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CONVEX REARVIEW MIRRORS:
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COMPLICATED THAN THEY APPEAR**

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Eric C. Traube

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

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16. Abstract <p>Convex rearview mirrors are currently prohibited in the U.S. as original equipment on passenger cars except for the exterior, passenger-side position. One of the primary reasons for this restriction is a concern that convex mirrors may cause drivers to overestimate the distances to following vehicles and therefore make unsafe maneuvers.</p> <p>There is a considerable amount of empirical evidence that convex mirrors do cause overestimation, but the effect is not theoretically well understood. No currently available model successfully predicts the magnitude of the distance overestimation. However, plausible theoretical considerations can be used to generate a previously untested prediction that, even if only qualitatively accurate, would be of practical significance: Eye-to-mirror distance should have a substantial effect on the magnitude of overestimation caused by convex mirrors. Specifically, longer eye-to-mirror distances (as are typical for passenger-side mirrors) should lead to more overestimation than shorter distances (as are typical for driver-side mirrors).</p> <p>This prediction was tested in a field experiment in which flat and convex mirrors were used on a car in both the driver-side and passenger-side exterior rearview mirror positions. Longer eye-to-mirror distance did lead to greater overestimation, although—as in previous studies—in both mirror positions the degree of overestimation was less than predicted by quantitative modeling. These results suggest that, to the extent that overestimation of distances to following vehicles is a concern for the use of convex rearview mirrors, that concern is less strong for the driver-side exterior position (which is relatively near to the driver's eyes) than for passenger-side exterior position (which is relatively far from the driver's eyes).</p>					
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Introduction

In 1982, Federal Motor Vehicle Safety Standard (FMVSS) 111 was amended to allow greater use of convex rearview mirrors on the passenger sides of cars and light trucks in the United States. The amendment also provided that when a convex mirror was used to fulfill the requirement for a passenger-side mirror it had to be marked with the warning, "Objects in mirror are closer than they appear." That warning was based on a concern that convex mirrors might cause drivers to overestimate distances, a potentially dangerous direction in which to bias judgments ("Preamble," 1982).

Although numerous formal studies have established that distance overestimation does occur (for a recent review see Flannagan, Sivak, & Traube, 1997), various questions about the nature and significance of the effect have never been fully resolved. For example, it has been argued that the overestimation caused by convex mirrors may not affect actual driving behavior when flat mirrors are also available, because drivers will recognize that convex mirrors do not provide accurate distance information and they will therefore use only flat mirrors to make distance judgments (Mortimer, 1971; Mortimer & Jorgeson, 1974). It has also been argued that drivers' perceptual adaptation to convex mirrors can substantially improve the accuracy of distance estimation with convex mirrors (Burger, Mulholland, Smith, & Sharkey, 1980; Flannagan, Sivak, & Traube, 1996).

The effect of convex mirrors on distance judgments is not well understood, even under the simplest circumstances (for example, when observers are first exposed to a convex mirror and are not likely to have adapted to it or to have adopted a strategy of compensating for the distorted distance information). No quantitative model has been proposed that is even approximately accurate in predicting the magnitude of the overestimation effect (Flannagan et al., 1997). In the absence of a satisfactory perceptual model, it is difficult to predict how such variables as the radius, size, and location of a convex mirror will affect distance judgments. Nevertheless, the formal modeling approach may be provisionally useful for guiding research. The purpose of the present study is to test the effect of a variable that, based on the best theoretical predictions available, should have a substantial effect on distance judgments: eye-to-mirror distance. This variable has particular practical significance for understanding potential differences between driver-side and passenger-side convex mirrors, because the eye-to-mirror distances involved are typically different by a factor of two.

Perceptual models

In this section we describe some aspects of image formation by convex mirrors that can be used to generate predictions about how those mirrors will affect distance judgments, and illustrate how those predictions apply to driver-side and passenger-side mirrors. Although none of the predictions that we discuss here are in even approximate quantitative agreement with previous results, it is interesting that (as we will see) they are all in qualitative agreement that convex mirrors on the passenger side (with greater eye-to-mirror distance) should make objects appear farther away than identical mirrors on the driver side.

The aspects of convex-mirror images that are most relevant to perception of distance are illustrated in Figure 1. In this example, spherical convex rearview mirrors, each with a radius of 1.4 m, are installed on the driver side and passenger side of a right-hand-drive car. The distances from the driver's eyes (assumed here for simplicity to be at a single location between what in reality would be two laterally displaced eye positions) to the mirrors are 0.6 m on the driver side and 1.2 m on the passenger side. An object with a projected width of 0.5 m is present 50 m behind the mirror location on each side of the car. The driver sees minified virtual images of the rearward objects, located behind the mirrors by a distance just slightly less than one half of the radius of curvature (approximately 0.7 m). On each side, the minification factor is 0.014 and the virtual image therefore has a width of 7 mm.

These circumstances lead to conflicting perceptual distance cues, and conflicting predictions concerning distance judgments. Consider first the driver-side mirror. The distance cue that is probably most important in this situation is the visual angle (as viewed from the driver's eye position) of the virtual image seen in the mirror. If the rearview mirror were flat, that angle would be 0.57 degrees (for a width of 0.5 m at a distance of 50.6 m), but in the 1.4-m convex mirror the combination of changes in size and location of the virtual image produces a visual angle of 0.31 degrees (for a width of 7 mm at a distance of 1.3 m). In order to form such an image, assuming that the object did not actually change size, the object would have to be at a greater distance, 93.5 m from the driver's eyes. Assuming a simple model in which the driver's perception of distance is based entirely on visual angle (and accurate memory for the actual sizes of familiar objects, such as the widths of vehicles), the object should be perceived as being 93.5 m away. The visual-angle model thus predicts that convex mirrors will lead to large overestimations of distance. However, the distortion of certain other distance cues by the convex mirror might be expected to cause an underestimation of distance.

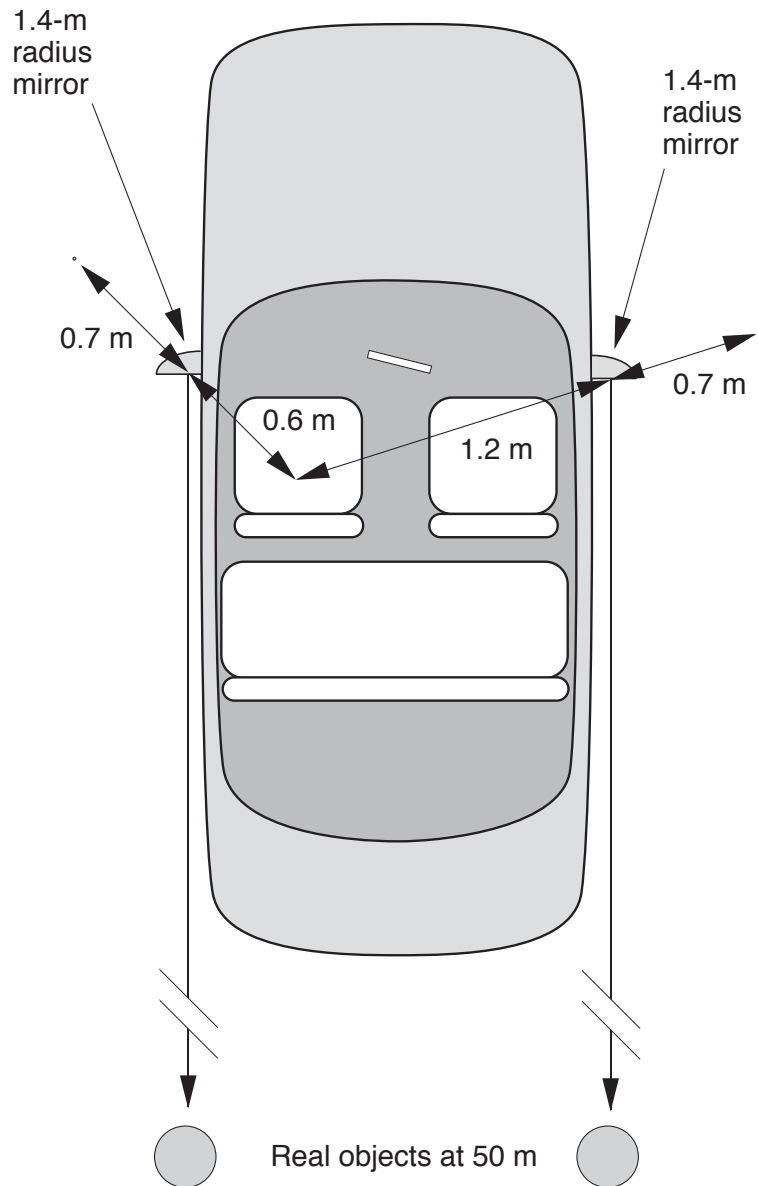


Figure 1. The locations and sizes of the objects and images involved in predicting the effects of driver-side and passenger-side convex rearview mirrors on distance judgments (approximately to scale except for the breaks indicated in the 50-m distances).

In the driver-side example in Figure 1, the virtual image is located 1.3 m from the driver's eyes. Because of this, in order to see the image as a single, fused image in proper focus the driver's eyes must actually be converged and accommodated at 1.3 m. In many situations, the binocular cues of vergence and binocular disparity, as well as

accommodation, have powerful effects on distance perception. In this case, a simple model that predicts distance perception on the basis of either binocular cues or accommodation would predict that the object would be seen as extremely close (and implausibly small). The actual distance and the two conflicting predictions for the perceived distance of the object are summarized in Table 1.

From a purely theoretical perspective, it is not clear how we should expect the conflicting cues to be resolved. However, there are at least two reasons that one might expect a rational observer to give greater weight to the visual-angle prediction. First, the prediction based on vergence or accommodation is implausibly short for objects that are normally seen in the driving environment. It is possible to imagine that, through either conscious or unconscious inference, a driver might simply reject the evidence provided by vergence and accommodation. Second, the distances about which it is most important to make judgments while driving are mostly too long (about 10 m or more) to be within the relatively short range in which vergence and accommodation are likely to be useful distance cues. It may be that drivers have learned to generally disregard those cues while driving.

Table 1
Actual distance, and two predictions for perceived distance, from the driver's eyes to the rearward objects in Figure 1. (All values in meters.)

	Location	
	Driver side	Passenger side
Actual distance	50.6	51.2
Predicted by visual angle	93.5	136.9
Predicted by vergence or accommodation	1.3	1.9

On the other hand, it does not seem safe to assume that vergence and accommodation play no role in distance perception in this context. It may be that a driver's perception of distance in a convex mirror is determined by some combination of these cues. Although most empirical results indicate that convex mirrors do in fact make distances appear somewhat longer than they actually are, the predictions of the visual-angle model have been violated in every quantitative study of the effects of nonplanar mirrors (Flannagan et al., 1997), and always in the direction that the visual-angle model

predicts greater overestimation of distance than actually seems to occur. Although the reasons for this are not fully clear, the possibility of a moderating influence of conflicting distance cues seems worth considering.

Turning now to the passenger-side mirror, the visual angle of the rearward object in a flat mirror would be 0.56 degrees (for a width of 0.5 at a distance of 51.2 m), but in the 1.4-m convex mirror it is 0.21 degrees (for a width of 7 mm at a distance of 1.9 m). The corresponding prediction for perceived distance is 136.9 m. The actual and predicted distances for both sides can be compared in Table 1.

Although both predictions based on visual angle and those based on vergence or accommodation have been violated by numerous past results, it is interesting that both methods of prediction indicate that objects should appear farther away with a convex passenger-side mirror than with an identical mirror on the driver's side. In spite of their quantitative failures, these models may in this case lead to a qualitatively valid prediction. Given the potential practical importance of a substantial influence of mirror position, and the strongly suggestive but inconclusive nature of the model-based predictions, we conducted an empirical field study to measure the effect of mirror position on distance judgments.

Method

Subjects

Eight paid subjects participated in this study. There were 4 younger subjects (ranging from 20 to 21 years old, with a mean of 20.2), and 4 older subjects (ranging from 74 to 79, with a mean of 76.2). Each age group had 2 males and 2 females. All subjects were licensed drivers.

Task

The task in this experiment was to make numerical estimates of the distance to a stationary vehicle positioned behind the observer's vehicle, one lane-width to the left or right, and seen through the left or right exterior rearview mirror. Throughout each session, subjects could see a car parked with its rear bumper 20 m in front of their eye position. They were told to consider this standard distance to be 100 units. They were told to choose whatever numbers reflected their perception of the distance to the rearward vehicle, trying to keep the numbers proportional to their perception of distance. Thus a distance that appeared half the example distance should be assigned a value of 50, and a distance that appeared one and a half times the example distance should be assigned a value of 150. This is a standard technique in the study of perception, generally referred to as magnitude estimation (e.g., Marks, 1974). Subjects' magnitude estimates are normally found to be quite systematic, although not necessarily calibrated to, or even linearly related to, measurement in conventional units.

Stimulus conditions

Sessions were conducted both during the day and at night. In the night condition there was no fixed lighting near the test site. The test cars had their low-beam headlamps and tail lamps illuminated. The locations of the three cars involved in the study are shown in Figure 2. The anchor car (used as a reference in the magnitude estimation task described above) was placed so that its rear bumper was 20 m from the subject's eyepoint. The rearward car could appear in any one of eight positions, 3.7 m (12 feet) to the left or right of the subject's car (measured center to center) and either 20, 30, 40, or 50 m behind the subject's car (measured from the exterior rearview mirrors of the subject's car to the front bumper of the rearward car).

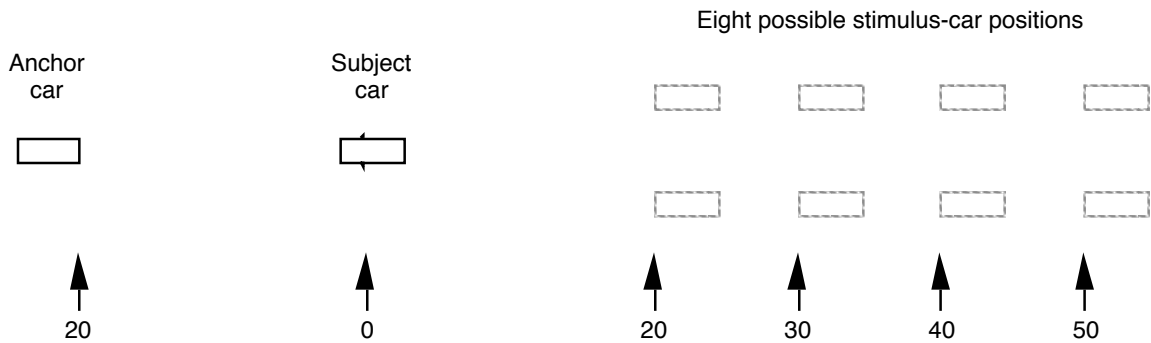


Figure 2. A diagram of the field setup, approximately to scale, showing the relative positions of the three cars. (The eight possible positions for the stimulus car are shown.) The positions of the two exterior rearview mirrors are shown on the subject's car. All cars faced in the same direction (left in this diagram). Numbered arrows indicate distances in meters from the subject's eyepoint.

Mirrors

Standard exterior rearview mirrors were used. The two sides were always matched—both flat, or both spherical convex with a radius of 1.4 m. The convex mirrors were marked with the standard warning about distortion of distance, but it was covered by black tape, which slightly reduced the vertical field of view. The interior rearview mirror was covered.

Procedure

Subjects participated individually. Each subject participated in two sessions, one during the day and one at night. The sessions were always on consecutive days. Half the subjects participated in the day session first, and half participated in the night session first.

Each subject was assigned to sit in either the driver seat or the front passenger seat of the subject's vehicle, and used that seat throughout both sessions. An equal number of subjects of each combination of age group and sex were assigned to each seating position. Because of this, the eye-to-mirror distances (near and far) were independent of the sides of the vehicle (driver side or passenger side). For half the subjects the driver side was the near side, and for the other half it was the far side. We balanced positions this way so that any asymmetrical aspects of the vehicle or its setting (e.g., presence of

the steering wheel only on the driver side, different backgrounds on the left or right) could not contribute to an overall effect of eye-to-mirror distance.

At the beginning of each session, subjects were instructed to seat themselves comfortably in the driver's seat and to adjust the seat track to a comfortable position. The subject's car had a manual seat adjustment with only fore-to-aft movement. For subjects who would use the front passenger seat, this adjustment was then transferred to that seat, and they moved to the passenger seat for the rest of the session. Eye-to-mirror distances were measured for both mirrors at the beginning of each session.

The subject's car and the forward anchor car remained stationary throughout the session. Each of a series of trials began with the subject looking forward, at the anchor car, and holding up two cards to block his or her views of the exterior rearview mirrors. The rearward car was moved into one of the eight positions it could occupy, and the subject was told to lower the cards and look toward either the driver-side or passenger-side mirror (whichever was appropriate for the position of the rearward car), and to make a numerical estimate of the distance to the rearward vehicle (as described previously).

Each session consisted of 32 trials, in 4 blocks of 8. Distance to the rearward car (20, 30, 40, or 50 m) and the side of the subject's car to which the rearward car appeared (driver side or passenger side) were varied randomly from trial to trial in such a way that the eight combinations of those two variables appeared once in each block. Mirror type (flat or convex) was constant for each block and was changed between blocks according to one of two schedules, balanced over subjects (either CFFC or FCCF for the four blocks, where C indicates convex and F indicates flat). For any one block, the type of mirror was the same on both sides of the car (both flat or both convex). Mirror aim was adjusted by the subjects each time the mirrors were changed; they were instructed to aim the mirrors so that the rear corner of their own vehicle was just visible at the inboard edges of the mirrors.

Results and Discussion

Eye-to-Mirror Distances

An analysis of variance was performed for eye-to-mirror distance, using age group (young or old), seating position (driver or passenger), session (first or second), and relative mirror position (same side or opposite side from the seating position) as independent variables. The effect of mirror position, shown in Table 2, was highly significant, $F(1,4) = 1018.7$, $p < .0001$. The interaction between seating position and relative mirror position was marginally significant, $F(1,4) = 10.3$, $p = .0327$, and is shown in Figure 3. Subjects in the passenger seat tended to be closer to the same-side mirror and further from the opposite-side mirror than subjects in the driver seat, as if they were sitting further from the midline of the vehicle. Inspection of the vehicle did not suggest why this might have been the case, and the effect is relatively small. The eye-to-mirror measurements suggest that the attempt to manipulate mirror distance independently from driver versus passenger side of the car was largely successful. No other variables had an effect. For example, the same-side and opposite-side distances were nearly identical for the young and old groups, as shown in Figure 4.

Table 2
Average eye-to-mirror distance for same-side and opposite-side mirrors, averaged over seating position (driver side or passenger side).

Mirror position	Distance (mm)
Same side (near)	651
Opposite side (far)	1226

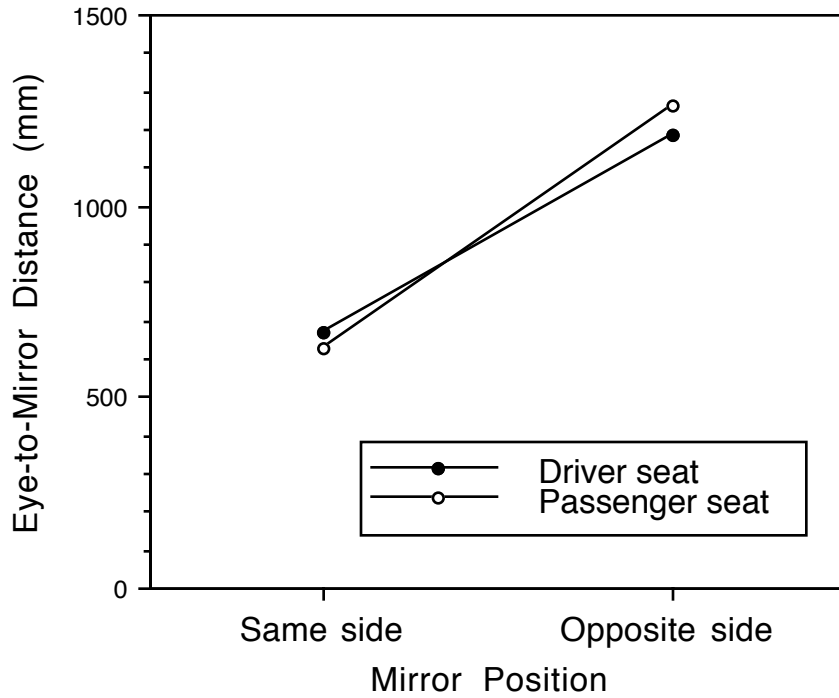


Figure 3. Eye-to-mirror distance for each combination of the participant's seat position, and position of the mirror relative to that seat position.

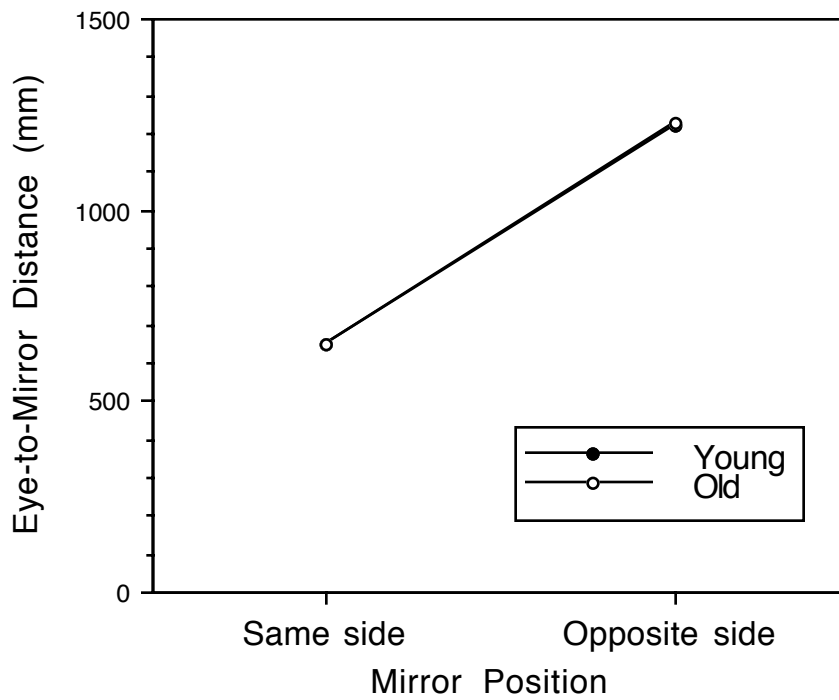


Figure 4. Eye-to-mirror distance for each combination of side of the vehicle and participant age group. The data for the young and old groups are difficult to distinguish in this graph because they are nearly identical.

Distance Estimates

An analysis of variance was performed for distance estimates, using age group (young or old), time of day (day or night), actual distance (20, 30, 40, or 50 m), mirror type (flat or convex), and mirror relative position (same side or opposite side) as independent variables. Overall, estimates were a linear function of actual distance, as shown in Figure 5. The analysis of variance indicated that this effect was highly significant, $F(3,18) = 94.2, p <.0001$. The dashed line in Figure 5 indicates where data would fall if subjects' judgments were in perfect absolute calibration with the magnitude estimation standard provided by the forward car (which was 20 m away and assigned the value 100 for anchoring the subjects' magnitude estimates). On average, subjects gave lower estimates than the standard indicated.

There were significant main effects of both mirror type, $F(1,6) = 69.4, p =.0002$, and mirror relative location, $F(1,6) = 8.87, p =.0247$. Distance estimates were longer for convex than for flat mirrors (165 versus 128), and for opposite-side mirrors than for same-side mirrors (150 versus 142).

There was little evidence that time of day affected distance judgments. The main effect of time of day was not quite significant, $F(1,6) = 5.15, p =.0637$. As shown in Figure 6, the effect of mirror type was nearly identical in the night and day conditions.

There was a significant interaction between mirror type and actual distance, $F(3,18) = 10.8, p =.0003$. The effect is shown in Figure 7. The overestimation with convex mirrors, relative to flat mirrors, seems to be greater at greater actual distances.

Figure 8 shows the effect of most interest—the interaction of mirror type and mirror relative position. This effect was highly significant, $F(1,6) = 44.6, p =.0005$, and is qualitatively in good agreement with the predictions outlined in the Introduction. As expected, mirror relative position has little or no effect on distance judgments when the rearview mirrors are flat. But when the mirrors are convex, the opposite-side (longer eye-to-mirror distance) location leads to substantially more overestimation of distance (relative to judgments with the flat mirror) than the same side (shorter eye-to-mirror distance) location. Overestimation of distance caused by the convex mirrors (estimates using the convex mirrors divided by estimates using the flat mirrors) is quantified in Table 3. Consistent with previous results, the amount of overestimation is substantially less than that predicted by the visual-angle model in Table 1, for both same-side and opposite-side positions. (The predictions in Table 1 apply to conditions that are very similar to, but not identical to, the conditions of this experiment. Using actual eye-to-mirror distances, shown in Table 2, and actual vehicle distances, the overestimation

proportions in Table 3 should be 1.91 and 2.68 for same side and opposite side, respectively.) However, in qualitative agreement with predictions based on visual angle and those based on accommodation and convergence, overestimation with opposite-side mirrors is almost twice as great, in percentage terms, as overestimation with same-side mirrors.

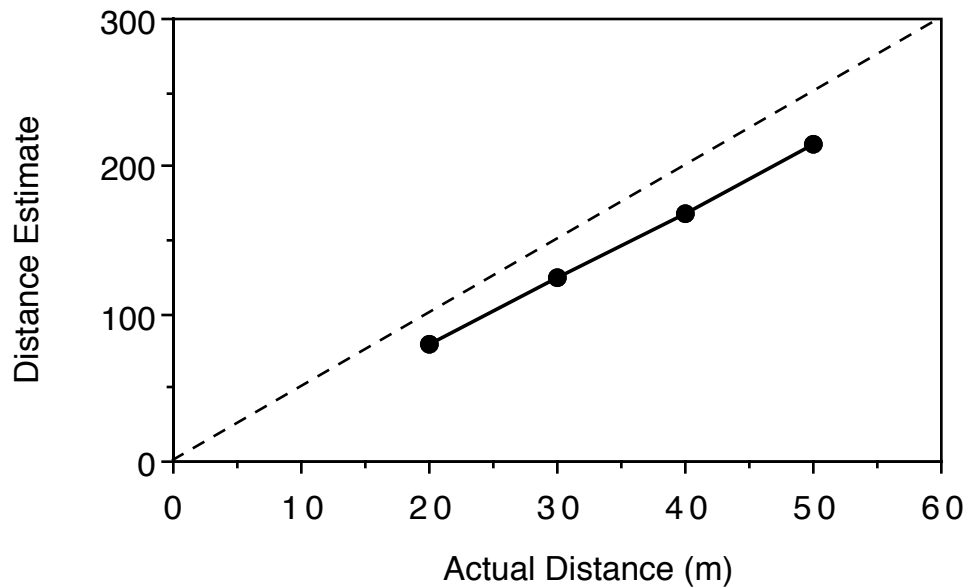


Figure 5. Distance estimates as a function of actual distance, averaged over all other independent variables. The dashed line indicates where data would fall if subjects' judgments were in perfect absolute calibration with the magnitude estimation standard provided by the forward car.

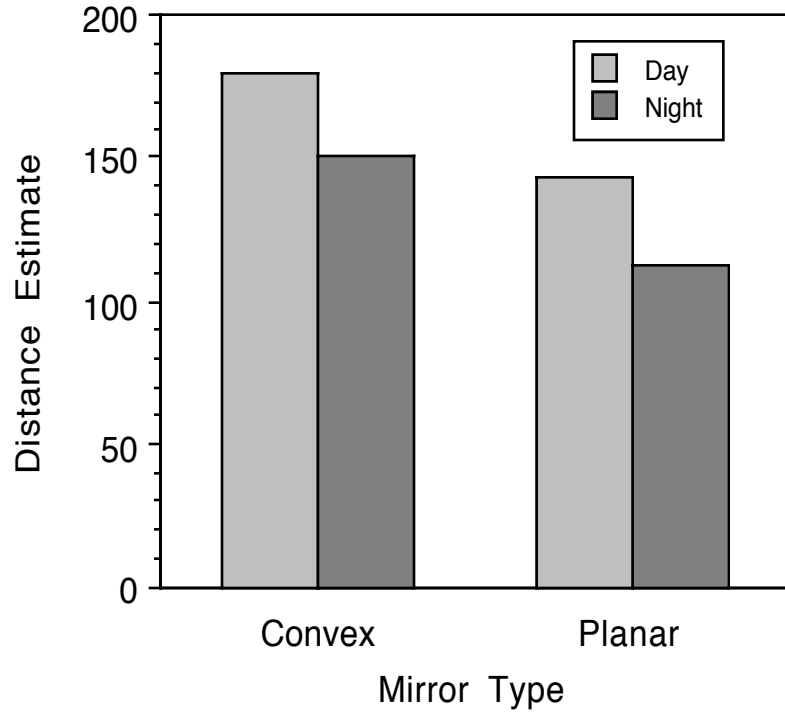


Figure 6. Distance estimates for each combination of mirror type and time of day. The effect of mirror type was the same under both light conditions. The tendency for judgments to be longer in the day was not statistically significant.

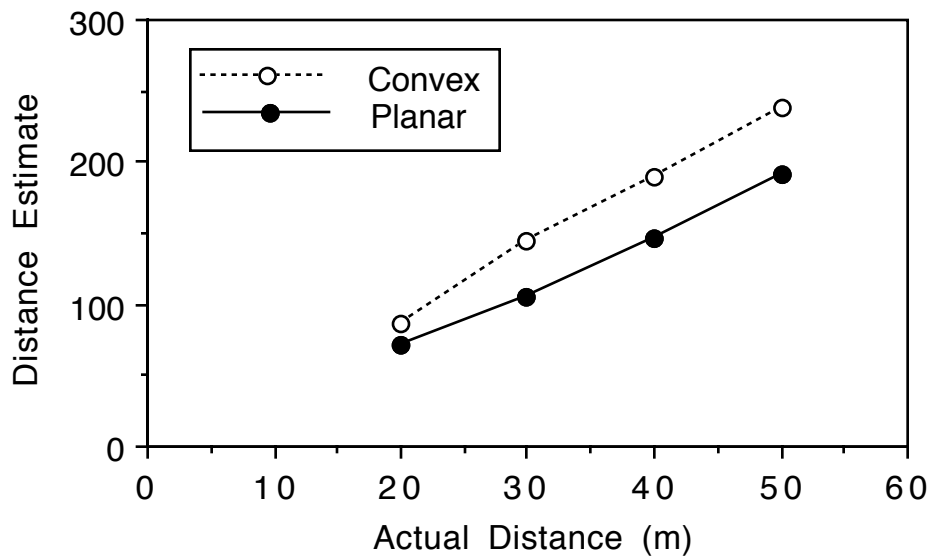


Figure 7. Distance estimates as a function of actual distance, shown separately for the convex and planar mirrors.

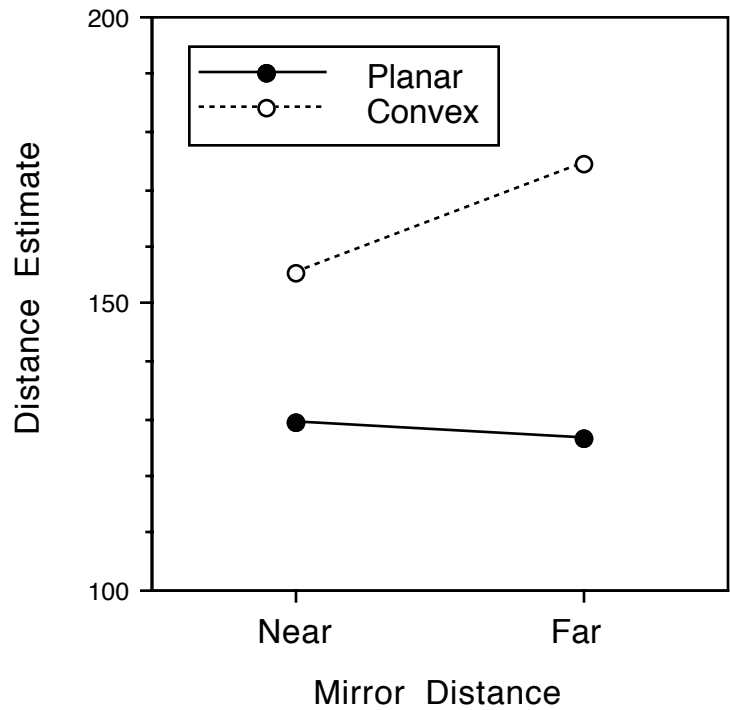


Figure 8. Distance estimates for each combination of mirror type and eye-to-mirror distance.

Table 3
Overestimation of distance (estimates using the convex mirrors divided by estimates using the flat mirrors) for same-side and opposite-side mirrors.

Mirror position	Overestimation index
Same side (near)	1.20
Opposite side (far)	1.38

Summary and Conclusions

The results reported here indicate that eye-to-mirror distance has a strong effect on the degree of overestimation of distance produced by convex rearview mirrors. Under the conditions of this experiment, a convex mirror at a distance that is typical of passenger-side rearview mirrors produced overestimation of distance that was, in percentage terms, about twice as great as that produced by the same mirror at a distance that is typical of driver-side rearview mirrors. Although a variety of factors need to be considered in determining the desirability of using convex rearview mirrors on the driver side, the fact that a major possible problem with convex mirrors—overestimation of distance—is more pronounced on the passenger side, suggests that adopting convex mirrors on the driver side would be less of a change than adopting them on the passenger side was in 1982.

Although the distance estimates observed in this experiment were not quantitatively in agreement with the predictions of the simple models of distance perception outlined in the Introduction, they were qualitatively in agreement with those predictions. These results therefore reinforce the conclusion that those models are not fully satisfactory, but also indicate that they have some predictive value.

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