The Ups and Downs of Camera-Monitor Systems: The Effect of Camera Position on Rearward Distance Perception

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Objective: This study investigates the effects of different positions of side-mounted rear-view cameras on distance estimation of drivers.

Background: Camera-monitor systems bring advantages as compared to conventional rear-view mirrors, such as improved aerodynamics and enlarged field-of-view. Applied research has mainly focused on the comparison between cameras and mirrors or on positioning of in-vehicle monitors. However, the positioning of the exterior camera awaits investigation given that the perspective of the observer at does affect depth perception at large.

Method: In two experiments, a total of 50 students estimated metric distances to static vehicles presented in realistic or 3D-rendered pictures. The pictures depicted the rearward scene of a car following the driver as viewed through a camera at varying vertical and horizontal positions. The following vehicle's size and environmental information varied among conditions and experiments.

Results: Lower camera positions led to distance overestimation and higher positions to underestimation. The effect increased as the distance to the following vehicle decreased. Moreover, larger vehicles led to stronger distance underestimation, especially in low camera positions. Interestingly, the main effect of camera position disappeared when the ego-vehicles' back was visible.

Conclusion: Different rearward viewpoints affect distance estimation of drivers, especially in close distances. However, a visible reference of one's own vehicle seems to mostly compensate this effect.

Application: In general, the rear-view camera should be mounted rather higher and to the front of the vehicle. Also, the vehicle's back should always be visible. Low camera positions are not recommended.

Keywords: camera-monitor systems, perspective, camera placement, distance estimation, design recommendations

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INTRODUCTION

Vehicle manufacturers are increasingly considering the implementation of camera-monitor systems (CMS). In such a system, the (driver-side) rear-view mirror is replaced by a combination of an exterior camera and an in-vehicle monitor. CMS have several advantages in comparison to traditional rear-view mirrors, such as improved aerodynamics, reduced emissions, enlarged field-of-view (Terzis, 2016), and last but not least the freedom of choice regarding camera and monitor placement. Unlike mirrors, CMS decouple the rearward viewing axis from the driver's viewing axis and thereby not only open up new opportunities but also raise a number of challenges. One challenge is to understand how the incongruence between camera axis and observer axis affects rearward depth perception of the driver. Basic research has already shown that shifts in perspective do influence distance perception (e.g., Daum & Hecht, 2009; Leyrer et al., 2015; Ooi et al., 2001). Thus, different camera positions can improve or deteriorate the rearward perception of drivers.

Distance Perception and the Effect of Perspective

When observers estimate the distance between themselves and a target, myriads of depth cues are usually available, such as ground texture, height in the visual field, aerial perspective, linear perspective, and motion parallax, to name just a few (Cutting & Vishton, 1995; Loomis & Knapp, 2003; Sedgwick, 1986; Sinai et al., 1998). Some of these cues are affected by vertical camera position, as is in particular the position of objects relative to the horizon. Sedgwick (1986) stated that in open fields, the visible horizon formed by the far boundary of the ground surface offers a more accurate indication for distance than do other cues, such as texture or height in the visual field. A cue that uses this horizon information is the angle of declination, sometimes referred to as angular declination below the horizon or vertical gaze angle (Gardner & Mon-Williams, 2001; Ooi et al., 2001; Sedgwick, 1986). According to Sedgwick, the angle of declination is the angle between the viewing axis from the observer's eye to the base of a target resting on the ground plane and the line drawn from the observer's eye to the horizon (Proffitt, 2006; Sedgwick, 1986). People can use this declination angle to compute the distance to the target (*D*), as the quotient between the known eye-height (*H*) and the tangent of the angle of declination ($D = H / tan\left(\alpha\right)$; Ooi et al., 2001). According to this approach, if the eye-height of an observer is artificially changed without updating *H*, this should change the angle of declination and consequently the perceived distance.

Although eye-height has mostly been investigated regarding its effect on size perception (e.g., Bertamini et al., 1998; Wraga & Proffitt, 2000), several researchers have shown that the angle of declination is a cue for absolute distance (Gardner & Mon-Williams, 2001; Li et al., 2011; Ooi et al., 2001). In a typical experimental setup, participants have to estimate distances while their view is altered by means of prism glasses. These glasses artificially change the vertical position of targets in the scene and consequently the angle of declination, leading to distance underestimation for up-shifted and overestimation for down-shifted viewpoints (Gardner & Mon-Williams, 2001; Ooi et al., 2001). More recently, studies have replicated these findings in real and virtual environments, by altering either the visual horizon (Messing & Durgin, 2005; Rand et al., 2011) or the virtual eye-height of participants (Corujeira & Oakley, 2013; Leyrer et al., 2011, 2015).

Daum and Hecht (2009) provided another possible explanation for the effect of eye-height on distance perception, based on an outdoor experiment involving distances up to 500 m. They hold that denser texture is indicative of larger distance. Among others, they varied the eye-height of participants in three steps: prone, upright, and elevated by standing on a platform 110 cm above the ground (Daum & Hecht, 2009). They found a significant distance overestimation in prone posture, as compared to an upright viewing position. Regardless of its explanation, the effect seems to be very consistent throughout the literature. As the viewpoint is shifted downwards, people increasingly overestimate the distance to a target, whereas raising the viewpoint results in an underestimation of distance. However, it remains to be seen whether this effect does generalize to the indirect and restricted view provided by CMS or a conventional rear-view mirror.

Distance Perception in Rear-View Mirrors and CMS

Whereas research regarding CMS is rather new, several studies have already investigated how people perceive their rearward environment through rear-view mirrors. Alongside distance judgment tasks, these studies often used more dynamic settings and time-to-contact (TTC) estimates, where participants judge when a target arrives at a predefined location. Most studies found that people tend to underestimate distance to objects viewed in rear-view mirrors (Carstengerdes, 2007; Fisher & Galer, 1984; Hecht & Brauer, 2007; Higashiyama & Shimono, 2004), whereby the amount of underestimation is dependent on the object's image size, but not on the mirror's distortion (in a convex mirror). Small images (as in strongly curved convex mirrors) lead to overestimation of both distance and TTC estimates compared to large images (as in planar mirrors) (Hahnel & Hecht, 2012; Hecht & Brauer, 2007). Similar paradigms have been used to compare mirrors and CMS. Schmidt et al. (2016) tested a prototype CMS against a conventional rear-view mirror in a field study and found a significant underestimation of distance as well as increased safety margins with CMS, most likely as a consequence of the underestimated distance. Flannagan and colleagues found similar results in two studies for both distance (Flannagan et al., 2002) and speed estimation (Flannagan & Mefford, 2005). We take this to indicate that in addition to effects of object size on distance and time estimates, the CMS suffers from distance compression, as is often found in head-mounted or computer displays (Grechkin et al., 2010; Willemsen & Gooch, 2002).

Existing literature on CMS has focused on identifying the optimal location for in-vehicle monitors, with a preference close to the traditional mirror position (Beck et al., 2017; Large et al., 2016; Murata & Kohno, 2018). However, research so far has largely neglected the positioning of the outside camera on the vehicle's body and thus the rearward perspective of the driver. The perspective change induced by a convenient but unusual camera position is expected to have an impact on perception in indirect viewing conditions. For example, Barfield et al. (1995) as well as Hendrix and Barfield (1997) showed that when people have to make judgments about the vertical and horizontal spacing between two objects in stereoscopic displays, the elevation of the observer's viewpoint has a strong effect on these judgments: higher viewpoints improve the estimation of horizontal object spacing. In another study, van Erp and Padmos (2003) investigated how the viewpoint of drivers affects lateral and longitudinal control of a vehicle when only indirect vision of the outside world is available. They found only small effects in terms of speed underestimation for higher camera positions. Similar results are observable when drivers have to judge their own speed while driving in larger vehicles: ego-speed is underestimated when seated in a van or truck, as compared to a sedan (Panerai et al., 2001; Rudin-Brown, 2004). However, these results might also be attributable to an increased feeling of safety when driving with a large vehicle and give no direct information about the perception of distance.

To the best of our knowledge, the only study investigating perspective changes and distance estimation in a context comparable to CMS is the work of Böffel and Müsseler (2015). In their first experiment, participants had to estimate their distance to a vehicle seen in a conventional side-mounted rear-view mirror. They varied the configuration of the mirror in a way that the target vehicle appeared in the center, top, or bottom of the mirror. Furthermore, the back of the participant's vehicle was either visible or not visible. Interestingly, Böffel and Müsseler (2015) found that perspective had an effect on distance estimation, with larger estimates for the vehicle shown at the top and smaller estimates for the vehicle shown at the bottom of the mirror. These results are in line with results from basic research on the vertical change of viewpoints (Daum & Hecht, 2009; Leyrer et al., 2015; Ooi et al., 2001). Thus, evidence suggests that assumptions derived from basic distance perception research might also generalize to conditions comparable to CMS.

Research Purpose

Our aims were to (a) evaluate whether different camera positions improve or deteriorate distance perception, (b) identify other factors that interact with the mounting position, such as the size of the following vehicle or the visibility of the ego-vehicle's back, and (c) derive practical design recommendations for CMS. Consistent with previous research, we used magnitude estimation where participants gave metric estimates of their perceived distance (Flannagan et al., 2002; Hecht & Brauer, 2007; Higashiyama & Shimono, 2004). In the first experiment, we explored how a displacement of perspective in two different dimensions (vertical and horizontal) affects distance estimates in a realistic environment. Then, we used 3D-rendered pictures to further investigate the effect of vertical displacement and other factors, namely visibility of the vehicle's back and size of the following vehicle (Experiment II).

EXPERIMENT I

To gain first insights into how different camera positions might influence distance estimation, we conducted an outdoor experiment in order to provide participants with a realistic setup not suffering from rendering or image resolution issues and thus providing a full range of static depth cues. Participants received pictures of two following vehicles placed behind an ego-vehicle and had to estimate two types of distances: egocentric distance, defined as the distance between the ego-vehicle and the first following vehicle, and exocentric distance, defined as the sagittal distance between the two following vehicles. Both types of estimation frequently occur in traffic and were thus chosen as important dependent variables. We hypothesized that participants would underestimate egocentric distance in the monitor. For exocentric distance, we expected compression even stronger than observed for egocentric distance (see, e.g., Li & Durgin, 2012; Li et al., 2011; Loomis et al., 1992).

Since displacement of a side-mounted rear-view camera on a passenger vehicle can occur vertically (high, low) and/or horizontally (fore-aft), we varied the camera position along these two dimensions. Vertical displacement of the camera should lead to relative distance underestimation for higher positions and overestimation for lower positions, compared to the conventional side-view mirror position (Daum & Hecht, 2009; Leyrer et al., 2015; Ooi et al., 2001). We hypothesized that this effect should occur in egocentric and exocentric distance estimation. Concerning the camera's horizontal position, the prediction is less clear. It might seem obvious that observers take the camera to be tied to the eye point. However, since the task was to judge distances with respect to the back of their vehicle, we hypothesized that participants would use this information to compensate the displacement in depth, thus leading to a nonsignificant effect of horizontal displacement.

Methods

Participants. Participants were students enrolled in a bachelor or master program in psychology at our university. They were recruited via an e-mail distribution list. In total, 20 participants volunteered for our study. The sample size was chosen based on an a priori power analysis for the within-subjects main effect camera position using G*Power 3.1.9.2 (Faul et al., 2007). For input, we used an effect size of $\eta^2_p = .361$, a significance level of $\alpha = .05$, and a correction value of $\varepsilon = .56$. The values for η^2_p and ε were based on other studies on perspective shift (Böffel & Müsseler, 2015; Daum & Hecht, 2009). The analysis resulted in a power of $1-\beta = .99$ for a sample size of 20 participants. All participants gave their written informed consent. Their age ranged from 19 to 34 years (*M* = 26.35 years, *SD* = 4.41 years). Four participants were male and 16 female. All participants had owned a valid driving license for a mean time period of 8.79 years (*SD* = 4.84 years) and seven participants owned a vehicle. The majority stated that they would use a vehicle at a maximum of three times a month and drive no more than 10,000 km per year. Only seven participants stated that they would drive more often or greater distances. Finally, all participants had normal or corrected-to-normal vision, as tested directly before the experiment with the aid of a printed Landolt ring optotype chart. They were naïve regarding the purpose of the study. This research complied with the tenets of the Declaration of Helsinki.

Experimental design. The experiment used a within-subjects factorial design with three factors. In total, three egocentric distances (10, 30, 45 m), three exocentric distances (5, 14, 23 m), and five camera positions (conventional, low, high, front, back) were fully crossed, which resulted in 45 experimental conditions. For the camera position, the conventional position of the side-mounted rear-view mirror represented the baseline for our comparisons and was at a height of 95 cm from the ground for the vehicle used in this experiment. The two vertical positions (low and high) were created by placing the camera 35 cm higher or lower than the conventional position. Regarding the two horizontal positions, the camera was placed 45 cm farther to the front or back of the vehicle, respectively. All 45 conditions were presented twice, resulting in a total of 90 experimental trials. For both

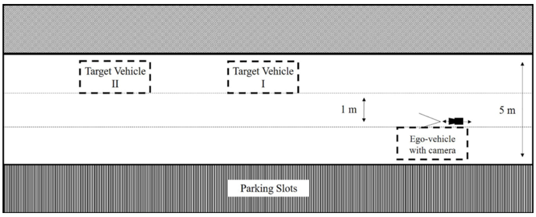

Figure 1. Schematic representation of the test environment from a bird's eye view.

measurements, we blocked the 5 camera positions and counterbalanced their order using a Latin square, resulting in 10 possible sequences, which were evenly distributed across the participants. The order of the remaining six conditions was randomized in each block. The metric distance estimates provided by participants represented the dependent variable.

Test environment, stimuli, and apparatus. The study took place in a separated area of a large parking lot, on a 200-m long and 5-m wide lane bordered by parking spots. Street lamps and trees were regularly arrayed along the lane and the surface of the parking spots consisted of a symmetric pattern, thus offering multiple depth cues. Three different vehicles were placed on the lane. The ego-vehicle, a black VW Polo IV, was placed close to the parking spots at the right part of the lane. The other two vehicles, a black BMW 1 and a blue VW Golf V, were target objects. They were placed to the left and behind the ego-vehicle. One of the two vehicles was placed closer behind the ego-vehicle, thus presenting the target for the egocentric judgment task. The second vehicle was placed behind the first vehicle, thus forming the space for the exocentric judgment task. The order of the two vehicles changed between the two measurement times and was counterbalanced across participants. Figure 1 schematically illustrates the test environment.

To create the photo-based stimulus representations, we used a Nikon D700 camera with a CMOS sensor and a focal length of 50 mm (horizontal field-of-view approx. 39.6°), which is comparable to the field-of-view offered by state-of-the-art side-mounted rear-view mirrors (Bach et al., 2006). The camera was mounted on a tripod and placed in the five camera positions on the driver side of the ego-vehicle. For each position, 18 pictures were taken for the three egocentric and exocentric distances as well as for the two possible orders of the target vehicles. The preparation of the stimuli was not part of the experiment itself. In the experiment, all pictures were presented via a Raspberry Pi 2 on a 7″ TFT LCD monitor with a resolution of 1,280 × 690 pixels. The monitor was placed inside the vehicle on the top of the dashboard at the driver side of the ego-vehicle, to the left of the driver. The original target vehicles were visible in the pictures, but not physically present during the experiment itself. Participants were seated in the driver's seat and the seat was adjusted to result in an eye-height of 120 cm from the ground and a distance of 60 cm away from the dashboard. Figure 2 shows three example stimuli. For a picture of the experimental setup inside the ego-vehicle, please refer to the supplemental material.

Experimental procedure. The experiment consisted of two parts. In the first part, after collecting informed consent, participants performed a short test of visual acuity to assure that they had normal or corrected-to-normal vision. Then, they were instructed to inspect the ego-vehicle and the environment in order to become accustomed with the visual scene. Participants then sat in the driver's seat, which was adjusted as described above. The experimenter gave procedural instructions, highlighted the two different estimation tasks for each stimulus, and defined egocentric (from the rear bumper of the ego-vehicle to the front bumper of the first vehicle) and exocentric (from the rear bumper of the first vehicle to the front bumper of the

Figure 2. Example stimuli of Experiment I. Pictures show the test environment from a low (left), a conventional (middle), and a high camera position (right). In all three pictures, the first target vehicle has a distance of 30 m from the observer's vehicle and the second target vehicle a distance of 14 m from the first target vehicle.

second vehicle) distances. Then, participants performed a short training consisting of two stimuli showing the same two vehicles as in the test blocks, with the first vehicle at 25 or 35 m and the second vehicle at a distance of 10 or 18 m to the first vehicle. Participants estimated egocentric and exocentric distances and, for calibration purposes, received feedback about the accuracy of their judgments only during this practice.

The second part of the study comprised the experiment itself. Participants estimated egocentric and exocentric distances for each of the 45 experimental conditions, viewed twice with different target orders for a total of 10 blocks. In each trial, the stimulus was presented for 5 s, followed by a blank gray screen. Participants voiced their metric estimates first for the egocentric distance and then for the exocentric distance, which were written down by the experimenter. After the last trial, participants filled out a short questionnaire on age, gender, and driving experience, and received a debriefing. The whole experiment lasted approximately 1 hr.

Data analysis. At the beginning of the analysis, raw distance estimates were transformed into a relative error ratio, which is the ratio of estimated distance to physical distance (Kornbrot et al., 2013). Relative estimation ratios are commonly used for distance estimates (e.g., Daum & Hecht, 2009; Geuss et al., 2012; Kline & Witmer, 1996). After transformation, we inspected the error ratios of each participant using boxplots. The ratios varied between and within participants, but no data point differed strongly enough from the remaining points to afford removal of a participant as an outlier. However, quantile–quantile plots of the residuals clearly deviated from normal distribution, for which case Kornbrot et al. (2013) recommend the use of a logarithmic (ln) accuracy measure. We transformed our error estimates accordingly and found that the residuals approximated normality. Thus, we used the logarithmic accuracy measure, henceforth called lnError, as the dependent variable for our analysis.

Egocentric and exocentric lnErrors were analyzed with a univariate 5 (camera position) × 3 (egocentric distance) × 3 (exocentric distance) repeated measures ANOVA (rmANOVA). We applied Huynh–Feldt correction (Huynh & Feldt, 1976) on the degrees of freedom where sphericity was violated and report the correction value (see Oberfeld & Franke, 2013, for a discussion of different correction methods and their influence on type I error). Planned contrasts *t*-tests were also calculated to compare the four experimental camera positions with the conventional camera position; however, only the *p*-values and, if significant, effect sizes are reported. All results were interpreted on a significance level of $\alpha = .05$. For all graphs, error bars were calculated as 95% within-subjects confidence intervals, using the approach of Cousineau (2005) and the correction proposed by Morey (2008). In Cousineau–Morey intervals, between-subjects variability is removed by participant-mean centering and then standard errors are calculated from the normalized data. Furthermore, we adjusted the Cousineau–Morey intervals by the factor $\sqrt{2}/2$, as recommended by Baguley (2012). After this adjustment, nonoverlapping intervals indicate a significant difference. For further information about the computation and adjustment of within-subjects errors, please refer to Baguley (2012). Analyses were performed with the statistical software R, using packages *afex* for Anova, *Rmisc* for within-subjects standard errors, and *ggplot2* for data illustration.

Results and Discussion

Overall, participants slightly overestimated egocentric distance by around 2.71 m (9.57%). Participants overestimated exocentric distances by 4.30 m (30.73%). For an overview of raw estimates, please refer to the supplemental material.

An rmANOVA on egocentric lnError revealed significant main effects of camera position, $F(4, 76) = 4.34$, $p = .009$, $\eta^2_p = .19$, $\tilde{\varepsilon} = .723$, physical egocentric distance, $F(2, 38) = 13.26$, $p = .001$, $\eta^2_p = .41$, $\tilde{\varepsilon} = .563$, and physical exocentric distance, $F(2, 38) = 9.42$, $p < .001$, $\eta^2_p = .33$, $\tilde{\varepsilon} = .998$. Furthermore, two interactions reached significance, that between camera position and physical egocentric distance, $F(8, 152) = 3.29$, $p = .004$, $\eta^2_p = .15$, $\tilde{\varepsilon} = .816$, as

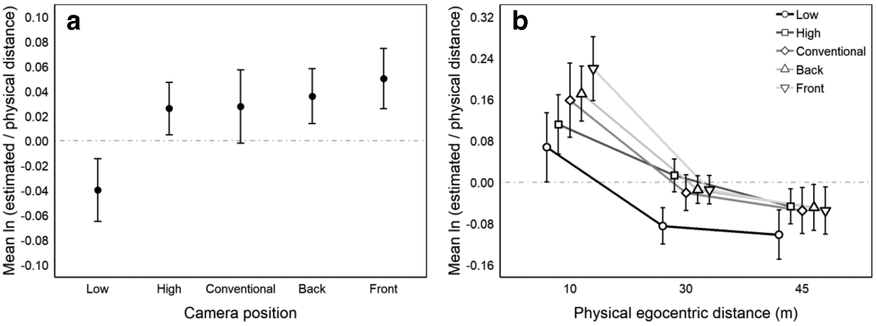

Figure 3. Interactions of camera position and egocentric distance (a), as well as camera position and exocentric distance (b) on egocentric lnError. Dotted horizontal lines represent perfect accuracy. Error bars represent adjusted 95% within-subjects confidence intervals, as recommended by Cousineau (2005), Morey (2008), and Baguley (2012). *y*-axes are adjusted, and for each *x*-axis category, means are horizontally displaced to facilitate readability.

well as between camera position and exocentric distance, $F(8, 152) = 2.36$, $p = .020$, $\eta^2_p = .11$, $\tilde{\varepsilon} = 1.000$. No other effects reached significance. Figure 3(a) illustrates the main effect of camera position. The low camera position resulted in underestimation compared to the conventional position ($p = .002$, $d_z = .43$). However, the conventional position was not significantly different from the other positions ($p > .05$). According to Figure 3(b), participants overestimated closer distances and underestimated farther distances. The lower position differed more strongly from the other positions for the medium egocentric distance. Finally, distance underestimation also increased with greater exocentric distance of the second vehicle.

The second rmANOVA analyzed the effects of camera position, physical egocentric distance, and physical exocentric distance on exocentric lnError. Again, the main effect of camera position was significant, $F(4, 76) = 9.89$, $p < .001$, $\eta^2_p = .34$, $\tilde{\varepsilon} = .779$. The effect of exocentric distance was also significant, $F(2, 38) = 63.45$, $p < .001$, $\eta^2_p = .77$, $\tilde{\varepsilon} = .550$, as well as the main effect of egocentric distance, $F(2, 38) = 16.33$, $p < .001$, $\eta^2_p = .46$, $\tilde{\varepsilon} = .661$. Regarding interaction effects, only the physical egocentric distance × physical exocentric distance interaction reached significance, $F(4, 76) = 7.41$, $p = .002$, $\eta^2_p = .28$, $\tilde{\varepsilon} = .532$. Figure 4(a) illustrates the main effect of camera position. In the low position, distance was underestimated in comparison to the conventional position ($p < .001$, $d_z = .42$). The other positions were not significantly different from the conventional position ($p > .05$). Figure 4(b) shows the interaction of egocentric and exocentric distance. Exocentric distance was strongly overestimated when the two vehicles were placed close to each other. This effect was strongest for the egocentric distance of 30 m.

Participants indeed underestimated larger egocentric distances despite the tendency to overestimate overall egocentric distance, especially for close distances. The same pattern of results was observed for exocentric distance, where participants overestimated the gap size even more strongly. Furthermore, the horizontally displaced viewpoints were not significantly different from the conventional position. Even if a nonsignificant test statistic is not a valid proof of the null hypothesis, considering the small effect sizes d_z and the confidence intervals, it is safe to say that estimates did not differ much between the three positions. Other than hypothesized, a lower camera position failed to produce stronger distance overestimation. On the contrary, a lower viewpoint led to distance underestimation compared to the conventional viewpoint in both distance tasks. Interestingly, the distance of the second following vehicle also affected egocentric distance estimates,

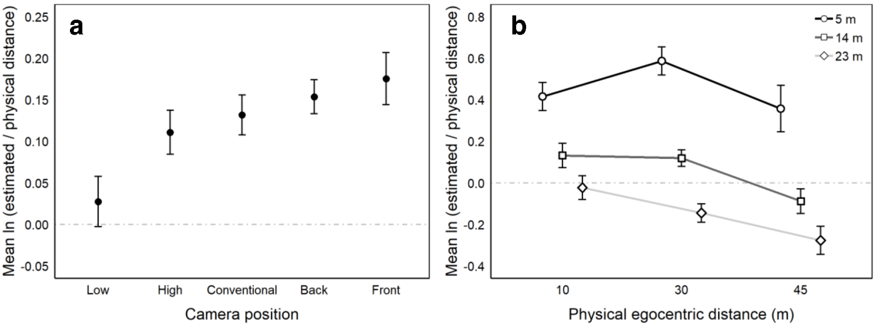

Figure 4. Main effect of camera position (a), as well as the interaction between egocentric and exocentric distance (b) on exocentric lnError. Dotted horizontal lines represent perfect accuracy. Error bars represent adjusted 95% within-subjects confidence intervals. *y*-axes are adjusted and for each *x*-axis category, means are horizontally displaced to facilitate readability.

which is surprising since the second vehicle should be irrelevant for determining the distance to a closer vehicle. However, research has demonstrated that judgments can be affected by seemingly task-irrelevant stimuli. For instance, in Baurès et al. (2014), participants made street-crossing decisions in the presence of a small and a large gap on two adjacent lanes. The large gap should have been irrelevant for the decision, but still influenced the decision to cross the street.

Could the lack of support for our hypothesis as well as the surprisingly high estimates of exocentric distance be explained by the experimental setting? A disadvantage of outdoor studies is the limited control of confounding factors. More specifically, it was not possible to control for lighting conditions, which have provided shadow cues of the two test cars in some, but not all, conditions. Several participants reported that they actively used these shadows and thus the performance of these participants might have varied across conditions, depending on the availability of shadow cues. Furthermore, the visibility of the second vehicle varied between conditions. Especially for large egocentric distances, it was sometimes difficult to see the second vehicle at all. This might explain the rather high variance of estimates for exocentric distance and the high amount of overestimation. Another constraint comprises the availability of static objects as landmarks for distance estimation. Since pictures were all static, several objects, such as street lamps, were available to the observer. Considering that during driving the scene constantly changes, this was a rather unrealistic setting. Some participants reported that they used these landmarks, but it remains unclear how this might have influenced the effect of perspective. Finally, a major difference between studies on perspective outlined in the introduction and in our experiment was that people had to estimate distances not from their own position, but from the back of their vehicle. This judgment is different from conventional egocentric distance estimation and might therefore not have produced a comparable effect of perspective. Consequently, we performed a lab experiment to (a) investigate the effect of vertical perspective shift under more controlled experimental conditions and (b) test other possible explanations for the results obtained here.

EXPERIMENT II

In Experiment II, we replicated and modified Experiment I in a controlled laboratory setting. Participants only performed an egocentric distance task. In some conditions, the back of the observer's vehicle was no longer visible, which made these conditions more comparable to other studies on perspective changes (e.g., Leyrer et al., 2015; Messing & Durgin, 2005; Rand et al., 2011). Furthermore, we increased the number of factor levels for physical egocentric distance. Two more vertical camera positions, one extremely low and the other extremely high, were added to the design. This should reveal whether our initial hypothesis that low camera positions produce distance overestimation is indeed untenable, or whether some contextual peculiarities of the outdoor experiment had suppressed their effect. Finally, we varied two more factors in order to investigate two potential causes for distance misestimation: the size of the target vehicle and the visibility of the ego-vehicle.

According to Gogel (1976; Gogel & Da Silva, 1987), if a familiar object is perceived as larger or smaller in size than expected or normal, observers can use this information to make inferences about the object's distance. Furthermore, the size of an object is increasingly overestimated as it extends above the observer's eye-height, starting at around 2.5 times the eye-height of an observer (Wraga & Proffitt, 2000). The following might be true for the effect of low camera positions: as the viewpoint of the camera is lowered, the rearward vehicle exceeds the observer's would-be eye-height, and therefore its size is increasingly overestimated. However, since a vehicle is of familiar size, the larger perceived size might be attributed to a smaller distance, thus leading to distance underestimation. To test this assumption, we presented two target vehicles of different sizes. If our assumption is true, the distance to the larger vehicle should be underestimated in comparison to the smaller vehicle, and this effect should be more pronounced for lower viewpoints. This would be comparable to findings from gap acceptance and TTC literature, where safety margins for crossing decisions increase and TTC judgments decrease for larger approaching vehicles (Caird & Hancock, 1994; DeLucia, 1991, 2013; Yannis et al., 2013).

Finally, we also varied the visibility of the ego-vehicle. Participants had to judge distance from bumper to bumper in Experiment I, but from their observer position in classic experiments of perspective. These two tasks might prompt different strategies. More specifically, the angle of declination is an important depth cue when judging distances from one's own position in space, but might be less important when judging distances with respect to a different reference point. Böffel and Müsseler (2015) have shown that a visible rear portion of the car increases distance underestimation when using a conventional side-view mirror. Experiment II tested this potential confound by varying the visibility of the ego-vehicle's back, henceforth called vehicle reference. We hypothesized that its visibility would lead to stronger distance underestimation. We also expected an interaction effect of camera position and vehicle reference, with estimates differing more strongly in conditions without a visible reference.

Methods

Participants. Again, participants were psychology students at our university and were recruited via an e-mail distribution list. This time, we did not perform another a priori power analysis. However, since the experiment focused on the interaction of camera position with vehicle reference and target size, respectively, we increased our sample size to $N = 30$ to ensure sufficient statistical power. For the second experiment, 30 students (13 males) volunteered and gave their written informed consent. Their age varied between 20 and 48 years (MW = 26.28 years, $SD = 5.70$ years). All participants had owned a valid driving license for a time period between 3 and 31 years (MW = 9.23 years, $SD = 5.52$ years) and 16 participants also owned a car. The majority stated that they would drive between 5,000 and 20,000 km per year and at least twice per week. Finally, participants had normal or corrected-to-normal vision, as confirmed by the Freiburg Visual Acuity Test (FrACT, Bach & Bach, 1996), and had not participated in the first experiment.

Experimental design. We used a fully crossed within-subjects factorial design. We combined six different physical egocentric distances (13, 26, 39, 52, 65, 78 m) with five vertical camera positions (extremely low, low, conventional, high, extremely high), two vehicle references (not visible vs. visible), and two target sizes (Mitsubishi Colt, L: 3.94 m, W: 1.70 m, H: 1.55 m; Scania Truck, L: 9.16 m, W: 2.49 m, H: 3.20 m). In the conventional position, the rear-view camera was placed at a height of

130 cm from the ground, which corresponds to the height of conventional rear-view mirrors on SUVs or small trucks. The other cameras were placed either 60 cm (normal low and high positions) or 125 cm (extreme positions) below and above the conventional position. All 120 conditions were presented three times during the experiment, resulting in 360 trials. The order of the factor vehicle reference was counterbalanced and for each level the five camera positions were again blocked and counterbalanced using a Latin square. For each block of vehicle reference and camera position, each combination of physical egocentric distance and target size was presented in randomized order.

Test environment, stimuli, and apparatus. Participants sat at a table in a small lab chamber. The chair was adjusted such that the eyes of the observer were 120 cm above the ground. The stimuli were presented on the same monitor as in Experiment I, which was placed to the left and 20 cm below the eye-level of the participant at a distance of 50 cm. A second monitor was placed directly in front of the participant. A picture of the setup can be found in the supplemental material.

Stimuli were rendered scenes of a virtual environment modeled with the 3D design software Autodesk 3ds Max 2018. In this environment, two different target vehicles were placed in the passing lane of a two-lane road. The road was covered with a normal asphalt texture with side markings but without a median stripe. The rest of the environment consisted of a grassy landscape around the road and blue sky. Both road and landscape stretched out to the visible horizon and no other depth cues were provided. The daylight was held constant by adding a virtual afternoon sun. To render the stimuli, we placed a virtual camera on the road in the right lane, close to the hypothetical median stripe, thus representing the position of a side-mounted mirror. The camera was a virtual replica of the camera used in the first experiment. We used a Mercedes G500 (*L*: 4.66 m, *W*: 1.76 m, *H*: 1.95 m) as ego-vehicle, since its size and shape provided a visible reference even in the extremely high camera position. In each of the five camera positions outlined above, 24 pictures (six egocentric distances, two vehicle references, two target sizes) were rendered, resulting in 120 pictures. They had a resolution of 1,280 × 690 pixels, comparable to those used in Experiment I. Figure 5 depicts three example pictures with visible reference in the conventional and the two extreme camera positions.

Experimental procedure. Participants were instructed to judge the distance either from their viewpoint or from the back of their ego-vehicle to the front bumper of the target vehicle. Also, participants received six instead of two pictures in the training block. The training stimuli were rendered in the same environment as the test stimuli, but with a visible median stripe. The target, an Audi A6 (*L*: 4.939 m, *W*: 1.886 m, *H*: 1.467 m), was placed 9, 44, or 80 m away from the viewpoint, thus covering the entire range of distances from the test blocks. In three training pictures, the reference of the ego-vehicle was visible, whereas in the others it was not. All six training stimuli were shown in the conventional camera position. Participants estimated their egocentric distance to the target and again received feedback about the accuracy of their judgments.

Figure 5. Example pictures of Experiment II. Pictures show the test environment from an extremely low (left), a conventional (middle), and an extremely high camera position (right). In all three pictures, the target vehicle has a distance of 13 m from the observer’s vehicle.

Then, participants estimated their egocentric distance for each combination of camera position, distance, vehicle reference, and target size thrice. Each trial started with blank screens. Then, a test stimulus appeared on the left monitor for 3 s, and participants estimated the distance to the target vehicle. After the stimulus had disappeared, participants verbally informed the experimenter, who entered the estimate as an integer value in meters via a keypad. After pressing enter, the next stimulus appeared on the left screen. At the end of the experiment, participants filled out a short questionnaire and received a debriefing. The whole procedure lasted about 1 hr.

Data analysis. The data analysis strategy was identical to the first experiment. This time, however, 21 extreme values (0.19%) were removed. Nine of these had values of zero, and were considered data entry errors. The remaining outliers differed strongly from all other data points, with error ratios of 5 or higher (i.e., metric estimates that were at least 5 times larger than the real physical distance), and thus were removed. Afterwards, data were aggregated for the three measurement times. All 30 participants entered the analysis. We again calculated lnError as a dependent variable, since it was the only accuracy measure with normally distributed residuals. We performed a 5 (camera position) × 6 (physical egocentric distance) × 2 (vehicle reference) × 2 (target size) rmANOVA on lnError, followed by one-sided paired-sample *t*-tests comparing the experimental camera positions with the conventional position. Analysis was performed using the same R packages as in Experiment I.

Results and Discussion

Consistent with Experiment I, participants overestimated the distance to the target vehicle by about 1.15 m (2.54%). A table with raw estimates is available in the supplementary material. The rmANOVA revealed significant main effects of camera position, $F(4, 116) = 11.93$, $p < .001$, $\eta^2_p = .29$, $\tilde{\varepsilon} = .63$, egocentric distance, $F(5, 145) = 25.62$, $p < .001$, $\eta^2_p = .47$, $\tilde{\varepsilon} = .30$, vehicle reference, $F(1, 29) = 19.41$, $p < .001$, $\eta^2_p = .40$, $\tilde{\varepsilon} = 1.00$, and target size, $F(1, 29) = 25.00$, $p < .001$, $\eta^2_p = .46$, $\tilde{\varepsilon} = 1.00$. Figure 6 illustrates the main effects. The conventional camera position differed significantly from the extremely low position ($p = .005$, $d_z = .38$), as well as from the extremely high position, ($p = .022$, $d_z = .21$). However, the other two positions did not differ substantially from the conventional position ($p > .05$). The egocentric distance shows the same pattern as in the previous experiment, with stronger underestimation of larger distances. A visible vehicle reference led to distance underestimation. Finally, the larger target vehicle produced stronger distance underestimation.

Several interactions also reached significance. The camera position × egocentric distance interaction was significant, $F(20, 580) = 10.62$, $p < .001$, $\eta^2_p = .27$, $\tilde{\varepsilon} = .37$. Figure 7(a) illustrates the interaction effect. The differences between the perspectives were strongest for closer distances and decreased with larger distances. The camera position × vehicle reference interaction was also significant, $F(4, 116) = 29.83$, $p < .001$, $\eta^2_p = .51$, $\tilde{\varepsilon} = .86$. Figure 7(b) depicts the interaction. If the vehicle reference was not visible, camera positions differed more strongly. However, when visible, the difference between the camera positions decreased.

Consistent with the two-way interactions, the three-way interaction between camera position, egocentric distance, and vehicle reference was significant, $F(20, 580) = 6.62$, $p < .001$, $\eta^2_p = .19$, $\tilde{\varepsilon} = .55$. As depicted in Figure 8, without a visible reference, the estimates for camera positions differed strongly for close distances, as was expected. However, when a reference was visible, differences between the camera positions disappeared, even for the closest distance.

The camera position × target size interaction also reached significance, $F(4, 116) = 19.57$, $p < .001$, $\eta^2_p = .40$, $\tilde{\varepsilon} = .80$. In the lower positions, estimates for the two target sizes differed more strongly than in the other positions. Finally, the interactions of egocentric distance and vehicle reference, $F(5, 145) = 9.45$, $p < .001$, $\eta^2_p = .25$, $\tilde{\varepsilon} = .49$, as well as egocentric distance and target size, $F(5, 145) = 5.93$, $p < .001$, $\eta^2_p = .17$, $\tilde{\varepsilon} = .78$, also reached significance.

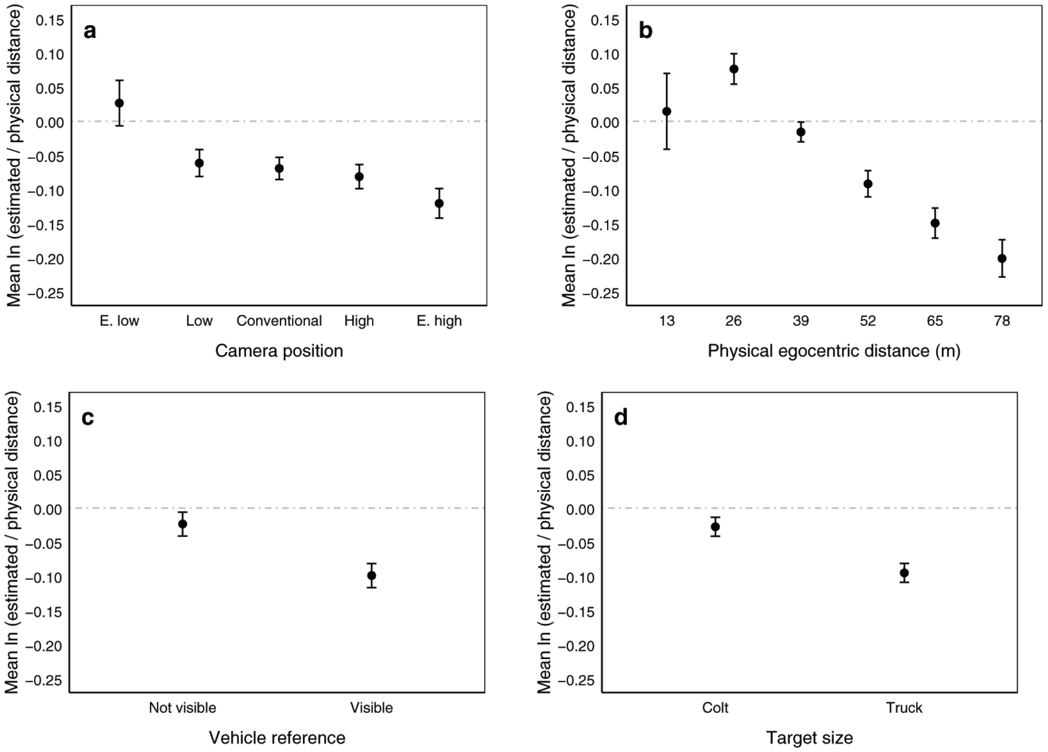

Figure 6. The main effects of camera position (a), egocentric distance (b), vehicle reference (c), and target size (d) on lnError. E.low and E.high correspond to the extremely low and extremely high camera positions, respectively. Dotted horizontal lines represent perfect accuracy. Error bars show adjusted 95% within-subjects confidence intervals.

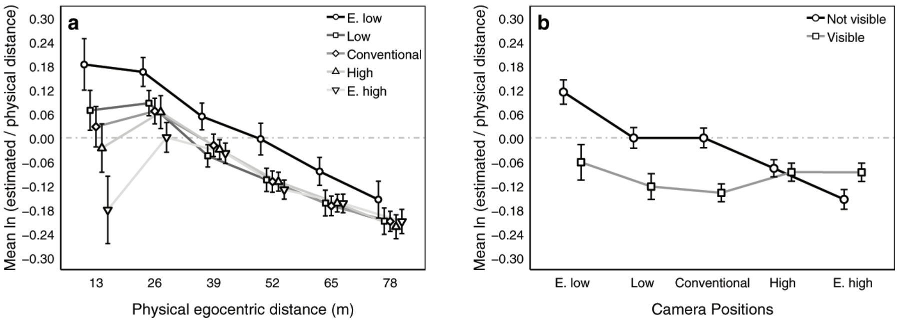

Figure 7. Interactions of camera position and egocentric distance (a), as well as camera position and vehicle reference (b) on lnError. E.low and E.high correspond to the extremely low and extremely high camera positions, respectively. Dotted horizontal lines represent perfect accuracy. Error bars show adjusted 95% within-subjects confidence intervals. Note that within each *x*-axis category, means are slightly set off horizontally to improve readability.

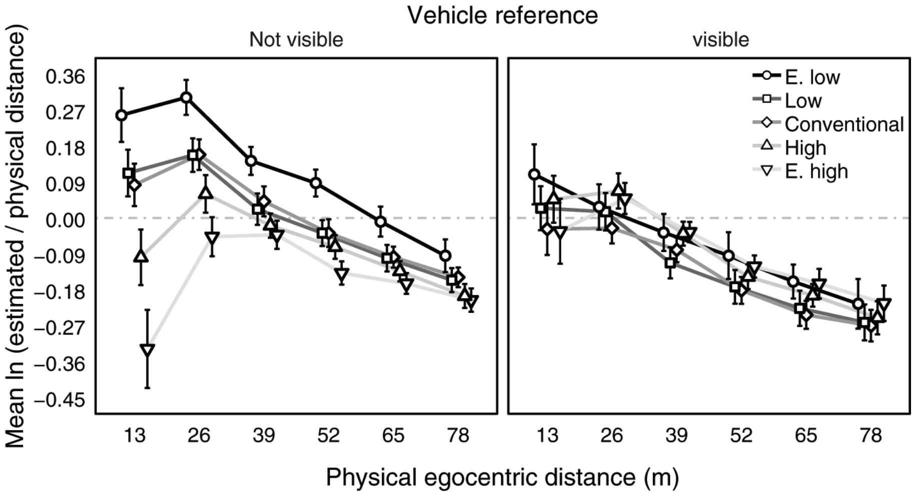

Figure 8. lnError as a function of egocentric distance, camera position, and vehicle reference. E.low and E.high correspond to the extremely low and extremely high camera positions, respectively. Dotted horizontal lines represent perfect accuracy. Error bars show adjusted 95% within-subjects confidence intervals. Note that within each *x*-axis category, means are slightly set off horizontally to improve readability.

We can conclude that the position of a side-mounted rear-view camera affects distance estimation. Without a visible reference, we successfully replicated the effect of perspective on distance estimation found by many other studies (Daum & Hecht, 2009; Gardner & Mon-Williams, 2001; Leyrer et al., 2015; Ooi et al., 2001): lower camera positions produced distance overestimation, especially for smaller distances. This is also consistent with a previous experiment not presented here, where the effect of camera position was even stronger. The interaction effect of camera position and distance can be explained with the angle of declination: the shorter the distance between object and observer, the larger the angular changes produced by a viewpoint shift, which in turn may create stronger impressions of changed distance (see Sedgwick, 1986). Why did this effect not surface in Experiment I? According to our results, the estimation of distances changes dramatically when observers make judgments from an exterior reference point. This was shown by the main effect of vehicle reference, its interaction with camera position, and the three-way interaction with position and distance. When participants estimated distances from the back of their ego-vehicle, the main effect of camera position as well as the interaction with distance almost disappeared (Figure 7(b) and Figure 8). Thus, the differences between the two experiments can at least in part be explained by the distance estimation task. Moreover, the size of the rearward target also affected distance estimation. As predicted, the larger target vehicle produced smaller distance estimates, especially in low camera positions, thus indicating an overestimation of target size in low perspective (Gogel & Da Silva, 1987; Wraga & Proffitt, 2000).

GENERAL DISCUSSION

In the two experiments, we have investigated the effects of perspective, target size, and vehicle reference on the estimation of rearward distance. The focus of our work is unique insofar as it does not focus on the placement of in-vehicle monitors or on the comparison of CMS to conventional side-mounted rear-view mirrors (as done by Beck et al., 2017; Flannagan & Mefford, 2005; Flannagan et al., 2002), but on the placement of the exterior camera, especially in the vertical dimension. In this case, basic perception research can speak to the applied issue of camera placement, ultimately leading to design recommendations to improve CMS. We can make several assertions about the effect of camera position on the perception of rearward distances: as long as no reference of the ego-vehicle is visible, shifting the rearward viewpoint of drivers up- or downward does influence the estimation of distances (Experiment II). As the perspective is shifted downward, participants increasingly overestimate distance, and vice versa for upward shifts. These findings are in line with those from basic research (Corujeira & Oakley, 2013; Daum & Hecht, 2009; Gardner & Mon-Williams, 2001; Leyrer et al., 2011, 2015; Messing & Durgin, 2005; Ooi et al., 2001; Rand et al., 2011; Sedgwick, 1986), as well as with the results from one of our previous experiments not presented here. Furthermore, the effect of perspective increases as the distance to the following vehicle decreases. This finding is consistent with the optics of the modified viewing angle; lowering or raising the viewpoint produces greater declination changes for smaller distances (Sedgwick, 1986). This is particularly important since drivers use side-mounted mirrors mainly to judge objects at close distances between 10 and 50 m, depending on their speed.

Moreover, Experiment II indicates that the size of the rear-view target is important for distance estimation, especially for a low rear-view perspective of the driver. Participants underestimated distances more strongly for a large vehicle than for a small vehicle. More importantly, vehicle size also interacted with camera position. As the camera was lowered, differences in vehicle size (truck vs. passenger car) had more pronounced effects. Both the main effect of vehicle size and the interaction with the camera position are consistent with theories of size and distance perception. In particular, the size-distance-invariance hypothesis (see Epstein et al., 1961; Gogel & Da Silva, 1987; Gogel, 1976; McCready, 1985) seems to apply. If objects familiar in size appear larger than usual (as induced by a lowered camera), this should produce distance underestimation. Another contributing factor is the overestimation of vertical target size as targets extend above the observers' eye-height (Wraga & Proffitt, 2000). This can explain the estimates produced by our participants. A comparable effect of vehicle size is known from TTC literature (see size-arrival effect; DeLucia, 1991).

Finally and most importantly, the effect of vertical camera position almost disappeared when participants could make use of the visual reference of their own vehicle (Experiments I and II). In Experiment II, we directly compared distance estimates with and without a visual vehicle reference. As expected, without reference, the effect of camera position was manifest. However, with reference, the effect almost disappeared, which was comparable to Experiment I. How can we explain this finding? First, people might use other distance cues when the additional visual reference is given. We have suggested previously that the effect of perspective was mostly caused by the angle of declination, which changes for different vertical camera positions. However, the angle of declination, being a cue related to egocentric distance, may take a back seat when the vehicle side becomes visible.

Another possible explanation arises when considering the relationship between eye-height and angle of declination. According to Sedgwick (1986), the distance to an object is a function of the eye-height and the declination angle of the observer, $D = H / tan\left(\alpha\right)$. Thus, as eye-height changes, the angle of declination changes accordingly, but perceived distance should remain constant. It follows that if perspective changes but the internal information about one's eye-height does not or is not updated correctly, the perceived distance should change. As von Castell et al. (2018) showed, participants seem to determine their eye-height based on visual information available to them in a virtual environment. Thus, participants in our study might have determined their eye-height incorrectly, maybe due to the rather sparse information available in the stimuli, and thus experienced a strong effect of perspective on perceived distance. Now, the vehicle's reference might have facilitated the determination of the observer's virtual eye-height (i.e., the vertical position of the camera), thus decreasing the effect of perspective on distance estimation. Figure 9 illustrates the

Figure 9. Example stimuli without reference (left) and with reference (right) in the conventional camera position. The target vehicle has a distance of 13 m from the observer (left) or from the back of the vehicle (right).

difference between a visible and a nonvisible vehicle reference.

Limitations and Recommendations for Further Research

The detrimental effects of lowered camera positions on the perception of rearward traffic need to be put into perspective. We have used static instead of dynamic stimuli, which is an abstraction of the actual use case. Once a vehicle is moving, several additional depth cues become available that facilitate rearward perception. Further research should focus on more dynamic settings in order to establish if low camera positions continue to be problematic in dynamic situations. Another potential shortcoming closely connected to the static design is the task used in our experiments. Even if metric distance estimation is often used when comparing different rear-view concepts, such as different types of rear-view mirrors (Böffel & Müsseler, 2015; Flannagan et al., 2002; Hecht & Brauer, 2007; Higashiyama & Shimono, 2004), it is rather uncharacteristic for driving. Future studies should use supplementary measures, such as TTC estimation, lane change performance, or last-safe-gap paradigms. Such methods have already been applied in other studies (Fisher & Galer, 1984; Flannagan & Mefford, 2005).

These measures are surely relevant for everyday driving tasks, such as performing lane changes. It should be noted, however, that distance estimation can also be important for these tasks. For example, if a vehicle is driving in an adjacent lane with the same speed, a driver should assess whether she can change the lane without violating the safety margin of the rearward vehicle. Furthermore, observers might use perceived distance for the computation of TTC in some conditions (for a discussion, Landwehr et al., 2013; Yan et al., 2011). Finally, parking is a specific driving task where the estimation of distances to static objects is more relevant than are dynamic measures.

Where to Place the Rear-View Camera

The main goal of our research was to investigate whether changes in perspective have a detrimental impact on depth perception in the context of CMS. We found that a low camera position indeed caused greater distance overestimation, in particular if no visual reference of the ego-vehicle is provided in the "mirror" image. The overestimation of distance can compromise driving performance and safety. Therefore, our first recommendation is to avoid extremely low camera positions. If the camera is placed lower than the conventional mirror position, designers should at least ensure that the ego-vehicle's reference is always visible. In contrast to low camera positions, higher positions are much more desirable, since they lead to distance underestimation and thus to increased safety margins. Thus, our second design recommendation is to place the rear-view camera at the eye-height of the driver or higher.

Third, rear-view cameras should not be mounted too far toward the back of the vehicle. This would reduce the visual reference and could lead to strong effects of vertical camera position on distance estimation. Instead, positions farther to the front of the vehicle are more desirable, since they increase the field-of-view and decrease blind spots. This also improves safety and might make sidelong glances superfluous. Thus, based on our results, the camera should be placed as high and as far to the front as possible. However, it should be emphasized that our recommendations are solely based on distance estimation tasks, and fore-aft camera position has not been manipulated systematically. More research has to be conducted focusing on dynamic driving-related measures in addition to distance estimation in order to formulate clear and applicable recommendations.

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KEY POINTS

- Different camera positions affect distance estimation to a following vehicle in the context of CMS.
- Higher camera positions lead to distance underestimation, whereas lower positions lead to distance overestimation.
- The effect of camera position increases as the distance to the following vehicle decreases.
- Other factors, such as the size of the following vehicle, affect distance estimation, especially for low camera positions. Large vehicles are underestimated in comparison to small vehicles.
- A visible reference of one's own vehicle mostly compensates the effect of camera displacement.
- Camera positions farther up or to the front of the vehicle are more preferable, whereas low camera positions and positions farther to the back cannot be recommended based on our results.

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SUPPLEMENTAL MATERIAL

The online supplemental material is available with the manuscript on the *HF* website.

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