Car Backlight Position and Fog Density Bias Observer-Car Distance Estimates and Time-to-Collision Judgments

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Objective: A series of experiments assessed biases in perceived distance that occur while driving as a function of the backlight position of the car ahead and fog density. **Background:** V. Cavallo, M. Colomb, and J. Doré (2001) have shown that smaller horizontal backlight separation and fog may result in increased estimates of the distance between an observer and a car of which only the backlights are visible. They also predicted that raising the height of the car backlights would lead to increasing distance estimates. **Method:** Distance perception was assessed in both static and dynamic computer-simulated scenarios in which the distance estimates were performed using a familiarized analog scale or using time-to-collision judgments for both pairs of backlights and single backlights. **Results:** In a series of five experiments, the horizontal separation and fog density effects were replicated. In addition, distance estimates were consistently larger with higher than with lower vertical backlight positions. **Conclusion:** There is reason to believe that biases in distance perception may be augmented by car backlight positions and by low-visibility weather conditions. **Application:** Car designers should take backlight placement seriously. Speed-dependent car-to-car distance control systems seem desirable to counteract biases in distance perception.

INTRODUCTION

Cars differ widely in both the horizontal separation and the vertical position of their backlights. Informal measurements showed that the center-to-center horizontal separation varies at least between 100 and 174 cm, and the vertical position varies at least between 53 and 164 cm (see Figure 1). In fact, traffic regulations in Germany allow for anything from 35 cm between the road surface and the lower end of backlights to as much as 210 cm between the road surface and the upper end of backlights.

Sports cars will necessarily have their backlights relatively close to the road surface. For other types of cars there are good practical reasons for placing backlights near the car roof. For instance, mild rear-end collisions typically leave backlights undamaged if these are placed at a certain height, thereby reducing repair costs. Unfortunately, such practical advantages may come at a price. Relative height in the visual field may serve as an important pictorial depth cue in that, other things being equal, objects below the horizon that appear higher in the field of view are seen as being farther away. If weather and daylight conditions are such that drivers see little more than the backlights of the car running ahead, then backlights placed at a greater height above the road surface might be seen as belonging to a car that is farther away than a car with backlights placed at a lower height. This implies a certain danger in that on average, a relatively shorter distance may be kept from cars with highly placed backlights, with obvious consequences for road safety.

From a similar perspective, Eberts and MacMillan (1985) have presented evidence suggesting that smaller cars get more hits from behind because they are perceived as being farther away. This should be so because the retinal image of a small car is smaller than that of some “modal car.” If this hypothetical modal car were indeed the

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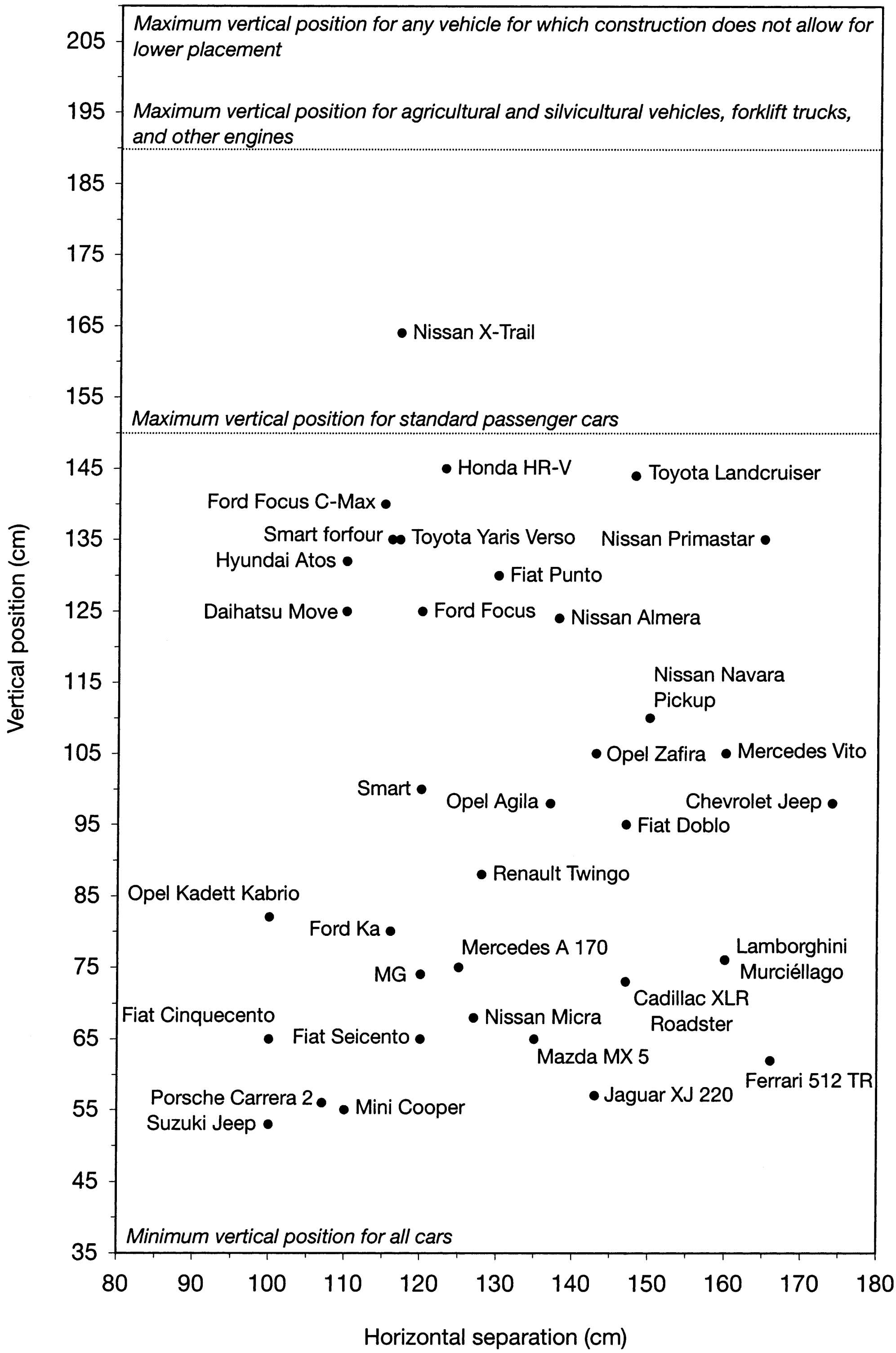

Figure 1. Horizontal separation and vertical position above the ground of backlights of a random sample of cars. (Minimum and maximum vertical positions were taken from §53 of the German Road Traffic Licensing Regulations [Straßenverkehrs-Zulassungs-Ordnung]; see http://bundesrecht.juris.de/bundesrecht/stvzo/index.html. Passenger cars must not be wider than 250 cm according to §23 of the German Road Traffic Licensing Regulations.)

standard for judging the distance between the observer and the car ahead, then size constancy dictates that the smaller retinal image must represent an object that is further away. Cavallo, Colomb, and Doré (2001) argued that in poor visibility conditions such as foggy weather drivers would use the horizontal separation of the backlights as a cue to the angular size of a car silhouette. If this is so, then larger or smaller backlight separations should result in smaller or larger observer-car distance estimates, respectively. In line with this expectation, Cavallo et al. (2001) reported that the horizontal backlight separation had a statistically significant effect on observers' distance estimates in a static viewing situation – that is, in an experimental hall filled with heavy artificial fog in which participants gave verbal distance estimates in meters to indicate how far away they perceived a pair of backlights mounted on a stand to be.

Interestingly, Cavallo et al. (2001) also manipulated the vertical backlight position, but this manipulation turned out not to affect the distance estimates, as would be expected if the relative height in the visual field is used as a distance cue by drivers. This surprising finding was one of the reasons we decided to reexamine the effects of the horizontal separation and vertical position of backlights in an independent set of experiments. As will become clear further on, a more general goal of the present set of experiments was to replicate and extend the results reported by Cavallo et al. (2001) while avoiding the methodological compromises they had to make given their experimental setup.

Exactly why the vertical backlight position did not affect the distance estimates in the study reported by Cavallo et al. (2001) is unclear. The authors suggested that the lack of an effect may have been attributable to there being no visual horizon, which would serve as a frame of reference while driving during nighttime fog. Alternatively, they argued that drivers may not use height in the visual field as a distance cue because they may have learned the irrelevance of this depth cue from the fact that the road ahead may move up and down.

We think it unlikely that a depth cue as universal as the height in the visual field should be discarded in the exceptional situation of driving during a foggy night, let alone in a static viewing condition in an experimental hall. Furthermore, there is evidence that even in the absence of a "real" horizon people seem to adopt some sort of "virtual" horizon (Ittelson & Kilpatrick, 1951). Finally, although there may be no horizon in a literal sense while driving in nighttime fog, it certainly seems plausible that the car's dashboard, the windshield contour, or the habitual viewing position while seated in a car could all serve as frames of reference for placing a "virtual" horizon.

There are at least two alternative explanations of the failure to find a vertical backlight position effect on the distance estimates. First, the vertical position manipulation used by Cavallo et al. (2001) may not have been powerful enough given their experimental setup. In their study, the vertical position varied between 40 and 90 cm. Even the maximum possible height was thus only a fraction of that found in real cars (see Figure 1). A more powerful manipulation of the vertical position variable might result in a detectable effect. Second, the verbal distance estimate in meters that was used as the dependent measure may not have been a sensitive measure of perceived distance. Explicit specifications of observer-car distances in meters may never be required in the context of driving, so the verbal estimation format was probably unfamiliar to the participants. It seems quite plausible that unfamiliar distance estimates may be insensitive to experimental manipulations because the latter are overshadowed by all sorts of unspecific effects of response bias, practice during the experiment, and so on. In addition, it seems possible that unfamiliar estimates are also easier to distort, which would also limit the generality of the reported findings. Cavallo et al. (2001) discussed the problem of verbal distance estimates, noting that indeed participants sometimes deviated extensively from the true metric distances. A closely related fact that needs to be considered is that the density of their artificial fog changed substantially during the study (it was produced periodically and then decayed, reaching unsuitable levels after 10 to 25 min), adding error variance to the already noisy estimation data.

Whereas the problems just discussed would help to explain the null effect of the vertical position manipulation, there are other limitations of the Cavallo et al. (2001) study attributable to the methodological compromises that had to be made given their experimental setup. Two of these limitations were relevant for the design of Experiment 1. First, their participants sat at a fixed position in a hall filled with artificial fog that was so heavy that only the static backlights, but no other objects inside the hall, could be seen. The experimental situation was thus free of important pictorial depth cues, such as texture gradient or linear perspective, let alone movement-related depth cues. In the real world these depth cues are available at least to some degree even while driving during nighttime fog, and simulation studies have shown that an increasing number of depth cues may reduce both the variability and the "overshooting" of distance estimates (Cavallo, Mestre, & Berthelon, 1997). It is unclear whether the observed effect of the horizontal backlight separation or a possible effect of the vertical backlight position would survive the (partial) availability of such pictorial depth cues. Second, only observer-car distances that varied between 8 and 28 m were studied. This also limits the generality of the findings in that familiar real-world observer-car distances may be much larger.

The present series of experiments used both static computer-simulated scenarios and dynamic episodes as experimental environments. It has been shown that experimental environments simulated by desktop computers can be ecologically valid in principle if they capture the essential aspects of real-life environments, making it possible to replicate real-world behavioral effects in laboratory environments with much better control over the relevant variables (Jansen-Osmann, 2002; Jansen-Osmann & Berendt, 2002). What is more, the simulations that we used allowed us to avoid many of the restrictions of the viewing scenarios of Cavallo et al. (2001).

We first present data from two experiments that used static computer-simulated scenarios. These experiments were designed to establish the basic pattern of findings from Cavallo et al. (2001) in the experimental paradigm used here. However, instead of giving verbal distance estimates, participants indicated perceived observer-car distances on an analog scale, the use of which they had practiced intensively before the experiment. Experiments 3 and 4 were designed to test whether the findings form Experiments 1 and 2 could be replicated (a) using simulated dynamic scenarios in which both the observer position and the car ahead were moving, so that movement-related distance cues in the optic flow were available; and (b) requiring a behavioral measure of perceived distance – that is, time-to-collision judgments. Finally, Experiment 5 was designed to test whether the vertical backlight position effect on perceived distance would be larger if only one backlight was visible instead of two.

EXPERIMENT 1

Experiment 1 was designed to replicate the horizontal backlight separation effect reported by Cavallo et al. (2001) within the computer-simulated scenarios on which the present experiments were based. In addition, the vertical backlight position was manipulated in an attempt to test the hypothesis put forward by Cavallo et al. (2001) that this depth cue is suppressed in driving contexts. In an attempt to maximize our chances of finding an effect, if one exists, we used relatively strong but still realistic manipulations of both the horizontal distance and the vertical position variables. In addition, we decided to use a relatively large sample to guarantee a high degree of statistical power even for effects that are not very large.

Method

Participants. Participants were 70 volunteers (41 women, 29 men) recruited via posters on campus and the local media. Their ages ranged from 20 to 58 years ($M = 27$). All participants had normal or corrected-to-normal vision. The participants were tested individually and were paid for their participation.

Materials. Three-dimensional scenarios were generated using POV-Ray for Macintosh (The POV-Team™, 2002) at a resolution of 1024 × 768 pixels. This software allows for the placing of objects in a 3-D scenario by specifying the observer-object distance in metric units. The necessary scaling is performed automatically within the simulation environment. Two sets of scenarios were generated, a training and a test set.

The training set depicted a plain, straight, two-lane street, viewed in daylight and equipped with a white center line and two lines marking the lateral limits of the road. The lateral lines were accompanied by poles, as they are typically found on country roads (German road sign Nos. 620-40 and 620-41). The 50-m interpole distances were selected to correspond to the norms for German country roads. The road was placed in a plain environment that was textured so as to resemble typical fallow land with no trees or bushes. The horizon was filled with a mountain range made up of the same texture as the environment to the left and right of the street.

In each training set scenario a modal car, viewed from the back, was placed on the road. The car had two clearly visible, light-emitting backlights, the simulated luminance of which was technically constant in all conditions but the apparent luminance was appropriately reduced as a function of the observer-car distance (more so in the test set scenarios that used a constant amount of nighttime fog). The simulated car was 180 cm wide and 150 cm high. Its color was light gray. The illumination was such that the sun appeared to be coming from a top-left angle with drop shadows extending to the right of the scene. On different trials the observer-car distance could vary between 35 and 65 m in intervals of 5 m. In order to introduce somewhat more variability, we allowed the car to be viewed from slightly different angles, which were created by varying the horizontal (50 or 150 cm distance from the road midline) and vertical (110 or 160 cm above the ground) observer positions. The size of the car as well as the backlights' horizontal separation (130 cm) and their vertical distance from the road surface (80 cm) were not varied but were scaled to provide the proper viewing angles for each of the observer-car distances. Combining the seven observer-car distances with the four different viewpoints resulted in 28 different training set scenarios.

The test set scenarios were similar to the training set scenarios with the following exceptions. First, the daylight was eliminated. Second, a constant amount of simulated fog was added to all scenarios. Fog was simulated using the POV-Ray command *fog* (type = 1). This command replaces the color of each pixel of an object in a scenario by a weighted mean of the color of the object and the color of the simulated fog. The proportion of the object color is given by $1 - \exp(-d/D)$, and the proportion of the fog color by $\exp(-d/D)$, in which d represents the distance of the object from the observer and D is a parameter that influences the density of the simulated fog. In all simulations the color of the fog was dark gray (<.2, .2, .2> in relative RGB values) with a transmission factor of .03. The transmission factor determines the minimal weight of the object color, such that even far-away objects may be visible, provided the object's color is sufficiently different from the color of the fog. Third, light sources were added that illuminated the first couple of meters on the road in the way headlights would during nighttime driving. Fourth, the observer-car distance varied between 40 and 60 m in intervals of 10 m. Fifth, the horizontal backlight separation was 150 or 100 cm, and the vertical backlight position was 50 or 160 cm above the road surface (measured center to center). We used these particular values because they correspond to extreme values of real-world cars (see Figure 1). Combining the three observer-car distances (40, 50, and 60 m) with the four backlight configurations and the four viewpoints (see training set) resulted in 48 different test scenarios.

Participants viewed the training and test scenarios in a dark room. The scenarios were presented on the 17-inch (43.2-cm) screen of an Apple eMac computer, which controlled the experiment. Viewing distance was 35 to 45 cm.

Procedure. The experiment started with a training phase in which each scenario was presented for 1 s, after which the screen turned dark gray. Participants then used an on-screen slider to indicate their observer-car distance estimate on a scale with no markers except for "0 m" and "75 m" at the start and at the end of the scale, respectively. After clicking an OK button, participants were informed about whether their estimate was sufficiently precise or not. Distances within ±7 m of the target distance were counted as sufficiently precise. After completing at least one block of 28 trials during which each training set scenario was presented once, participants entered the main experiment only if their distance estimates were correct in more than 70% of the last 28 trials. Otherwise the training was continued until this correctness criterion was met, but only up to a total of 100 trials, after which the training was terminated. In the latter case, participants were given the option to repeat the training or to quit the experiment.

The main experiment consisted of 240 trials during which each of the 48 different nighttime scenarios was presented five times. The presentation order was random. Trials were identical to those of the training phase with the following exceptions. First, the presentation duration was reduced to 500 ms so as to mimic a brief glance at the scenario. Second, feedback was only presented after every 12th trial and was provided as a summary feedback. Third, distance estimates within ±10 m of the target distance were counted as sufficiently precise to be scored as correct for the summary feedback.

Design. The independent variables were observer-car distance (40, 50, and 60 m), horizontal backlight separation (150 and 100 cm, henceforth *wide* and *narrow*), and vertical backlight position (50 and 160 cm above the road surface, henceforth *low* and *high*). All variables were manipulated within subjects. For the critical vertical and horizontal backlight position manipulations, we wanted to detect effects in the distance estimates that were at least as large as $f = .20$ (i.e., somewhat smaller than "medium" effects according to the conventions introduced by Cohen, 1977), and we assumed a population correlation of $\rho = .60$ between the distance estimates within the levels of each of these variables (this is equivalent to assuming $\eta^2 = .17$ as the population effect size). An a priori power analysis showed that given desired error probabilities of $\alpha = \beta = .05$, a sample size of $N = 67$ was needed. (The power calculations were conducted using the G•Power program; Erdfelder, Faul, & Buchner, 1996.) We were able to recruit $N = 70$ participants so that the power was actually slightly larger at $(1 - \beta) = .96$.

In all experiments reported in this paper, a multivariate approach was used for all within-subject comparisons. In our applications, all multivariate test criteria correspond to the same (exact) F statistic, which is reported. The level of α was set to .05 for all analyses. Whenever H_0 had to be rejected, the partial η^2 is reported as a measure of relative effect size – that is, the variance explained relative to the variance not explained by any of the other experimental variables (see Cohen, 1977, p. 412).

Results. As is obvious from Figure 2, the observer-car distance estimates varied considerably as a function of the experimental variables. Most interestingly, estimated distances were much larger for narrow than for wide horizontal separations, and they were much larger for high than for low vertical backlight positions.

A 3×2×2 multivariate analysis of variance (MANOVA) showed that the distance estimates varied significantly as a function of the observer-car distance, $F(2, 68) = 395.62, p < .001, \eta^2 = .92$,

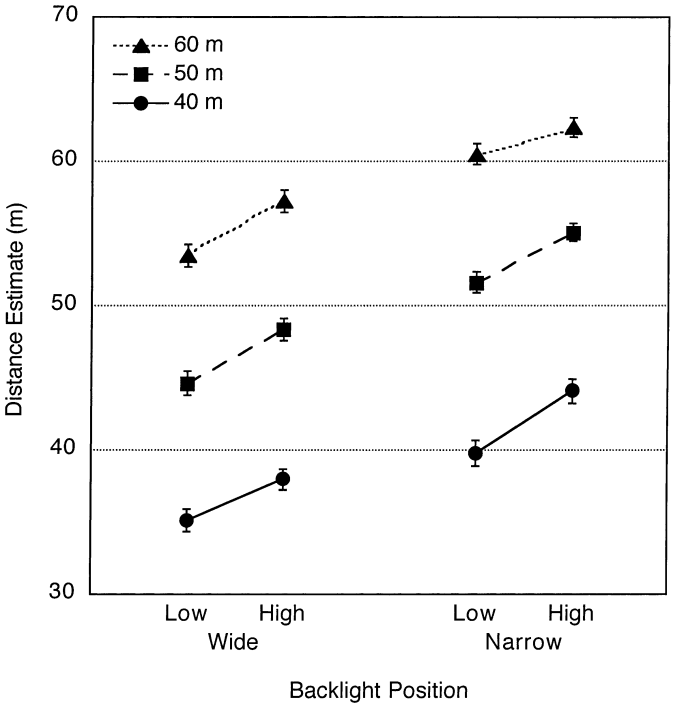

Figure 2. Mean distance estimates as a function of observer-car distance, horizontal backlight separation, and vertical backlight position (Experiment 1). The error bars represent the standard errors of the means.

the horizontal separation, $F(1, 69) = 281.20$, $p < .001$, $\eta^2 = .80$, and the vertical position, $F(1, 69) = 141.45$, $p < .001$, $\eta^2 = .67$. However, the distance variable interacted significantly with the horizontal separation, $F(1, 69) = 7.74$, $p < .001$, $\eta^2 = .10$, and the vertical position, $F(1, 69) = 3.65$, $p < .03$, $\eta^2 = .05$. These interactions reflected that the effect of the horizontal backlight separation was highest for the medium observer-car distance (it was 5.4, 6.8, and 6.1 m for the 40-, 50-, and 60-m observer-car distances, respectively), whereas the effect of the vertical backlight position was highest for the two smaller observer-car distances (it was 3.6, 3.6, and 2.8 m for the 40-, 50-, and 60-m observer-car distances, respectively). The interaction between horizontal separation and vertical position was not significant, $F(1, 69) = 1.68$, $p > .20$. Finally, the three-way interaction was significant, $F(2, 68) = 22.50$, $p < .002$, $\eta^2 = .40$, reflecting primarily that for wide horizontal separations the vertical position effect was smaller for the small than for the large distance, whereas for the narrow horizontal separation the reverse was true.

Discussion

Both the horizontal separation between backlights and their vertical position had considerable effects on observer-car distance estimates in the nighttime scenes used here. The horizontal separation effect replicates an effect that has already been reported by Cavallo et al. (2001). The vertical position effect is novel and inconsistent with the post hoc conclusion of Cavallo et al. (2001) that height above the ground would be suppressed as a distance cue for driving situations because it was unreliable. In fact, in terms of a standardized effect size measure, the sizes of both the horizontal backlight separation and the vertical backlight position manipulations were quite large.

It may seem tempting to interpret the observed bias literally – for instance, in terms of the distortion in meters between the low-wide and the high-narrow backlight configurations (approximately 9 m), which would also occur in real-life driving situations. However, this interpretation would be unwarranted simply because there are too many differences between the experimental laboratory situation used here (static, single task, etc.) and the situation of driving in the real world (dynamic, multiple tasks, etc.). Nevertheless, the present findings suggest that there may be a real problem lurking, and it may exist for both the horizontal separation *and* the vertical position of car backlights.

EXPERIMENT 2

As mentioned, fog may affect distance perception indirectly by reducing the quality and availability of the distance cues, but it may also affect distance perception directly by "contaminating" the atmospheric perspective distance cue. Because of particles in the air, more distant objects appear lower in contrast, seem to have softer edges, and shift color toward the blue end of the spectrum visible to the human eye (Fry, Bridgman, & Ellerbrock, 1949). The difference in appearance between close and distant objects along these dimensions may thus be used as a distance cue (O'Shea, Blackburn, & Ono, 1994). The higher concentration of small water droplets in the air at higher fog densities should have effects on the appearance of objects that are similar to those of greater observer-object distances under normal circumstances. There is evidence that this is indeed the case for unfamiliar objects (Ross, 1967), and Cavallo et al. (2001) have reported that the same holds for backlights of cars, suggesting that at least in their experimental environment the atmospheric perspective dominated the familiar size depth cue implied by the horizontal backlight separation. However, as with the horizontal separation and vertical position manipulations, Cavallo et al. (2001) had to make methodological compromises because of their experimental setup.

First, Cavallo et al. (2001) compared only two viewing conditions, one with and one without artificial fog. Unfortunately, these two viewing conditions were confounded by whether a closed experimental hall (needed to produce the artificial fog) or an open football field (for the "clear" viewing condition) was used. The two physical settings differ in many potentially relevant variables. For instance, at least some ground texture was probably visible in the open football field but not in the experimental hall filled with heavy artificial fog, so there may have been a disparity in the depth cues available in the two settings. Also, if participants believed that the maximum possible observer-car distance was larger for the unfamiliar experimental hall than for a football field, then this could also explain the larger distance estimates with fog than with clear viewing conditions. As long as it is unclear whether, or how, such variables affected the verbal distance estimates, one cannot uniquely interpret those results.

Second, it was not possible for Cavallo et al. (2001) to produce artificial fog that was constant for all observer-car distances and at the same time guarantee that no parts of the experimental hall were visible without eliminating the visibility of the backlights at some observer-backlight distances. As the latter requirement was crucial, thicker fog had to be used for shorter distances, which means that the fog density manipulation was confounded with the observer-car distance. Here, too, it seems important to unconfound these variables and to manipulate them orthogonally.

Third, in the setup used by Cavallo et al. (2001), backlights were mounted on a movable stand and no car silhouette was visible. This represents only one possible situation while driving during fog. Realistically, the silhouette of a car that is approached from behind will come into view sooner or later, and it seems reasonable to expect that from then on the silhouette size will serve as a more potent familiar size depth cue than will the horizontal backlight separation alone. This more potent depth cue could eliminate or at least reduce the fog density effect. If so, then one should expect a reduction of the fog density effect at shorter distances.

Finally, we thought it important to test the hypothesis that fog biases distance estimates using not only one level of fog density, as in Cavallo et al. (2001). Instead, we used four different levels of fog density.

Method

Participants. Participants were 40 volunteers (23 women, 17 men) recruited via posters on campus and the local media. Their ages ranged from 19 to 44 years ($M = 28$). All participants had normal or corrected-to-normal vision. The participants were tested individually and were paid for their participation.

Materials. The training set scenarios were identical to those used in Experiment 1. The test set scenarios were similar to the training set scenarios with the following exceptions. First, the daylight was eliminated and light sources were added that illuminated the first couple of meters on the road in the way headlights would during nighttime driving. Second, four variants of each scenario were generated using four different levels of fog density. The fog levels were selected such that the three differences in density between adjacent levels of the four-level fog density variable seemed approximately equal to five different observers. At the lowest density, the car's silhouette was still visible. At the highest density, only the backlights were visible, and only barely so. Combining the three observer-car distances (40, 50, and 60 m) with the four different levels of fog density and the four viewpoints (see the description of the training set of Experiment 1) resulted in 48 different test scenarios.

Procedure. The procedure was the same as that of Experiment 1.

Design. The independent variables were observer-car distance (40, 50, and 60 m) and fog density (from low through medium and high to very high). All variables were manipulated within subjects. We decided that the fog density effect on the distance estimates should be at least of size $f = .25$ (i.e., "medium" according to the conventions introduced by Cohen, 1977), and we assumed a population correlation of $\rho = .60$ among the levels of this repeated measures variable (this is equivalent to assuming $\eta^2 = .39$ as the population effect size). An a priori power analysis showed that given desired error probabilities of $\alpha = \beta = .05$, a sample size of $N = 32$ was needed. However, we were able to recruit $N = 40$ participants so that the power $(1 - \beta)$ was .99 and thus even larger than what we had planned for.

Results

Figure 3 illustrates that the observer-car distance estimates increased not only as a function of the observer-car distance but also as a function of the fog density.

A 3×4 MANOVA showed that distance estimates varied significantly as a function of the observer-car distance, $F(2, 38) = 211.65, p < .001, \eta^2 = .92$, and fog density, $F(3, 37) = 6.10, p < .002, \eta^2 = .33$. The distance and fog density variables also interacted, $F(6, 34) = 7.00, p < .001, \eta^2 = .55$, reflecting the fact that the maximum fog-induced bias in the distance estimates was larger at the 40-m observer-car distance than at the 60-m observer-car distance. In fact, post hoc MANOVAs showed that the fog density effect was significant at 40 m, $F(3, 37) = 12.95, p < .001, \eta^2 = .51$, and

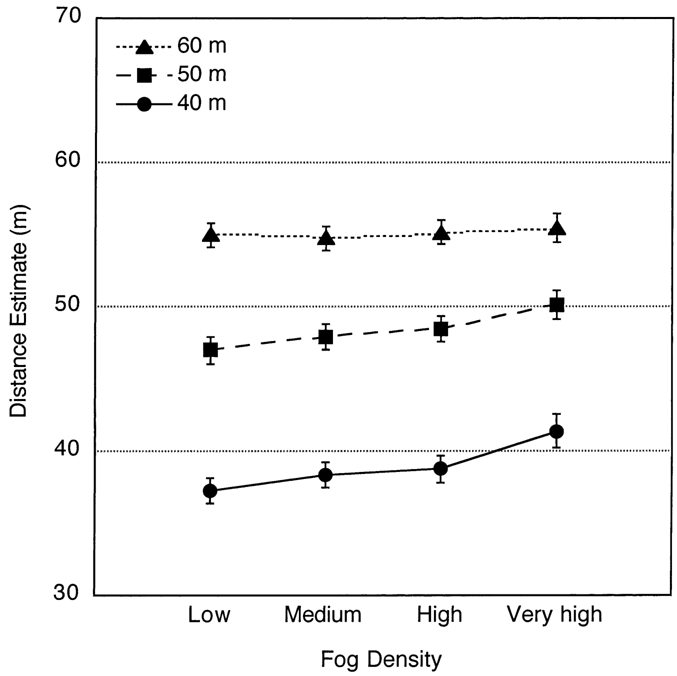

Figure 3. Mean distance estimates as a function of observer-car distance and fog density (Experiment 2). The error bars represent the standard errors of the means.

at 50 m, $F(3, 37) = 5.56, p < .001, \eta^2 = .31$, but not at 60 m, $F(3, 37) = 0.55, p > .64, \eta^2 = .04$.

Discussion

The fog density manipulation affected the distance estimates considerably, although the effects were not quite as large as those of the backlight position manipulations in Experiment 1. Interestingly, the observer-car distance and the fog density effects interacted significantly. The fog density effect became progressively smaller as the observer-car distances were increased (with differences in the distance estimates between the lowest and the highest fog density levels of 4.12, 3.13, and 0.46 m at observer-car distances of 40, 50, and 60 m, respectively), which is the opposite of what one would expect if the car silhouette that became visible at lower observer-car distances served as a familiar size depth cue that reduced the fog density effect. Quite to the contrary, with the car silhouette in view in addition to the backlights, it seems to have become easier for the visual system to pick up the fog density manipulation. This is quite plausible given that the area in the visual field covered by the car silhouette is larger than the area covered by the backlights alone, so that the atmospheric perspective depth signal should become more salient with than without the car silhouette.

In sum, then, both Experiments 1 and 2 replicated, using computer-simulated scenarios, key findings of the Cavallo et al. (2001) study while avoiding some possibly important restrictions necessitated by their experimental setup. In addition, Experiment 1 established the vertical position effect that was to be expected but was not found by Cavallo et al. (2001), and Experiment 2 illustrated the possibly important interaction between fog density and the observer-car distance.

However, there are at least two obvious limitations with both Experiments 1 and 2. First, the perceived distances were still derived from explicit estimates (albeit on a familiarized analog scale rather than in verbalized metric units). Second, the scenarios were static, and neither the observer's position nor the car ahead were moving as they would in real-life driving situations. As a consequence, information normally extracted from the optic flow (changes in texture gradient, changes in angular separation of the backlights of a car ahead, speed and direction of movement, changes in luminance and contrast of the backlights and the silhouette of the car ahead, etc.) was not available. For instance, when approaching a moving car from behind, it is important to know when a collision would occur so that braking or swerving maneuvers can be initiated early enough. During the approach, the angular separation between the backlights increases, as does the size of the car silhouette provided that the weather conditions are such that it can be seen. The angular separation of the backlights (as well as, if available, the angular separation of the outer edges of the car silhouette) and the rate at which the angular separation grows are both readily available in the visual array. From these variables, the time to contact with the approached object can be computed relatively easily (Lee, 1976), and it appears that such computations are indeed performed at a neural level (Laurent & Gabbiani, 1998). Thus, there is good reason for using the time-to-contact concept when analyzing driving behavior (Cavallo & Laurent, 1988; DeLucia, Bleckley, Meyer, & Bush, 2003; Lee, 1976).

As with pictorial depth cues, it is unclear whether any backlight position or fog density effects would survive the availability of optical flow information. This may potentially limit the generality of the findings from Experiments 1 and 2. Therefore, Experiments 3 and 4 were designed to test whether the findings of Experiments 1 and 2 could be replicated using dynamic scenarios in which both the observer position and the car ahead were moving. Further, instead of requiring explicit distance estimates, we used time-to-collision estimates to derive a measure of the perceived distance between the observer and the car ahead. More precisely, participants viewed an episode as if they were sitting in a car driving along a country road. Another car was driving ahead at a lower speed so that observers experienced themselves as approaching that car. The view was interrupted at an unpredictable moment, and participants had to indicate when they believed that a collision would occur. The length of the interval between the interruption of the view (the screen went dark) and the indication by the participant of the point in time at which the collision was expected served as the measure for the perceived observer-car distance. Note, however, that we will report this dependent measure as a "distance estimate" which is possible because both the observer and the car ahead were moving at constant velocities. To illustrate, a time-to-collision estimate of 4000 ms corresponded to an estimated observer-car distance of 50 m. This distance measure is reported for Experiments 3, 4, and 5 for better compatibility with the results of Experiments 1 and 2.

EXPERIMENT 3

Experiment 3 was designed to replicate conceptually the horizontal separation and vertical position effects of Experiment 1 but using the dynamic episodes and the time-to-collision judgments just described.

Method

Participants. Participants were 40 volunteers (23 women, 17 men) recruited via posters on campus and the local media. Their ages ranged from 20 to 36 years ($M = 25$). All participants had normal or corrected-to-normal vision. The participants were tested individually and were paid for their participation.

Materials. Movies were composed of sequences of 3-D scenarios that were joined to form a continuous movie at a frame rate of 25 frames/s. The individual scenarios were analogous to those used in Experiment 1. They were generated using POV-Ray for Macintosh (The POV-Team™, 2002) at a resolution of 800 × 600 pixels in 16.7 million colors.

There were five types of movies: a training movie and four test movies. In all movies the observer's perspective was that of a person sitting in a car that moved along a country road at a constant speed of 90 km/h while another car was moving ahead at a constant speed of 45 km/h. The observer position was always 110 cm above the ground and 150 cm from the road midline. Technically, all movies were 16 s long, during which the observer "traveled" a distance of 400 m. However, participants viewed only "episodes" that were subsequences of the movies.

The training movie displayed a daylight situation as in Experiment 1, with the exception that there were no constant distances between the observer and the car ahead, as the observer's perspective was that of continuously closing up on the other car while driving along a straight country road. More precisely, the training movie began with a 200-m distance between the observer and the car ahead and it ended when the observer's car collided with the car ahead. Displaying only subsequences of the training movie created the episodes for the training phase. A total of 28 different training-phase episodes were created by varying and combining orthogonally (a) the distance from the car ahead when the screen went black (35, 40, 45, 50, 55, 60, and 65 m) and (b) the length of the traveled distance to the point at which the screen went black (112.5, 150, 187.5, and 225 m).

The four test movies displayed a foggy nighttime situation as in Experiment 1, with the exception, as during training, that there were no constant distances between the observer and the car ahead, as the observer's perspective was that of continuously closing up on the other car while driving along a straight country road. Technically, the test movies began with a 240-m distance between the observer and the car ahead, and they ended when that distance was 40 m (the shortest distance used in the test phase). The four test movies differed in that the horizontal separation between the backlights of the car ahead was either 150 or 100 cm and the vertical backlight position was either 50 or 160 cm above the road surface. Displaying only subsequences of each test movie created the episodes for the test phase. For each movie a total of 12 different test phase episodes were created by varying (a) the distance from the car ahead when the movie stopped (40, 50, and 60 m) and (b) the length of the traveled distance to the point at which the movie stopped (112.5, 150, 187.5, and 225 m). Thus, combining the two levels of both horizontal separation and vertical backlight position variables with the 12 different test phase episodes created 48 different test phase episodes.

Procedure. The experiment started with a training phase during which the entire training movie was presented three times. Next, participants practiced the time-to-collision judgments. They were told to watch the episode until the screen turned black and to indicate, by pressing the mouse button, the point in time at which "their car" would collide with the car ahead. They were instructed to imagine that a person on the backseat would lean forward and cover their (the driver's) eyes. During training, a time-to-collision judgment was counted as correct when the mouse click occurred while the observer's car would have been within ±17.5 m of the rear end of the car ahead. After completing at least one block of 28 trials during which each training set episode was presented once, participants entered the main experiment, but only if their distance estimates were correct in more than 70% of the last 28 trials. Otherwise the training was continued until this correctness criterion was met, but only up to a total of 100 trials, after which the training was terminated. In the latter case, participants were given the option to repeat the training or to quit the experiment.

The main experiment consisted of 96 trials during which each of the 48 different nighttime episodes was presented twice. The presentation order was random. Trials were identical to those of the training phase with the following exceptions. First, feedback was presented only after every 8th trial and was provided as a summary feedback. Second, distances within ±22.5 m of the target distance were counted as sufficiently precise to be scored as correct for the summary feedback.

Design. As in Experiment 1, the independent variables were observer-car distance (40, 50, and 60 m), horizontal backlight separation (150 and 100 cm, henceforth *wide* and *narrow*) and vertical backlight position (50 and 160 cm above the road surface, henceforth *low* and *high*). All variables were manipulated within subjects. For the critical vertical and horizontal backlight position manipulations, we wanted to detect effects in the distance estimates that were at least of size $f = .25$ (i.e., "medium" effects according to the conventions introduced by Cohen, 1977), and we assumed a population correlation of $\rho = .70$ (revised in light of the sample data from Experiment 1) among the levels of these repeated measures variables (this is equivalent to assuming $\eta^2 = .29$ as the population effect size). An a priori power analysis showed that given desired error probabilities of $\alpha = \beta = .05$, a sample size of $N = 34$ was needed. However, we were able to recruit $N = 40$ participants so that the power $(1 - \beta)$ was .98 and thus even larger than what we had planned for.

Results

Figure 4 shows that, as in Experiment 1, the observer-car distance estimates varied considerably as a function of the experimental variables. Most interestingly, time-to-collision judgments indicated that the perceived observer-car distances at the point at which the visual display was interrupted were much larger for narrow than for wide horizontal backlight separations, and they were much larger for high than for low backlight

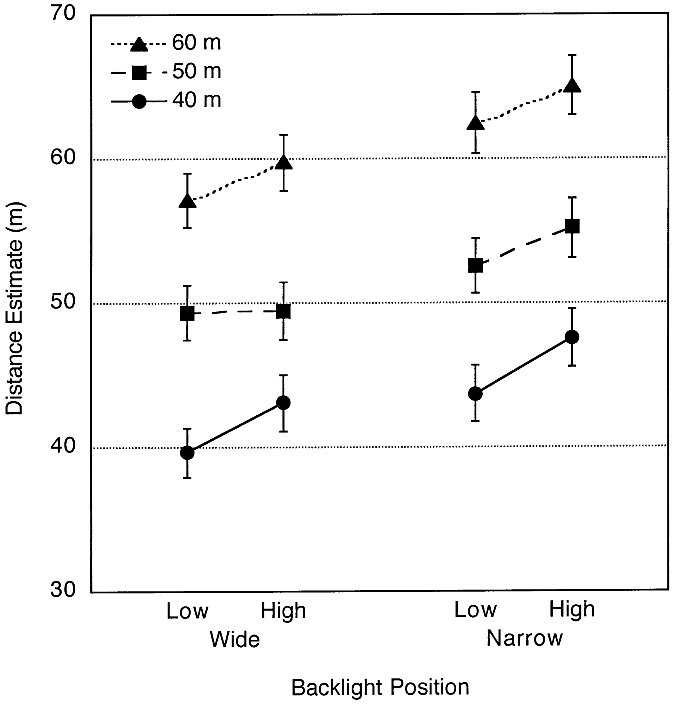

Figure 4. Mean distance estimates as a function of observer-car distance, horizontal backlight separation, and vertical backlight position (Experiment 3). The error bars represent the standard errors of the means.

positions. At a descriptive level, the data appear to be slightly noisier (larger standard errors) than those of Experiment 1, which is probably attributable to the smaller number of participants and the smaller number of data points per participant in each of the cells of the experimental design.

A 3x2x2 MANOVA showed that distance estimates varied significantly as a function of the observer-car distance, $F(2, 38) = 155.29, p < .001$, $\eta^2 = .89$, horizontal separation, $F(1, 39) = 46.04$, $p < .001, \eta^2 = .54$, and vertical position, $F(1, 39) = 19.51, p < .001, \eta^2 = .33$. The distance variable did not interact significantly with the horizontal separation and vertical position variables, although it should be noted that the distance by vertical position interaction just failed to reach the conventional significance level, $F(1, 39) = 2.89, p = .06$, $\eta^2 = .13$.

Discussion

Experiment 3 essentially replicated the results of Experiment 1 in showing that both the horizontal separation and the vertical position effects observed with explicit distance estimates in static displays survived when movement-related distance cues became available and time-to-collision judgments were used to assess perceived distance between the observer-position and the car driving ahead. The replication of the vertical position effect is particularly important because it contradicts the assumption of Cavallo et al. (2001) that height above the ground would be suppressed as a distance cue in driving situations because it was perceived as unreliable.

EXPERIMENT 4

Experiment 4 was designed to replicate conceptually the fog density effect of Experiment 2 but by using the same experimental situation as in Experiment 3.

Method

Participants. Participants were 40 volunteers (21 women, 19 men) recruited via posters on campus and the local media. Their age ranged from 19 to 55 years ($M = 26$). All participants had normal or corrected-to-normal vision. The participants were tested individually and were paid for their participation.

Materials. Movies were composed as in Experiment 3. The training movie was identical to that of Experiment 3, but the four test movies reflected four levels of the fog density variable, as in the test scenarios of Experiment 2. However, the chosen fog densities were lighter than those used in Experiment 2. This was so because they were selected such that the backlights of the car ahead could be seen during the entire episode even at the highest fog density (albeit only vaguely at the largest distance, and only to the dark-adapted eye). As in Experiment 3, displaying only subsequences of each test movie created the episodes for the test phase. For each movie a total of 12 different test phase episodes were created by varying and combining orthogonally (a) the distance from the car ahead when the movie stopped (40, 50, and 60 m) and (b) the length of the traveled distance to the point at which the movie stopped (112.5, 150, 187.5, and 225 m). This resulted in 48 different test phase episodes, each of which was presented twice so that the entire test phase comprised 96 episodes.

Procedure. The procedure was the same as that of Experiment 3.

Design. The independent variables were observer-car distance (40, 50, and 60 m) and fog density (from low through medium and high to very high). All variables were manipulated within subjects. As in Experiment 2, we assumed that the fog density effect on the distance estimates should be at least of size $f = .25$, and we assumed a population correlation of $\rho = .60$ among the levels of this repeated measures variable (this is equivalent to assuming $\eta^2 = .39$ as the population effect size). An a priori power analysis showed that given desired error probabilities of $\alpha = \beta = .05$, a sample size of $N = 32$ was needed. However, we were able to recruit $N = 40$ participants so that the power $(1 - \beta)$ was .99 and thus even larger than what we had planned for.

Results

Figure 5 illustrates, as in Experiment 2, that both the observer-car distance and the fog density affected the time-to-collision judgments.

A 3×4 MANOVA showed that distance estimates varied significantly as a function of the observer-car distance, $F(2, 38) = 163.12$, $p < .001$, $\eta^2 = .90$, and fog density, $F(3, 37) = 19.65$,

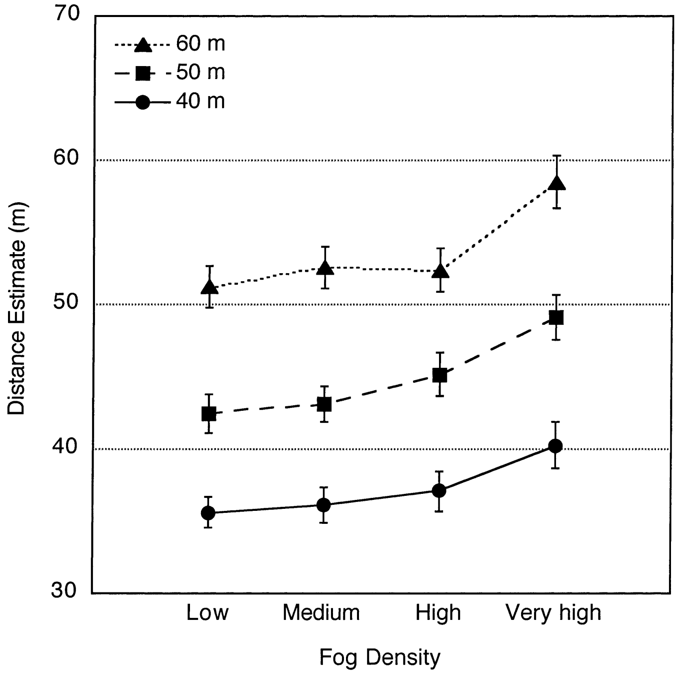

Figure 5. Mean distance estimates as a function of observer-car distance and fog density (Experiment 4). The error bars represent the standard errors of the means.

$p < .001$, $\eta^2 = .61$. The distance and fog density variables also interacted significantly, $F(6, 34) = 2.38$, $p < .05$, $\eta^2 = .\ 0.30$, probably reflecting the fact that the two intermediate fog densities differed in all but the 60-m distance condition. Post hoc analyses showed that the fog density effect was significant at 40 m, $F(3, 37) = 7.29$, $p < .001$, $\eta^2 = .37$, at 50 m, $F(3, 37) = 28.98$, $p < .001$, $\eta^2 = .43$, and at 60 m, $F(3, 37) = 20.30$, $p < .001$, $\eta^2 = .34$.

Discussion

Experiment 4 essentially replicated the results of Experiment 2 in showing that the fog density effects observed with explicit distance estimates in static displays survived when movement-related distance cues became available and time-to-collision judgments were used to assess the perceived distance between the observer's position and the car driving ahead.

As in Experiment 2, the observer-car distance and the fog density effects interacted significantly. This time, however, the fog density effect became progressively larger as the observer-car distances were increased (with differences in the distance estimates between the lowest and the highest fog density levels of 4.69, 6.70, and 7.25 m at observer-car distances of 40, 50, and 60 m, respectively), which is the opposite of what was observed in Experiment 2 with static displays. The pattern observed in Experiment 4 is thus what one would expect if the car silhouette that becomes visible at lower observer-car distances served as a familiar size depth cue that reduces the fog density effect. We think that the difference between the results in Experiments 2 and 4 reflects the difference in the absolute levels of fog density that were used. More precisely, the highest density fog in Experiment 4 was lighter than the highest density fog used in Experiment 2 because of the requirement that the backlights of the car ahead were to be seen during the entire episode, which covered a larger distance than the maximum viewing distance in Experiment 2. In other words, the viewing conditions in Experiment 4 were never as bad as those in the high fog density conditions in Experiment 2.

EXPERIMENT 5

An aspect of the study by Cavallo et al. (2001) that has not been mentioned yet is that they investigated the difference between a single visible backlight and two backlights. This manipulation was motivated by the fact that cars may (or, as in Europe, must) be equipped with high-luminance rear fog lights, which are much brighter than ordinary backlights. However, cars may have only a single fog light, which comes into view at much larger distances than do the normal backlights. Cavallo et al. (2001) found that a single backlight resulted in larger distance estimates than did two backlights in their foggy viewing condition, which was interpreted as indicating that having two backlights facilitates use of the familiar size depth cue (henceforth *facilitation* hypothesis). Alternatively, however, it could be that the availability of only a single backlight simply induces a bias such that a smaller vehicle is "expected" if only one backlight is visible (henceforth *bias* hypothesis).

If the facilitation hypothesis were correct, then we would expect smaller distortions in distance perception by variables such as the vertical backlight position with two backlights, as compared with only one backlight. This is because use of the familiar size cue should be facilitated when two backlights are visible rather than only one, which, in turn, should counteract the distortion induced by the vertical position variable. In statistical terms, the facilitation hypothesis implies an interaction between the number of backlights and the vertical backlight position variables. If, in contrast, the bias hypothesis were correct, then we would simply expect larger distance estimates for single backlights than for pairs of backlights, independent of other variables such as the vertical backlight position. These two hypotheses were tested in Experiment 5. Another goal of this experiment was to see if we could again replicate the vertical position effect observed in Experiments 1 and 3.

Method

Participants. Participants were 42 volunteers (20 women, 22 men) recruited via posters on campus and the local media. Their ages ranged from 19 to 47 years ($M = 26$). All participants had normal or corrected-to-normal vision. The participants were tested individually and were paid for their participation.

Materials. Movies were composed as in Experiment 3 with the exception that test movies using the narrow horizontal separation were replaced by a condition in which only a single backlight was visible. The single backlight was the left backlight of the car so as to conform to German regulations concerning the placement of the rear fog lights. Along the vertical dimension the positions of the pairs of backlights and the single backlight were identical.

Procedure. The procedure was the same as that of Experiment 3.

Design. The independent variables were observer-car distance (40, 50, and 60 m), number of backlights (two and one), and vertical backlight position (low and high). All variables were manipulated within subjects. For the critical number of backlights and backlight position manipulations, we wanted to detect effects in the distance estimates that were at least of size $f = .25$, and we assumed a population correlation of $\rho = .70$ among the levels of these repeated measures variables (this is equivalent to assuming $\eta^2 = .29$ as the population effect size). An a priori power analysis showed that given desired error probabilities of $\alpha = \beta = .05$, a sample size of $N = 34$ was needed. However, we were able to recruit $N = 42$ participants so that the power $(1 - \beta)$ was .98 and thus even larger than what we had planned for.

Results

Figure 6 illustrates, as in Experiment 3, that the observer-car distance estimates increased not only as a function of the observer-car distance but also as a function of the vertical backlight position. In addition, the observer-car distance estimates were clearly larger when only one backlight was used, as opposed to two backlights.

A 3×2×2 MANOVA showed that distance estimates varied significantly as a function of the observer-car distance, $F(2, 40) = 126.04$, $p < .001$, $\eta^2 = .86$, number of backlights, $F(1, 41) = 31.20$, $p < .001$, $\eta^2 = .43$, and vertical position, $F(1, 41) = 46.31$, $p < .001$, $\eta^2 = .53$. In addition, the distance by vertical position interaction showed that the overestimation attributable to the vertical position of the backlights was more pronounced at shorter distances, $F(1, 41) = 3.65$, $p < .05$, $\eta^2 = .15$. Importantly, the interaction between vertical position and number of backlights was not significant, $F(1, 41) = 0.96$, $p > .33$, $\eta^2 = .02$. This is incompatible with the facilitation hypothesis, and it is compatible with the bias hypothesis.

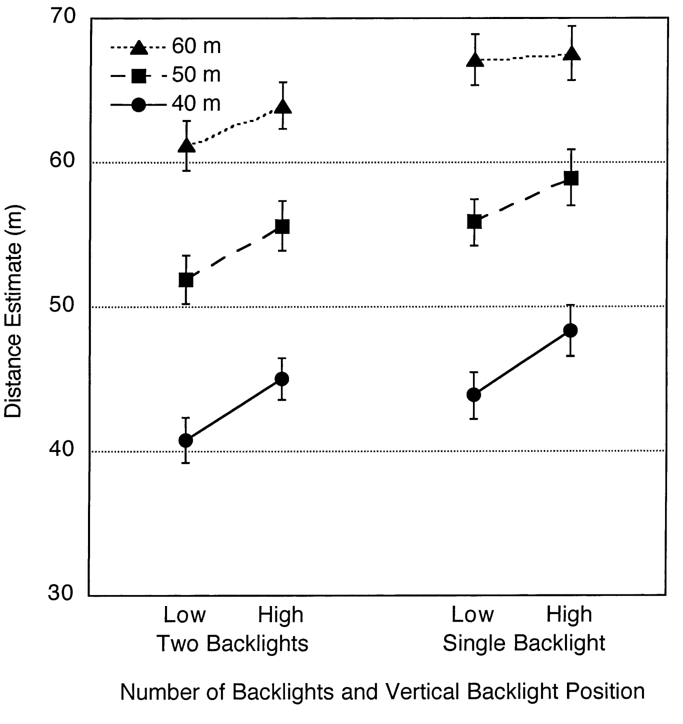

Figure 6. Mean distance estimates as a function of observer-car distance, number of backlights, and vertical backlight position (Experiment 5). The error bars represent the standard errors of the means.

Discussion

When only a single backlight was visible, estimates of the observer-car distance were increased relative to the scenarios with pairs of backlights by about 4 m, and this was so independent of the vertical position of the backlights. In other words, the availability of two backlights rather than only one backlight did not improve the distance estimation by facilitating the use of the familiar size cue. Instead it seems that viewing only one backlight biased participants toward assuming a smaller angular size of the vehicle, which was then perceived as being farther away, just as smaller cars under normal viewing conditions are perceived as being farther away (Eberts & MacMillan, 1985).

This points to a possible problem when using only a single fog backlight. However, it should be mentioned that the simulation in the present Experiment 5 as well as that of Cavallo et al. (2001) neglected the fact that in real-world driving situations, the pair of ordinary backlights would come into view at some point, so that the bias introduced by an invalid familiar size cue may be corrected. Nevertheless, it is clear that vehicles that have only a single backlight, most notably motorbikes or cars with one broken backlight, could be at a greater risk of being hit from behind because their distance from the observer is typically overestimated relative to that of other vehicles.

GENERAL DISCUSSION

The present series of five experiments replicate and extend the findings reported by Cavallo et al. (2001). The experiments replicate those earlier findings in showing large effects of both horizontal backlight separation and fog density on distance estimates in the predicted direction. The present experiments extend those earlier findings in demonstrating consistently, in three separate experiments, a vertical backlight position effect – that is, larger distance estimates as a result of higher backlight positions. Cavallo et al. (2001) had predicted this effect but failed to find it in their data. The vertical backlight position effect on the distance estimates was quite large and very reliable. It was obtained (a) independent of whether the distance estimates were performed using a familiarized analog scale or using time-to-collision judgments, (b) in both static and dynamic computer-simulated scenarios, and (c) for both single backlights and pairs of backlights.

Furthermore, the effects of horizontal separation, vertical position, and fog density were observed despite the fact that more depth cues were available in the present computer-simulated scenarios than in the simulated scenarios used by Cavallo et al. (2001) in which the fog was so heavy that nothing but the illuminated backlights could be seen. In particular, these effects were observed in the presence of pictorial depth cues such as texture gradient (road surface), linear perspective (road side lines), and familiar size (partial visibility of the car silhouette), and they were still observed when movement-related depth cues were additionally available in the dynamic episodes used in Experiment 3 to 5. All of this points to the generality of the findings reported here.

The sizes of the effects were quite large in terms of standardized effects sizes, but inductive inferences as to the possible size of these effects in real-life driving situations are of course not justified. We simply do not know how large the biasing effects on distance estimates would be while driving on a normal road. However, the present experiments together with those of Cavallo at al. (2001) suggest that there is a basis for a real problem. Cars with backlights placed closely together as well as vehicles having only a single visible backlight (cars with high-luminance fog backlights at a greater distance, cars with one backlight broken, motorbikes, etc.) will appear smaller, and thus probably farther away, as a result of which they might be approached faster and braking might begin later. Therefore, these cars could be more likely to be involved in rear-end collision accidents in foggy weather. This appears plausible because under normal viewing conditions it has already been shown that small cars appear farther away, which may well be one reason why small cars are hit from behind at a higher-than-average rate (Eberts & MacMillan, 1985).

Of course, the same may be true for cars with backlights at high vertical positions, particularly considering that car bodies get narrower near the roof, so that backlights that are positioned higher up are also likely to be positioned closer together, in which case the biasing effects of the vertical position and the horizontal separation would operate jointly. If weather and daylight conditions are such that drivers see little more than the backlights of the car running ahead, then according to the data reported here cars with backlights placed at a greater height above the road surface should be perceived as being farther away than cars with backlights placed at a lower height. In that case, the advantage of saving money by not having to replace expensive backlights after mild rear-end collisions (because they are placed higher than the area in which the damage typically occurs) may come at the price of a greater chance of involvement in a rear-end collision in the first place.

Studies such as those of Cavallo et al. (2001) and the present experiments are important in that they point to a problem that would not be obvious from other sources, such as crash databases. A first reason for this is that car-type-specific accident patterns are not readily available in crash databases such as the OECD's International Road Traffic and Accident Database (see http://www.bast.de/htdocs/fachthemen/irtad/english/irtadlan.htm). However, even if such data were available, then one would face another major problem when comparing, for instance, accident patterns for car types with low-wide as opposed to high-narrow backlight configurations. In essence, accident types associated with single car types are multiply determined. Variables such as driver type (e.g., some car types are more likely than others to be driven by high-risk drivers), seasonal driving pattern (e.g., some car types are more likely than others to be driven during the summer), and road-type-specific driving patterns (e.g., some car types are more likely than others to be driven on highways) are important determinants of accident frequencies (Schepers & Schmid, 1996). Such variables may amplify, mask, or counteract any backlight position effects to an unknown degree, such that unconfounded conclusions about the contribution of backlight position to accident risk would be impossible.

It goes without saying that biases in distance perception most likely are not the sole sources for inadequate driving behavior during fog (Hawkins, 1988). For instance, at night drivers tend to drive faster than the speed at which they could safely avoid collisions with unexpected obstacles (Leibowitz, 1988), and during foggy conditions people drive faster as the fog density increases (Snowden, Stimpson, & Ruddle, 1998). Social-psychological factors may also play a role in that drivers may feel the need to speed up in an attempt to closely follow the car ahead while being pushed toward higher speeds by the pestering lights of a car that is following them (Schönbach, 1996). However, the present experiments and those of Cavallo et al. (2001) suggest that an increase of the estimated distance to an object as a function of increasing fog density also contributes to the high accident risk when driving in low-visibility conditions.

In sum, there is reason to believe that biases in distance perception may be augmented by decisions about backlight positions and by low-visibility weather conditions.

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