estimates were longer for the faster vehicle ($M_{54km/h} = 3.77$, $SD_{54km/h} = 2.45$) than for the slower vehicle ($M_{36km/h} = 3.27$, $SD_{36km/h} = 2.09$). In addition, as indicated by Fig. 7, panel b, mean TTP estimates increased significantly with the simulated TTP. The differences between the mean TTP estimates decreased at longer simulated TTPs. With respect to the CV, camera height had a significant effect (see Fig. 7, panel c). In the low camera, the proportional variation of the TTP estimates increased, compared to the conventional height ($p = .003$, $d_z = 0.53$). However, the high and conventional camera heights did not differ significantly ($p = .499$). Finally, the CV was largest for the shortest simulated TPP and decreased with simulated TTP (Fig. 7, panel d).

The results of the rmANOVAs on the speed estimates and their CV are shown in Table 4 and Fig. 8. Most importantly, camera height had no substantial effect on the speed estimates. However, according to Fig. 8, panel c, the CV was smaller in the high camera than in the conventional camera ($p = .002$, $d_z = 0.64$), whereas the low and conventional camera did not differ significantly ($p = .071$). Furthermore, speed estimates were higher for the faster target vehicle ($M_{54km/h} = 36.30$ km/h, $SD_{54km/h} = 12.73$ km/h) than for the slower vehicle ($M_{36km/h} = 28.15$ km/h, $SD_{36km/h} = 9.84$ km/h; see also Fig. 8, panel b). The camera height × velocity interaction also reached significance (Fig. 8, panel a). The difference between the camera heights were slightly larger for the slower velocity, but the effect was small. Finally, the simulated TTP affected the speed estimates (Fig. 8, panel b) and the CV (Fig. 8, panel d) significantly.

The last two rmANOVAs focused on the distance estimates and the respective CV. In these two models, the camera height and the simulated final distance, calculated from the simulated TTP and velocity, represented the within-subjects factors. The results are shown in Table 5 and Fig. 9. The effect of camera height on the distance estimates was significant. As Fig. 9, panel a, illustrates, distance estimates were shorter for the low camera ($p = .001$, $d_z = 0.67$) and longer for the high camera ($p < .001$, $d_z = 0.64$), compared to the conventional camera height. The camera height × simulated distance interaction also reached significance (Fig. 9, panel b). Similar to the TTP estimates, the effect of camera height slightly increased for larger distances. In the largest distance, the distance was estimated longer in the low camera than in the other two conditions. Moreover, the mean distance estimates increased proportional to the simulated distance. With respect to the CV, a significant main effect of camera height was observed. As shown in Fig. 9, panel c, the CV was larger for the low camera ($p = .001$, $d_z = 0.67$) and smaller for the high camera ($p = .049$, $d_z = 0.38$), compared to the conventional camera. Finally, the CV was larger for the shorter simulated distances and decreased with larger simulated distances (Fig. 9, panel d).

In summary, the TTP and distance estimates of our subjects were fairly accurate. Even more importantly, the main effect of camera height on these two estimates was consistent with the changes in $GS_{50\%}$ observed in Experiment I. The $GS_{50\%}$ was smaller in the high and larger in the low camera position, which is compatible with a longer perceived TTP and distance in the high position compared to the low position. Camera height also affected the trial-by-trial variation (precision) of the estimates. The variation in the TTP and distance estimates was larger in the low and, at least with respect to the distance estimates, smaller for the high camera position. These effects of camera height on the TTP and distance estimates were not mirrored in the speed estimates, which were similar across the camera positions. Taken together, the data from Experiment II are compatible with the assumption that the subjects in Experiment I might have relied on their perception of TTP or distance in rearward gap selection. As the faster velocity of the approaching vehicle resulted in longer TTP estimates and shorter selected gaps, D_{final} or other heuristic cues were probably taken into account. In the second part of the analysis, we quantified the relative importance of D_{final} and other optical cues in the estimation of TTP, and the relative importance of the perceived TTP, perceived speed, and perceived distance in the gap selection.

Table 3
Results of the rmANOVA for the TTP estimates and the respective CV.

Factor	F	df_{num}	df_{den}	p	η^2_p	$\hat{\varepsilon}$
TTP Estimates						
Camera Height	29.19	2	60	< 0.001	0.49	0.66
TTP_{sim}	106.54	7	210	< 0.001	0.78	0.16
Velocity	66.90	1	30	< 0.001	0.69	1.00
Camera Height × TTP_{sim}	5.23	14	420	< 0.001	0.15	0.46
Camera Height × Velocity	4.53	2	60	0.020	0.13	0.86
TTP_{sim} × Velocity	9.14	7	210	< 0.001	0.23	0.43
Coefficient of Variation						
Camera Height	4.78	2	60	0.013	0.14	0.97
TTP_{sim}	17.64	7	210	< 0.001	0.37	0.64
TTP_{sim} × Velocity	2.62	7	210	0.029	0.08	0.68

Note. Only significant effects are displayed. All other effects: $p > .11$. $N = 31$. TTP_{sim} = simulated TTP. df_{num} = numerator degrees of freedom. df_{den} = denominator degrees of freedom. η^2_p = effect size partial eta squared. $\hat{\varepsilon}$ = Greenhouse-Geisser correction of the degrees of freedom.

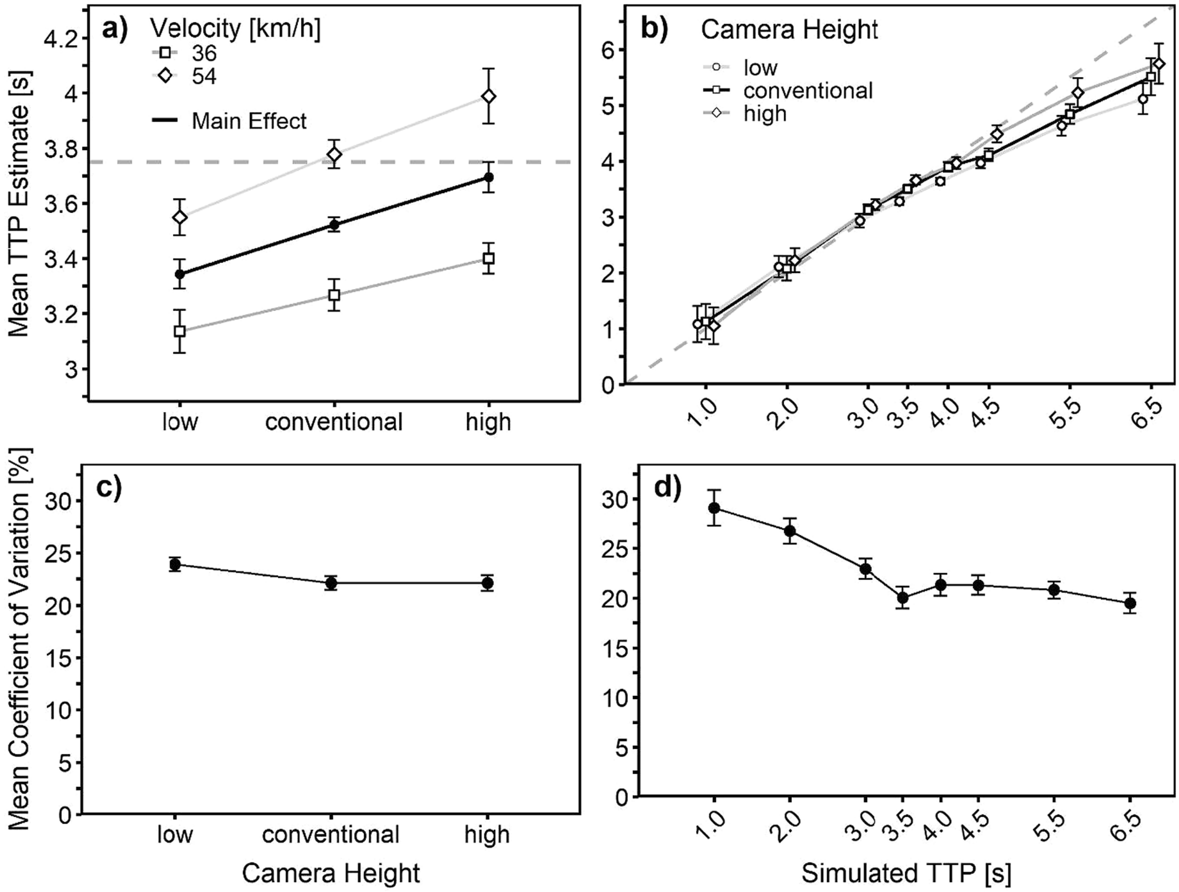

Fig. 7. Panels a and b: Mean TTP estimates as a function of camera height and velocity (a) and as a function of camera position and simulated TTP (b). The dashed grey lines indicate perfect performance. The black line in panel a represents the camera height main effect. Panels c and d: Mean coefficient of variation as a function of camera height (c) and simulated TTP (d). Error bars show 95% within-subjects confidence intervals. *y*-axis is truncated in panel a) and means are horizontally displaced in panel b) to improve readability. $N = 31$.

Table 4
Results of the rmANOVA on the speed estimates and the respective CV.

Factor	*F*	df_{num}	df_{den}	*p*	η^2_p	$\hat{\varepsilon}$
Speed Estimates						
TTP_{sim}	36.95	7	196	< 0.001	0.57	0.20
Velocity	140.56	1	28	< 0.001	0.83	1.00
Camera Height × Velocity	5.11	2	56	0.012	0.06	0.90
Coefficient of Variation						
Camera Height	4.86	2	56	0.012	0.15	0.96
TTP_{sim}	17.64	7	196	< 0.001	0.14	0.75

Note. Only significant effects are displayed. All other effects: $p > .08$. $N = 28$. TTP_{sim} = simulated TTP. df_{num} = numerator degrees of freedom. df_{den} = denominator degrees of freedom. η^2_p = effect size partial eta squared. $\hat{\varepsilon}$ = Greenhouse-Geisser correction of the degrees of freedom.

3.2.2. Weighting of the simulated final distance in the estimation of TTP

The subject-wise multiple linear regression models on the TTP estimates included the predictors inverse final declination angle (α^{-1}_{final}), inverse final change rate of the declination angle ($\ln(\dot{\alpha}^{-1}_{final})$), simulated *TTP*, and final simulated distance (D_{final}). Overall, the model fit was good, with R^2 ranging between 45.27% and 93.95% ($M = 73.33\%$, $SD = 11.16\%$). Fig. 10 depicts the mean standardized regression coefficients (left panel). Apparently, all predictors were significantly associated with the estimated TTP – the CIs do not overlap with 0. Strikingly, α^{-1}_{final} was negatively related to the TTP estimates. This was not the case when including α^{-1}_{final} as sole predictor in the individual models. We take this to be the result of the relatively high correlations among the predictors (see Table 2). Such sign reversals have been observed earlier (Keshavarz et al., 2017). The normalized GDWs were higher for *TTP* and D_{final} than for the other

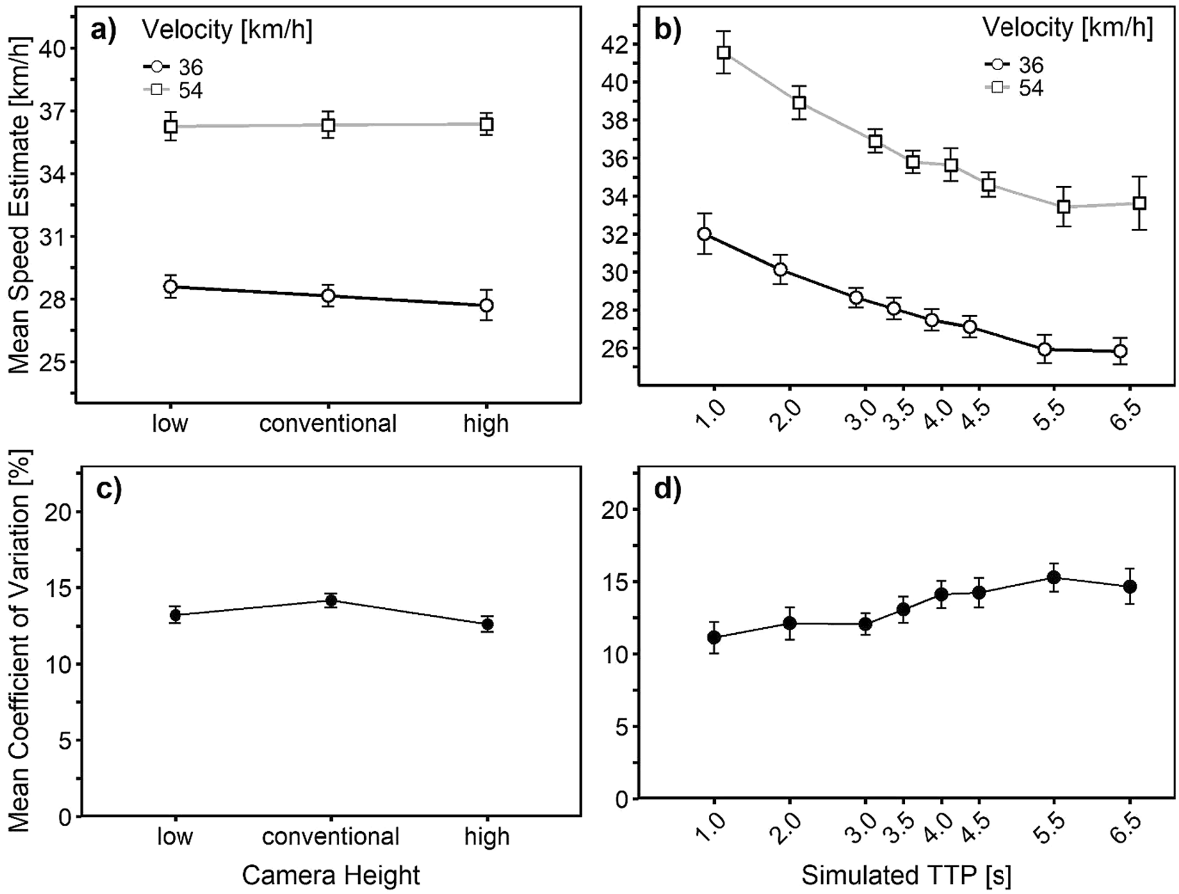

Fig. 8. Panels a and b: Mean speed estimates as a function of camera height and velocity (a) and as a function of simulated TTP and velocity (b). *y*-axes are truncated to improve readability. Panels c and d: Mean coefficient of variation as a function of camera height (c) and simulated TTP (d). Error bars show 95% within-subjects confidence intervals. $N = 28$.

Table 5
Results of the rmANOVA on the distance estimates and the respective CV.

Factor	F	df_{num}	df_{den}	p	η^2_p	$\hat{\varepsilon}$
Distance Estimates						
Camera Height	23.62	2	58	< 0.001	0.45	0.67
Simulated Distance	329.62	13	377	< 0.001	0.92	0.11
Camera Height × Simulated Distance	11.02	23	754	< 0.001	0.28	0.35
Coefficient of Variation						
Camera Height	15.27	2	58	< 0.001	0.35	0.98
Simulated Distance	13.12	13	377	< 0.001	0.31	0.41

Note. Only significant effects are displayed. All other effects: $p > .16$. $N = 30$. df_{num} = numerator degrees of freedom. df_{den} = denominator degrees of freedom. η^2_p = effect size partial eta squared. $\hat{\varepsilon}$ = Greenhouse-Geisser correction of the degrees of freedom.

two predictors (Fig. 10, right panel). As indicated by the CIs, the differences were significant ($p < .001$). The two predictors explained around 70% of the proportion of variance explained by the individual models. In contrast, the GDWs for D_{final} and TTP did not differ significantly ($p = .734$).

3.2.3. Weighting of perceived TTP and perceived distance in gap selection

Subject-wise multiple logistic regressions were calculated, including an intercept term, using $\hat{V}^{-1}_{med}$, $\widehat{TTP}_{med}$, and $\hat{D}_{med}$ measured in Experiment II as the predictors, and modelling the probability of a positive gap selection decision ("The gap can be safely entered") in Experiment I. The predictive power of the models was high, with AUC ranging from 83.75% to 98.81% ($M = 93.54\%$, $SD = 4.24\%$). The mean standardized regression coefficients are depicted in Fig. 11, left panel. As expected, all three predictors were significantly

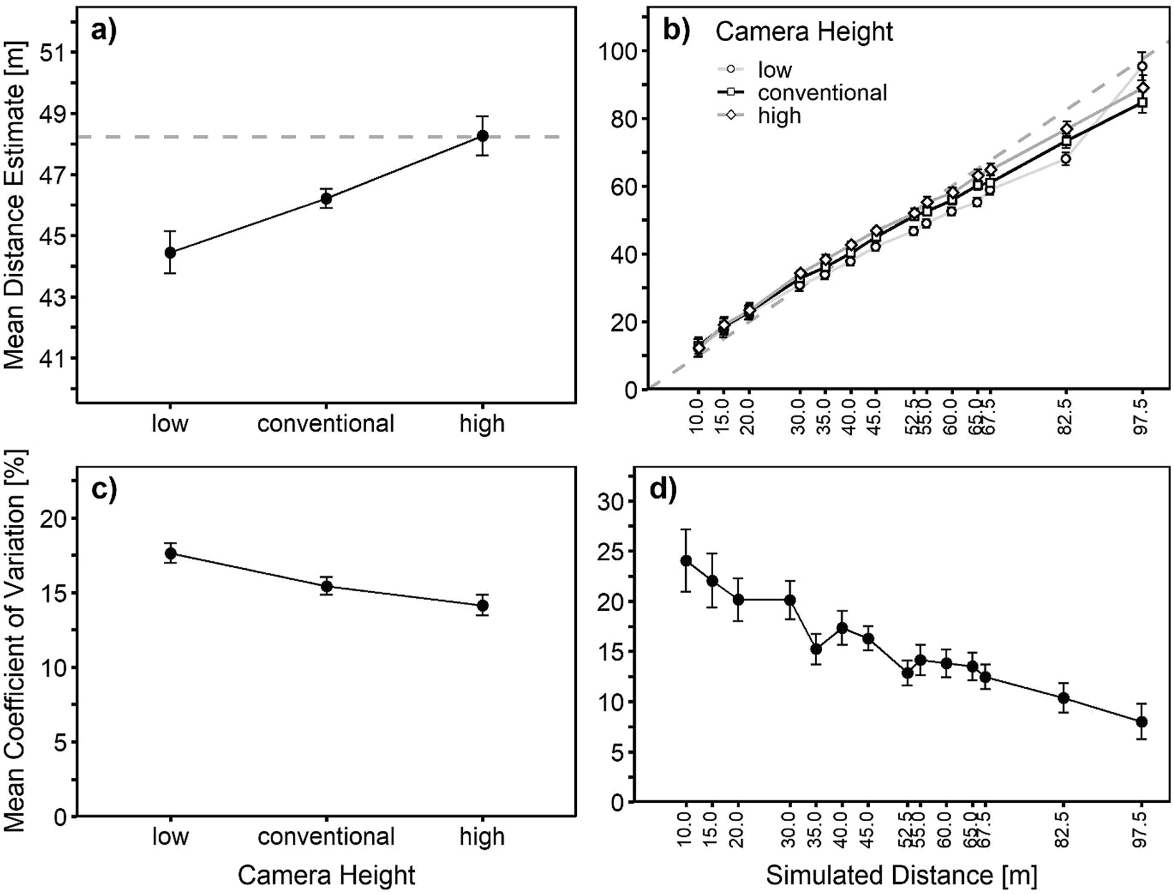

Fig. 9. Panels a and b: Mean distance estimates as a function of camera height (a) and as a function of camera height and simulated distance (b). The dashed grey lines indicate perfect performance. Panels c and d: Mean coefficient of variation as a function of camera height (c) and simulated distance (d). Error bars show 95% within-subjects confidence intervals. In panel a, *y*-axis is truncated to improve readability. $N = 30$.

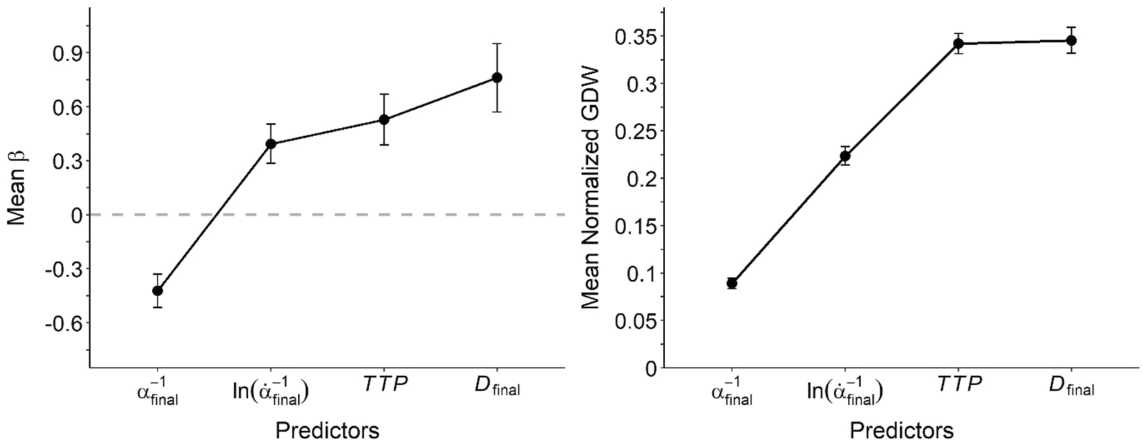

Fig. 10. Left panel: Mean standardized coefficients of the subject-wise regression models on the TTP estimates. Right panel: Mean normalized general dominance weights (GDWs) for the TTP estimates. The error bars show 95% confidence intervals (CIs). α_{final}^{-1} = inverse final declination angle. $\ln(\dot{\alpha}_{final}^{-1})$: logarithm of the inverse final rate of change of the declination angle. *TTP* = simulated TTP. D_{final} = final simulated distance to the target vehicle. $N = 31$.

associated with the gap selection, as their CIs do not overlap with 0. Moreover, as shown in the right panel of Fig. 11, the mean normalized GDW was significantly larger for $\widehat{D}_{med}$ compared to $\widehat{TTP}_{med}$ ($p < .001$, $d_z = 0.77$). The normalized GDWs of the two predictors were significantly larger than the GDW of $\widehat{V}^{-1}_{med}$ ($p < .001$, $d_{z\_TTP\text{-}V} = 5.45$, $d_{z\_D\text{-}V} = 5.69$).

4. General discussion

The purpose of the presented experiments was to identify the sources of information that might guide drivers' rearward gap selection. The experiments focused on a specific driving scenario, where the driver wants to enter flowing traffic from a stationary state (i. e. when parking on the roadside). Experiment I investigated whether a high rear-view camera increases and a low rear-view camera decreases the size of the gaps considered safe, which would be in line with an effect on distance estimation observed earlier (Bernhard & Hecht, 2020). Unexpectedly, raising the camera shortened the size of the gap selected with a probability of 50% ($GS_{50\%}$) and lowering the camera enlarged it. To understand the effect, Experiment II examined the perception of TTP, speed, and distance and their connection with gap selection in more detail. The camera-height effect on $GS_{50\%}$ was mirrored in the TTP estimates and distance estimates, but not in the speed estimates. A high camera produced longer and a low camera shorter distance and TTP estimates. This is consistent with the camera-height effect on gap selection, as, for example, shorter perceived distance and shorter perceived TTP are expected to result in larger selected gaps. Moreover, regression analyses indicated that when estimating TTP, subjects relied as much on distance information as they relied on the simulated TTP, which is compatible with previous results (DeLucia et al., 2016; Keshavarz et al., 2017). In fact, according to the weights obtained in the second dominance analysis, perceived distance turned out to be a slightly more important predictor for gap selection than the perceived TTP.

A strong reliance on distance cues in TTP estimation has been observed earlier (DeLucia et al., 2016; Keshavarz et al., 2017). Moreover, influences of monocular depth and size cues have been observed many times with respect to TTP estimation (DeLucia, 1991; DeLucia, Kaiser et al., 2003; Hecht et al., 2015; Landwehr et al., 2013; Landwehr et al., 2014; Oberfeld et al., 2011; Petzoldt, 2016) and gap selection (Alexander et al., 2002; Baurès et al., 2014; Petzoldt, 2014; Yannis et al., 2013). Here, we investigated gap selection as well as the perception of TTP, speed, and distance at the same time and in a realistic scenario. Our data thus provide more detailed information about the relationship between these variables. Considering the results of our regression analyses as well as the highly consistent effects of camera height observed in the mean estimates (Experiment II) and $GS_{50\%}$ (Experiment I), TTP estimation and gap selection in CMS seem to be based to a considerable extent on distance (or size) information. Interestingly, the results from the regression analyses also indicate that the perceived distance is the most important predictor for gap selection, slightly exceeding the role of perceived TTP. This is somewhat at odds with the assumption that gap selection is based solely on perceived TTP (e. g. Dommes & Cavallo, 2011; Petzoldt, 2014). At least in rearward vision, drivers seem to employ distance-based strategies when selecting gaps.

Furthermore, our regression analyses indicated that perceived speed is less important than perceived distance for gap selection. This assumption finds support in the effect of the simulated velocity – greater velocities resulted in longer TTP estimates and smaller selected gaps, as was observed earlier (e. g. Alexander et al., 2002; Keshavarz et al., 2017; Law et al., 1993; Oberfeld et al., 2011; Petzoldt, 2014). Importantly, this does not mean that speed information is not incorporated in TTP estimation and gap selection. Note that speed, final distance, and TTP are closely related. Considering the relatively high accuracy of TTP estimates, subjects must have included speed information in their estimation. And since the perceived TTP was an important predictor for gap selection, the speed information in turn indirectly affected the gap selections. However, perceived distance explained a relatively large amount of the variance in the mean selected gaps, above the distance information already included in the TTP estimates. Thus, our results do indicate that perceived distance is weighted higher than perceived speed in gap selection.

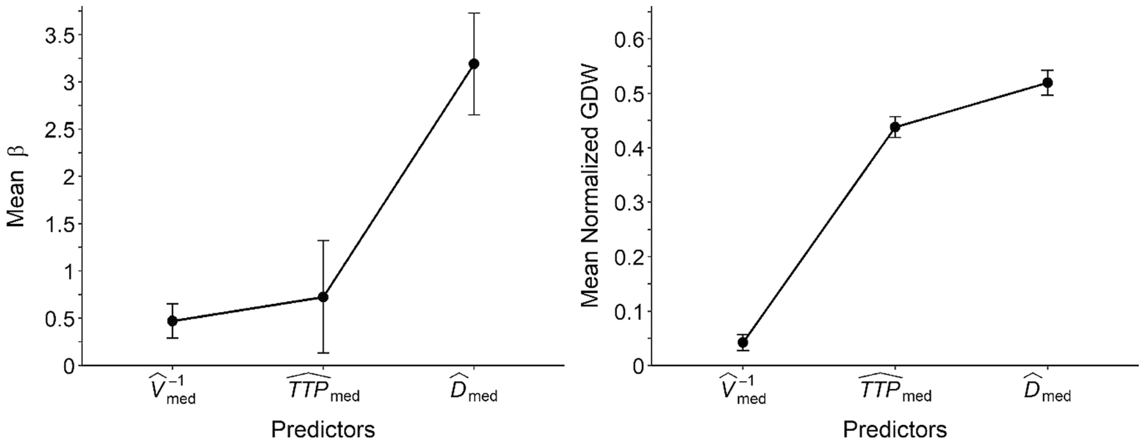

Fig. 11. Right panel: Mean standardized coefficients of the subject-wise logistic regression models on gap selection. Left panel: Mean normalized general dominance weights (GDWs) for gap selection. The error bars show 95% confidence intervals (CIs). $\widehat{V}^{-1}_{med}$ = inverse median estimated speed. $\widehat{TTP}_{med}$ = median estimated final TTP. $\widehat{D}_{med}$ = median estimated final distance. $N = 30$.

Surprisingly, the observed effect of camera height on distance estimation was opposite to the effects observed earlier (Bernhard & Hecht, 2020; Daum & Hecht, 2009; Leyrer et al., 2015; Ooi et al., 2001). How can we explain this? In Experiment II, distance was estimated to be longer in the high camera condition but was still underestimated in absolute terms. Therefore, the relatively larger distance estimates for the high camera position could be the result of a more accurate overall judgement of distance. In addition, several cues could have produced the impression of shortened distance in the low camera condition. For instance, the simulated distance was perfectly correlated with the optical size of the rearward vehicle (ϕ). Subjects might have inferred distance from size, as has been proposed earlier (Gogel, 1976; Gogel & Da Silva, 1987), and the approaching vehicle might have appeared larger as it extended above the observer's eye-height when the camera was low (Wraga & Proffitt, 2000). Furthermore, the rearward vehicle occluded more background objects in the low camera condition. An effect of occlusion on TTP estimation has been observed earlier (DeLucia, Kaiser et al., 2003). In any case, our subjects probably did not rely on the declination angle, as this would have produced opposite camera-height effects (see Fig. 2; Gardner & Mon-Williams, 2001; Ooi et al., 2001; Sedgwick, 1986). This was also confirmed by our regression analysis, which showed only a small dominance weight for α_{final}^{-1}.

Stationary observers seem to actively incorporate surrounding objects and use them as landmarks in distance and TTP estimation. If no landmarks are available, observers might prioritize internal information, such as the declination angle. However, if objects are present, observers use external information, for example information derived from occlusion or relative distance between objects. Accordingly, distance was perceived shorter in low camera positions when estimates had to be made in an outdoor experiment with many landmarks (Bernhard & Hecht, 2020, Experiment I), but longer in a virtual environment without any landmarks (Bernhard & Hecht, 2020, Experiment II), compared to higher camera positions. This would be in line with an ecological approach to perception (Gibson, 1979). Finally, in CMS angular information is minified in the small monitor image and might therefore be difficult to extract for the human observer. In our experiment, the declination angle in the final video frame ranged between 0.26 and 1.38 degrees for the low camera (Fig. 2). It seems rather difficult to infer distance based on these small differences.

4.1. Limitations

The experiments at hand investigated the perception of a stationary driver who is parked at the roadside. Consequently, we cannot estimate whether and to what extent the presented results will generalize to dynamic driving scenarios which entail driver self-motion, as for example during a lane change on a highway. In this case, other motion cues induced by ego motion, such as motion parallax, have been observed to affect TTP estimation (e.g. DeLucia, Kaiser et al., 2003). Moreover, the camera-height effect might not generalize to driver self-motion, as stationary surrounding objects are not available during driving. Therefore, drivers might have to rely on other information, such as optical sizes or the declination angle. In this case, we expect camera-height effects similar to our earlier experiment (Bernhard & Hecht, 2020). However, we take that the short trial duration of 1.5 s used in our experiments is representative for a short glance into the mirror that would also be applicable during driving. Therefore, we hypothesize that the relationship among distance, TTP, and gap selection still holds in driver self-motion. Consequently, changes in distance estimation should also translate to TTP estimation and gap selection.

At this point, it is important to emphasize that the present research does not speak to the question whether TTP is judged on the basis of explicit calculations (cognitive arithmetic), or whether it is judged more or less intuitively and merely enters consciousness late in the process – although we believe that it is judged intuitively. The aim of the present research was to identify the sources of information upon which the lane-change decisions and TTP estimations of our subjects were based. Once this is known, we can design experiments to address the important issue of cognition vs. intuition. Our data clearly show that distance information had a particularly strong effect on these estimations and/or decisions. In a next step, one could examine whether this reliance on distance information hold up for more complex and cognitively demanding tasks, such as dynamic driving.

In addition, our experiments were conducted in a safe environment and used virtual stimuli. Our stimuli depicted a more or less realistic scene, but the scenario might be perceived differently in a real-world environment. However, note that some of our results replicate observations from field studies and experiments using real-world scenes (e. g. Beggiato et al., 2017; Cavallo & Laurent, 1988; Schleinitz et al., 2020; Yannis et al., 2013). This indicates that our results should hold up in a more applied context. For future research, it would of course be important to validate the current findings and hypotheses using high-fidelity driving simulators and real-world environments.

Furthermore, the velocity of the approaching vehicle varied only in two steps. A larger variation in approach speed, together with a variation in vehicle size, would make it possible to further disentangle the effects of distance cues, size cues, and TTP on gap selection and TTP estimation. In this regard, please also note that the size of the camera height effect strongly depends on the range of heights used. Using a smaller range that is more feasible for sedans is expected to decrease the camera height effect. This has also been observed earlier (Bernhard et al., 2021).

Moreover, our subjects were rather young and were mostly university students. This is not representative for the population of vehicle owners in Germany, who range between 17 to over 80 years, with owners between 45 and 65 years representing the largest group (Kraftfahrt-Bundesamt, 2020). Other experiments have found age differences in gap selection (Lobjois & Cavallo, 2009; Petzoldt, 2014; Stafford et al., 2019) and TTP estimation (DeLucia, Bleckley et al., 2003; Schiff et al., 1992). We assume that the relative differences observed here do still apply for older drivers. However, this should be validated by future research using a more representative sample (see Saeed et al., 2020, as example).

Finally, and most importantly, Experiment I and II were performed by different subjects. Thus, the median values of perceived distance, perceived TTP, and perceived speed across subjects of Experiment II were analyzed for their association with the individual gap selection decisions in Experiment I. Using a within-subjects design, where gap selection decisions as well as the estimation of distance, speed, and TTP are studied in the same subjects, would make it possible to gain an even more detailed insight into the relations between these variables at the individual level. Nevertheless, our results were very consistent and mostly in accordance with previous research.

4.2. Implications for theory and practice

Our experiments aid the understanding of which information drivers use to estimate the TTP of an approaching vehicle and determine the safety of a gap before merging into the traffic, when using information provided in a rear-view mirror or CMS. More specifically, drivers seem to use a distance-based strategy – they rely to a considerable extent on distance cues, especially when selecting gaps. The regression analysis indicated that our subjects also relied on the perceived TTP. Whereas this was expected, the privilege of distance in gap selection is problematic from a safety perspective. It introduces potential risks in gap selection, as drivers might choose smaller temporal gaps in front of faster vehicles. Future research should determine whether this also generalizes to more realistic simulations of driver self-motion and to more complex driving situations. Especially in complex situations, the importance of heuristic cues may even increase. Furthermore, speed, distance, and object size should be varied independently from each other in future research to disentangle the weighting of these variables in TTP estimation and gap selection.

In Experiment I, the size of the selected temporal gaps decreased with greater approach velocity, possibly due to the observed distance-based strategy. We observed a difference in gap size of 1 s on average for the two approach velocities of 36 km/h and 54 km/h. The selection of smaller gaps in front of faster vehicles could increase the risk of lane change crashes. Practitioners should therefore investigate efficient countermeasures. For instance, augmented mirrors could display the actual TTP of an approaching vehicle or issue warnings against dangerous lane changes. Displaying the actual TTP in a rear-view monitor increased estimation accuracy (Smith et al., 2016). However, it also increased driver distraction away from the road. Therefore, providing lane change recommendations, for example with an extended lane change assistant, might be the better solution.

Finally, the $GS_{50\%}$ was smaller in the high camera position than in the lower camera positions, showing a tendency towards risky decisions. However, we did not observe differences in the DL between the three camera heights. Thus, subjects were equally precise in judging the gaps at all three camera positions. When looking at the decisions from Experiment I more closely, we found that subjects would have chosen a time gap below the critical TTP (i.e., the longest time gap that would have resulted in a collision, assuming the approaching vehicle did not brake, see Fig. 6) with a probability of 23.84% in the high and with a probability of 14.15% in the low camera position. This confirms the conclusion that the high camera position has a potential to decrease the safety of gap selection decisions. Consequently, based on the present results, a low camera position seems to be preferable. However, this might not generalize to actual driving. For instance, drivers underestimate distance to a greater extent when driving and should therefore maintain larger safety margins (Moeller et al., 2016). Consequently, future studies should investigate whether higher camera positions also lead to riskier decisions in actual driving, before providing design recommendations for CMS.

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CRediT authorship contribution statement

C. Bernhard: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **D. Oberfeld:** Validation, Formal analysis, Writing – review & editing. **H. Hecht:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Appendix A:. Estimation of critical gap sizes for Experiment I

To estimate TTP_{crit}, we calculated the time it would take a driver to accelerate to the velocity of the approaching vehicle, using the formula $t_v = v / a$, with v being the velocity of the approaching vehicle in m/s, and a the acceleration rate of the ego-vehicle. For a, we assumed an acceleration rate of 3.0 m/s^2, which represents a lower acceleration limit of a mid-range car (Burg & Moser, 2009). Next, we estimated the distance (d) the ego-vehicle would have travelled in the time t_v by the formula $d = 0.5 \times a \times t_v^2$, and the time the approaching vehicle would need to cover this distance, $t_d = d / v$. Finally, TTP_{crit} was calculated as $TTP_{crit} = t_v - t_d$.

Appendix B:. Description of the dominance analysis approach

In the dominance analysis approach, the relative importance of each predictor of a model is determined by creating regression models containing every possible subset of the remaining predictors, including one model containing only the intercept term. Then, the changes in the variance accounted-for (ΔR^2) that resulted from adding the predictor of interested to all possible regression models are calculated. The *General Dominance Weight* (GDW), that is the mean of these squared semipartial correlations (ΔR^2), was calculated for each predictor and subject. The sum of the GDWs across predictors is the proportion of variance accounted-for (R^2) by a specific model. The normalized GDWs were calculated by dividing the GDWs of each model by their respective R^2.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2022.02.015.

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