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Convex rear view mirrors compromise distance and time-to-contact judgements

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Convex rear view mirrors increasingly replace planar mirrors in automobiles. While increasing the field of view, convex mirrors are also taken to increase distance estimates and thereby reduce safety margins. However, this study failed to replicate systematic distance estimation errors in a real world setting. Whereas distance estimates were accurate on average, convex mirrors lead to significantly more variance in distance and spacing estimations. A second experiment explored the effect of mirrors on time-to-contact estimations, which had not been previously researched. Potential effects of display size were separated from effects caused by distortion in convex mirrors. Time-to-contact estimations without a mirror were most accurate. However, not distortion, but visual angle seemed to cause estimation biases. Evaluating advantages and disadvantages of convex mirrors is far more complex than expected so far.

Keywords: Rear-view mirror; Convex mirrors; Time-to-contact; Distance estimation

1. Introduction

Mirrors have become a common tool for everyday activities, such as shaving or driving. However, surprisingly few studies exist that explore perceptual abilities with regard to mirror images. The existing studies tend to focus on static perception while neglecting motion. The present study was carried out to establish the extent to which distances and temporal events are distorted when the only perceptual access to a relevant object is through a mirror.

The human factors implications of such research are far-reaching. This paper first summarizes the human factors of rear-view mirrors, then touches on basic research on mirrors and finally reports two experiments, one with stationary objects and one with moving objects viewed through mirrors of different convexity.

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1.1. *Human factors of rear-view mirrors*

Convex mirrors are widely recognized to be helpful devices for the acquisition of indirect vision (e.g. Moukhwas 1987, Mourant and Donohue 1977). In cars, convex passenger-side mirrors may not have much advantage over planar mirrors (for an overview, see Ayres *et al*. 2005), whereas convex driver-side mirrors have been reported to reduce the number of accidents (Luoma *et al*. 1995, 2000). In 2002, an EU commission proposed a reduction of the radius of convex driver-side rear view mirrors from 1800 mm to 1200 mm. The reason was a desired reduction of the blind area to enhance safety. The blind area is defined as: 'the area around a vehicle [. . .] that is not visible to the operators, either by direct line-of-sight or indirectly by use of internal and external mirrors' (Beaupre *et al*. 2003).

The US Department of Transportation regulates driver side rear-view mirrors to have a curvature between 889 mm and 1651 mm. There are very different opinions about the optimal curvature for rear view mirrors. The recommended radii range from about 900 mm to 1800 mm, as recommended by different international departments. A radius of 1800 mm was formerly preferred in Europe. Notwithstanding this rather detailed recommendation, owners' manuals warn that objects in convex mirrors are closer than they appear. In some countries, passenger side mirrors even have a warning to this effect printed on the mirror surface itself. The ubiquity of these warnings stands in stark contrast to the paucity of empirical research on distance perception in convex mirrors. It is largely unknown to what extent the distortions introduced by convex mirrors affect perception, with some notable exceptions. Fisher and Galer (1984) reported that smaller radii decreased driver safety margins when confronted with videotaped scenes. Higashiyama and colleagues found that convex mirrors do cause distance overestimation (Higashiyama *et al*. 2001, Higashiyama and Shimono 2004). It is unknown, however, if higher degrees of convexity cause more distortion and if distance is overestimated in all situations and contexts. Moreover, to the authors' knowledge, quantitative analyses of distance estimation errors and time-to-contact (TTC) estimations have not yet been carried out.

1.2. *General perceptual problems with mirrors*

Concerning static perception in mirrors, it is known that it is very difficult for humans to predict at what point an object will become visible to an approaching observer (Croucher *et al*. 2002, Bertamini *et al*. 2003, Hecht *et al*. 2005). Overestimations of the size of the reflected area are prevailing; that is, the typical observer walking parallel to a mirror hanging on a wall thinks that he/she begins to see his/her mirror image sooner than is actually the case. These results were found with different methods, such as paper-and-pencil tasks, fake mirrors and computer simulations with and without animation. Furthermore, there seems to be a high tolerance for incorrect reflections as well as for distortions. Even the correct knowledge of the laws of reflection or expertise with mirror laws often fails to reduce the large deviations from actual mirror reflection that observers are willing to tolerate.

Distance estimations on the basis of convex mirrors may be problematic because such mirrors reflect and distort at the same time. As early as 1930, Oliver Weber experimented with curvilinear mirrors and found adaptation effects (Weber 1931). Observing objects in concave and convex mirrors can alter the perception of objects in planar mirrors or the real world. Distortions are likely to hinder the assessment of absolute as well as of relative distances. Likewise, for moving objects, Fisher and Galer (1984) pointed out that: ‘varying the curvature of convex mirrors distorts not only the rate of change of image size of target vehicles, but also of the entire optical flow field surrounding the target’.

Two experiments to supplement and expand the existing controversial findings were conducted. The first experiment concerned static distance estimations with the goal to replicate Higashiyama *et al.* (2001) while employing direct estimations of distances from the observer and distances between objects in a real scene.

The second experiment concerned motion perception in mirrors and built on Fisher and Galer’s (1984) findings that when observers judge the last moment to safely carry out a driving manoeuvre, the use of convex mirrors causes this point to be later in time. This finding implies that convex mirrors should increase TTC estimates. This hypothesis was tested by having observers make direct TTC estimations on the basis of computer-generated stimuli. David Lee (1976) formulated the so-called tau-theory, which suggests that people do not need information about distance, speed or acceleration to be able to compute the exact time of an impending collision. Instead, they use information about the relative rate of expansion of the object’s retinal image, which is extracted from the optical flow field. This optical information directly specifying TTC has been called tau. A driver, for example, might start to brake when tau reaches a special critical value. Hecht and Savelsbergh (2004) discuss additional processes that could modify the initial tau estimate. Variables such as perceived size and size change, binocular perception and the change of an object’s shape seem to influence TTC estimates. Thus, it is quite conceivable, although not foreseen by Lee’s theory, that TTC estimates are compromised by convex mirrors in spite of the tau parameters being unchanged.

2. Experiment 1

The first experiment was conducted to replicate the finding that convex mirrors lead to an overestimation of distances and to further examine potential perceptual biases when judging distances on the basis of convex mirrors. The question of distance distortion was addressed with an absolute distance estimation task using different mirrors. Higashiyama *et al.*’s (2001) results imply that targets in convex mirrors appear to be farther away than in planar mirrors. Their findings were reassessed with a more direct estimation method. Furthermore, a closer look was taken at the influence of convex mirrors on the perceived spacing of two objects. If all dimensions of the world are affected by mirror distortion (Fisher and Galer 1984), the perceived position of two objects in space should also be affected by convex distortion.

Two different hypotheses were tested. First, the smaller the radius of a convex mirror (the larger the curvature) the farther objects should appear to be from the observer because the scenes in those mirrors are compressed. Second, in the same manner convexity of mirrors should lead to an overestimation of lateral spacing of objects.

2.1. *Method*

2.1.1. Participants. A total of 29 participants (nine male, 20 female) volunteered for the study. Their age ranged from 17 to 63 (mean 27.43) years. Most of them were students at the Johannes Gutenberg University in Mainz, Germany. Participants had normal or corrected-to-normal vision. Participants were tested individually. The purpose of the study was not revealed to them until after their data had been collected.

2.1.2. Apparatus and stimuli. The experiment was conducted outdoors on a field covered with gravel. The field's dimensions were approximately 55×45 m. It was selected because it provided a level surface without any salient landmarks or orientation points. Participants had not seen the field before the experiment nor knew its dimensions. The participants sat in front of the mirror and were asked to look into it. Their eye point was level with the mirror's centre but displaced to the right of the mirror's centre by 45°. The distance between the participants' interpupillary point and the mirror was 0.7 m.

Pairs of wooden poles were positioned on the field, one pair at a time. All individual poles varied randomly in length and width to remove shape and size cues.

Three different circular mirrors each with a diameter of 36 cm were used. Their curvature radii were indefinite (planar mirror), 1800 mm and 800 mm. Mirrors were made of float glass coated with a mirror layer and attached to a wooden frame. The visual angle was about 29°.

2.1.3. Design. Distance of the poles from the observer and their spacing were varied within participants. There were three different distances (10, 30 and 45 m). The poles of a given pair were always placed an equal distance to each side of the observer's line of sight, the distance to the observers was measured from a virtual point exactly between the poles. The poles could be spaced at 2, 4 and 6 m. Fully crossed, distance and spacing produced nine combinations of distance and pole spacing. Mirror curvature was varied between participants. Three different groups were tested. One group (ten participants) used a planar mirror, a second group used the 1800 mm convex mirror (ten participants) and the third group used the 800 mm convex mirror (nine participants). Thus, two within-subject factors (distance and spacing) were complemented with one between participants factor (mirror curvature).

2.1.4. Procedure. A distance of 5 m was shown to the participants as a reference. This distance was given not in the mirror, but in the real world and was visible to them all the time during the experiment. After having received instructions, participants were asked to estimate the distance (in m) from themselves to the imaginary midpoint between the poles. Note that the poles were placed behind the observers while already seated in front of the mirror with closed eyes. Then observers were asked to estimate the distance between these two poles (see figure 1). The order of distances and spacings was determined at random. The same random order was followed for all participants.

Participants could not see themselves or other persons, including the experimenter, in the mirror.

2.2. *Results*

Figure 2 shows the average estimation errors. Even though a trend for errors to be larger with convex mirrors can be seen upon close inspection, this trend did not reach significance ($p > 0.1$) according to a repeated measures ANOVA.

As seen in figure 2, distances tended to be underestimated. In the planar mirror judged distances were smaller than the target distance (t tests on errors were significant for all distances, $3.86 < t < 5.27$), whereas distances in convex mirrors were not significantly different from zero in any of the distance conditions. Thus, it could not be shown that participants systematically overestimated distances in the convex mirrors. Also, a repeated measures ANOVA brought no significant effects of mirror type on distance estimation ($F(1, 26) = 0.924$, $p = 0.410$). When underestimation was expressed in percent

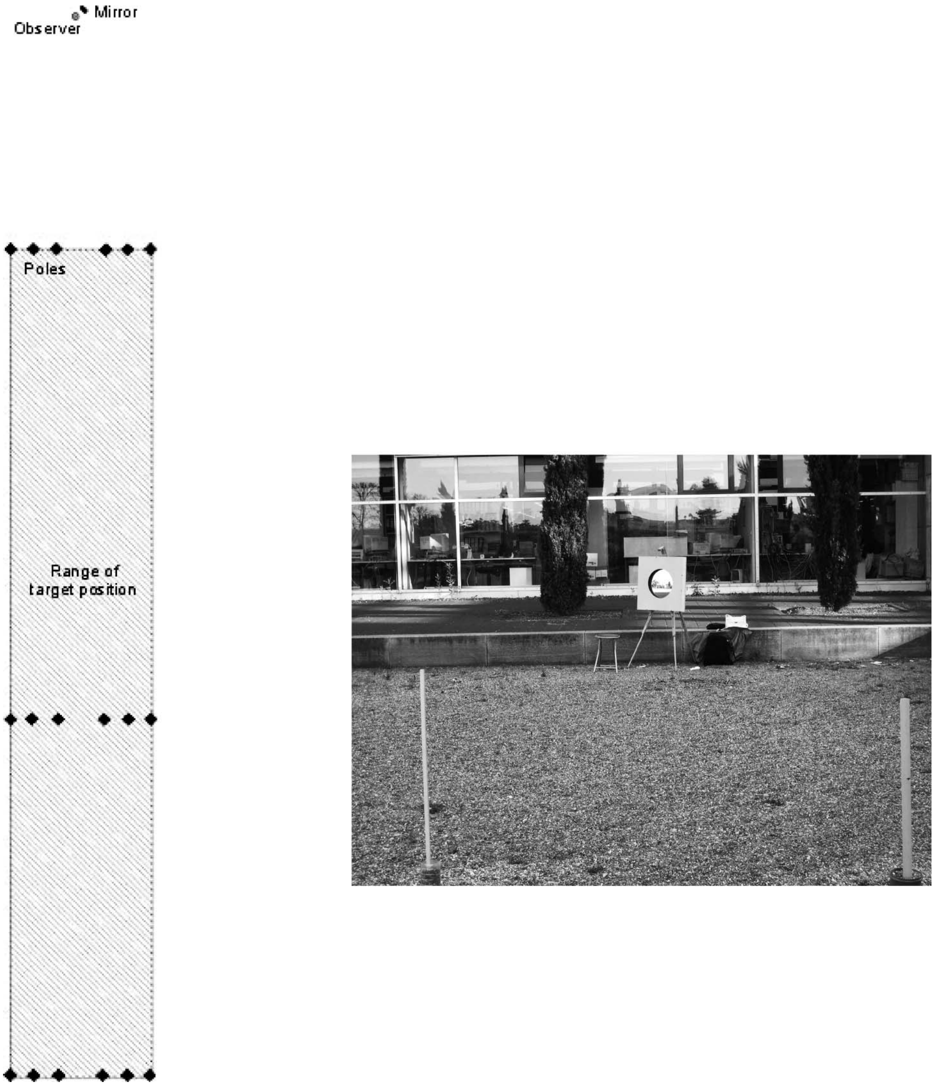

Figure 1. Schematic view of terrain layout and photograph of setup. In three different mirrors (radius: infinite; 800 mm; 1800 mm) participants saw poles on a gravel-covered field. They had to estimate (in m) the distance to the poles and the spacing of the poles.

of the actual distance, no differences between target distances were found. With regard to the spacing estimates, observers tended to overestimate the distance between the poles; however, this tendency did not reach significance ($F(2, 29) = 2.710$, $p = 0.085$).

The variability of the estimates was analysed separately. Whereas the average estimation errors were unaffected by mirror curvature, the variability in the responses suffered markedly for convex mirrors compared to the planar mirror. Exemplar estimate distribution for the second estimate of the 10 m target is shown in figure 3. The variances of estimations differed systematically with the type of mirror as indicated by Levene tests of equality of variances. Comparing the estimation variances in the planar to those in the most convex mirror separately for each distance estimation, results showed variance to

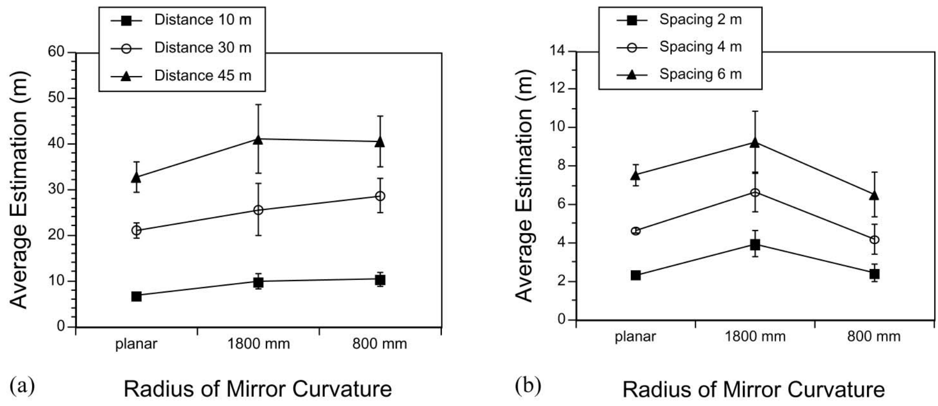

Figure 2. (a) Distance estimations by mirror type. Distances were 10, 30 and 45 m. Average distance estimation errors and standard errors of the mean are plotted; (b) Spacing estimations by mirror type. Spacings were 2, 4 and 6 m. Average spacing estimates and standard error of means are plotted.

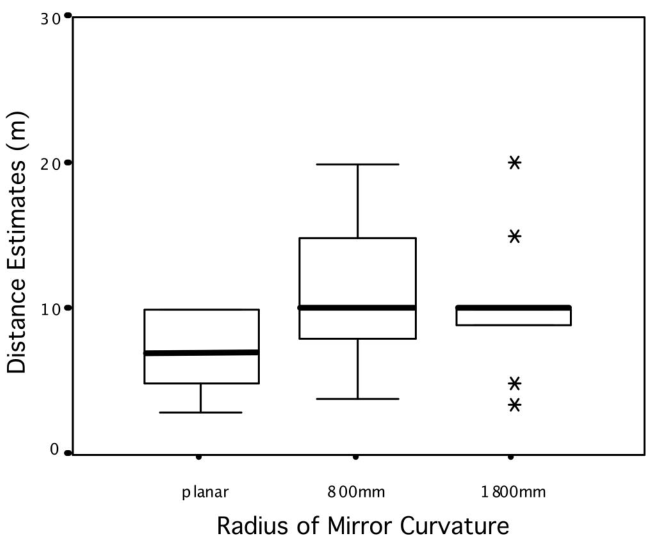

Figure 3. Variability of distance estimates for the 10 m target as expressed by the box plot. The bold line represents the median, the box contains 50% of observations, the bars contain roughly 90%. *Indicate outliers.

increase with convexity (F(9.192), $p = 0.008$ for near distances), (F(3.555), $p = 0.077$, for intermediate distances); and (F(1.863), $p = 0.190$, for large distances). Likewise, variability increased from the planar to the 1800 mm convex mirror (F(3.371), $p = 0.083$; F(5.831), $p = 0.027$; and F(4.808), $p = 0.042$ for the respective distances). The comparison of the variances between the two convex mirrors failed to show significant results. Thus, while curvature of the mirror increased distance estimation variability, a stronger curvature of the mirror had no additional effect.

A comparison of the planar to the convex mirror with a curvature of 1800 mm with regard to the variability of spacing estimations led to highly significant results (F(17.748), $p = 0.001$), (F(24.375), $p < 0.001$) and (F(11.492), $p = 0.003$). Comparing the planar to the most convex mirror, results were (F(3.826), $p = 0.067$), showing a tendency, (F(7.427), $p = 0.014$) and (F(4.585), $p = 0.047$), both being significant. Again, the comparison between the two convex mirrors failed to reach significance (F(3.762), $p = 0.069$).

2.3. *Discussion*

The experiment failed to replicate the findings of Higashiyama *et al.* (2001), as no systematic overestimation of distances with convex mirrors could be shown. Instead, the results show that convex mirrors lead to significantly more variance in both distance and spacing estimations, with spacing estimations being affected more clearly. It was found that the variance of distance estimations increased with convex mirrors. Thus, it could be shown that more convex mirrors may produce the same average distance estimates as do planar mirrors, but convexity leads to larger variability of these estimates and thus to larger errors in both directions. Note that the mirror curvatures were tested between groups. It is thus hard to determine whether all observers will produce more variable estimates when confronted with convex mirrors. However, the relatively large number of outliers suggests that some observers are affected more than others, maybe due to a lack of training with convex mirrors. In older cars in Germany, as owned by many students, the driver-side mirror is still planar.

A caveat: It was decided to keep mirror size constant at all times. This has resulted in visual angles (e.g. between the two poles of a pair) being smaller in the convex than in the planar mirrors. This could be a potential confounder, which may exert an unduly large influence. It is not possible to avoid the confounder in a real-world setting without changing the position of the mirror. However, future computer-generated experiments could vary mirror shape and image size independently.

It is conceivable that the reference distance being given in the real world but not in the 'mirror world' had an impact on judged distances. It was decided to provide a real world standard in order to calibrate judgements to a reference that was free of distortions. This decision was based on the rationale that, if anything, a mirror-world standard should improve performance. Thus, the world reference is considered to strengthen the interpretation of the data toward convexity not changing the average estimated distance.

It is possible that this study failed to find a systematic overestimation of relative distances in convex mirrors because the farthest distance did not exceed 45 m. Higashiyama and Shimono (2004) suggest that the size constancy mechanism is just starting to break down at this range. It may be that up to 45 m, distance and size or spacing estimates are relatively unaffected by distortion. Surpassing the 45 m mark may then lead to more serious estimation errors. Be this as it may, an exploration of dynamic stimuli in mirrors was considered to be more revealing.

3. Experiment 2

TTC estimations of mirror objects have not been reported, with the possible exception of Fisher and Galer's (1984) study, in which they solicited judgements that reflect contact times. It was decided to collect direct TTC estimates with a standard prediction motion paradigm in which observers saw an approaching object in a mirror. After a few seconds, the object was occluded and a response had to be made at the moment of the would-be collision with the observer.

It was hypothesized that mirrors make TTC estimations more difficult. Errors and delay in reactions might arise from the unusual viewing situation. Although tau theory does not predict any mirror effects (the optical information for TTC remains unaffected by distortion), the hypothesis is based on the rising number of studies that show how extraneous variables, such as object size, exert an influence on timing accuracy (see DeLucia 1999, Hecht and Savelsbergh 2004). As mirrors shrink the image in comparison to a view through a window, potential effects of size and visual angle have to be carefully separated from effects caused by distortion in convex mirrors.

3.1. *Method*

3.1.1. Participants. Eight participants were tested; seven of them female and one male. Their age ranged from 23 to 36 (average 28.9) years. All but one of them were psychology students at the Johannes Gutenberg Universität Mainz, Germany. Participants had normal or corrected-to-normal vision. Half of them had already participated in experiment 1. None of the participants had expertise in a TTC sport such as volleyball or badminton.

3.1.2. Apparatus and stimuli. A computer simulation of approaching vehicles was used to test TTC estimation. Two circular mirrors, each with a diameter of 36 cm, were used to view the display indirectly. Their curvature radii were indefinite (planar mirror) and 800 mm. The mirrors were made of float glass coated with a mirror layer and mounted on a wooden frame. They were put onto an easel such that their edges were covered by an occluder with a circular opening.

In the simulation, which was programmed using the language Python (and Vizard), a red car drove on a country road. It approached the participant and was occluded before it 'reached' the observer. The speed of the car and the timing of the occluder were varied. The on-time of the stimulus was 3 s in all cases.

3.1.3. Design. Six different viewing conditions were blocked within subjects. Three viewing conditions were mirror manipulations while the other three controlled for visual angle: direct view of the monitor, indirect view via a planar mirror, via a convex mirror, direct view of a remote monitor, direct view with reduced display size 1 and direct view with reduced display size 2 (see table 1). The orders in which the blocks were seen were counterbalanced between subjects. The last two conditions were tested on a separate day. The participants' task was to press a mouse button at the time they thought the car would have reached the participants' position.

For each viewing condition, a block of 80 randomly ordered trials was presented. The trials varied in starting position and speed of the car as well as in the absence or presence of a truck serving as a task-irrelevant distractor. Four different starting positions of the car were crossed with four different approach speeds. The resulting 16 trials were presented five times, once with a truck moving in the same direction as the car, once with a truck moving in the opposite direction and three times with no truck present The speed of the truck was varied randomly to be within 50% faster or slower than the car. If present, the truck remained visible until a response by the participant had been made.

Table 1. Visual angles and viewing distances for each condition of the experiment.

Condition	Visual angle (°)	Viewing distance from mirror/screen (m)	TTC estimate
1. monitor	25.75	0.7	accurate
2. planar mirror	14.65	0.7	~100 ms late
3. convex mirror	4.9	0.7	~100 ms late
4. remote monitor	4.9	3.7	>200 ms late
5. reduced display size 1	14.65	0.7	~100 ms late
6. reduced display size 2	4.9	0.7	~300 ms late

TTC = time-to-contact.

In the first condition, the participants sat straight in front of the monitor. The distance between the participants' interpupillary point and the screen was 0.7 m. They were free to move their heads without restriction. In the second condition, a planar mirror was placed on an easel in front of the screen such that the participant who sat next to the monitor facing rearward could only see the reflection of the scene in the mirror but not the monitor. A right–left reversal of the simulation was generated to compensate for the scene reversal of the mirror. The distance between mirror and eyes was 0.7 m to match distance between mirror and screen in the first condition. The third condition was exactly as the second one, but a convex mirror with a curvature of 800 mm was mounted onto the easel. In the fourth condition, remote monitor, the participant sat at a distance of 3.73 m from the screen and had to perform the task from this distance without a mirror. With this viewing distance the visual angle of the scene yielded by the convex mirror condition was matched. It was decided to add two more control groups in order to provide matching visual angles for the planar and convex mirror conditions by means of reducing the size of the display rather than increasing the viewing distance. The initial participants agreed to come in again for this testing.

The sequence of the first four conditions was assigned for each subject using the Latin squares method. The last two conditions were presented in both orders, each to one half of the participants.

3.1.4. Procedure. Before the experiment, participants were given instructions and practice. The practice consisted of 20 trials of an approaching car and was conducted without a mirror. After each practice trial a numerical feedback (in ms) was given to the participants. Negative numbers meant that the reaction came sooner than the would-be collision, while positive numbers meant that the TTC was overestimated. After practice, the randomly assigned sequence of trials was tested without providing any feedback. Participants pressed a mouse button to initiate the next trial and were free to take breaks any time. A small questionnaire assessed sex, age, field of study, expertise in sports and handedness. Finally, eye dominance was tested.

3.2. *Results*

As shown in figure 4, only TTC estimations that were made without any mirrors or size manipulations were accurate. Planar and convex mirrors equally caused TTC estimates to be late. The control conditions that presented reduced-size scenes produced even larger TTC errors on the late side.

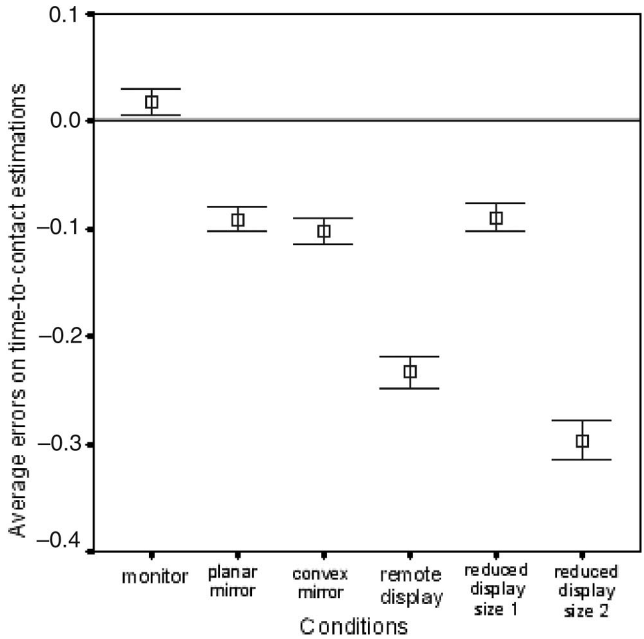

Figure 4. Average errors (s) on time-to-contact estimation. Positive numbers mean early reactions, negative indicate overestimations of time-to-contact. Means and standard error of means are plotted.

A repeated measures ANOVA showed that TTC was estimated best in the condition without a mirror, which differed significantly from the planar mirror condition ($F(1,7) = 6.40$, $p = 0.0393$), the convex mirror ($F(1,7) = 6.50$, $p = 0.0381$), the remote condition, ($F(1, 7) = 6.661$, $p = 0.0369$) and from reduced display size 2 ($F(1, 7) = 15.13$, $p = 0.0060$), but failed to reach significance with the fifth condition, reduced display size 1 ($F(1, 7) = 3.08$, $p = 0.1228$). Estimation of TTC with the planar mirror only differed significantly from the no mirror condition ($F(1, 7) = 6.40$, $p = 0.0393$) and just failed to be significantly different from the reduced display size 2 condition ($F(1, 7) = 5.12$, $p = 0.0582$). The convex mirror condition differed significantly from the first condition with no mirror ($F(1, 7) = 6.50$, $p = 0.0381$) and from the reduced display size 2 condition ($F(1, 7) = 9.46$, $p = 0.0179$). The remote condition reached a significant difference in contrast to the first condition (monitor) ($F(1, 7) = 6.61$, $p = 0.0396$). The reduced display size 1 condition only differed from the reduced display size 2 trial ($F(1, 7) = 18.97$, $p = 0.0033$). TTC estimations in the display size 2 condition differed significantly from those in the no mirror condition ($F(1, 7) = 15.13$, $p = 0.0060$), the convex mirror condition ($F(1, 7) = 9.46$, $p = 0.0179$) and the reduced display size 1 condition ($F(1, 7) = 18.97$, $p = 0.0033$).

In summary, the most accurate estimations were made while directly viewing the monitor. Estimations with a planar mirror, a convex mirror, from a distance to the screen and with a size reduction to the same visual angle as perceived in a planar mirror all caused overestimation of TTC. The smallest visual angle tended to produce the most pronounced delay in response. A remarkable result is the comparison of the convex mirror with the reduced display size 2, both of which produced the exact same visual angle. Observers did better with the convex mirror and thus seemed to compensate for some of the reduction in size. In other words, the convex distortion was processed differently than a mere size reduction.

The truck, which appeared in about half the trials, did not have any measurable effects on the estimations.

3.3. *Discussion*

The present results invite a reinterpretation of Fisher and Galer's (1984) findings. During their video-based experiments they noted that larger mirror curvatures (i.e. smaller radii) lead to a decreased safety margin when the observer had to decide when to initiate the manoeuvre to pass a car. Fisher and Galer attributed this effect to the mirror curvature and not to the concomitant reduction in visual angle. The present results suggest that if a mirror has to be used, it might actually be preferable to use a convex over a planar mirror provided the image size remains the same. Obviously, if the radius of the convex mirror becomes too small, the reduction in size of the mirror image will be considerable and the planar mirror will be preferable.

The experiment at hand shows that visual angle is more critical than curvature. Tasks, in which participants had to estimate TTC in a simulation of reduced size led to the largest estimation errors, exceeding even the bias caused by the convex mirror in the experiment. The visual angle of the display seems to be the single most important factor for TTC estimation of objects that can only be seen through a mirror. As curvature and visual angle are necessarily interdependent, convex mirrors entail a smaller visual angle than both planar mirrors and direct vision. Thus, two things must be kept in mind: a reduction of curvature reduces the visual angle and thus the image size. If manufacturers want to keep mirrors small for aerodynamic or aesthetic reasons, as prevailing in sports cars, they resort to small curvatures. This will make drivers overestimate TTC and thus considerably reduce the margin of safety.

4. General discussion

This study failed to replicate findings that suggest systematic estimation errors when judging the distance of objects seen through a convex mirror. When a real world standard was provided, estimates of distance and spacing of objects were remarkably accurate on average. However, an increase of variability on both measures was found when the objects were viewed through convex mirrors. In contrast, moving objects viewed through mirrors caused systematic overestimations of TTC.

At first sight, the results of the first experiment do not confirm the findings obtained by Higashiyama *et al.* (2001) and Higashiyama and Shimono (2004). They found a systematic overestimation of distances perceived in convex mirrors, which they attributed to the reduction of angular and linear size creating the impression that targets were farther away. When taking a closer look at their data, however, it becomes apparent that their finding of distance overestimation is carried by mirror radii that were more extreme than the smallest radius tested in the present experiments. At moderate radii of 800 mm, 1000 mm or above, such as is typical for automotive driver-side mirrors, their observers produce results that are very similar to the present results, that is, fairly accurate performance. Thus, the data obtained in experiment 1 are compatible with the studies carried out by Higashiyama and colleagues. This is very encouraging because there were a number of procedural differences between their experiments and the present experiments that might have affected the results. The mirrors were larger and the actual distances in the field were larger in our experiment 1. Thus, when viewing stationary targets in convex mirrors the radius seems to be able to vary within quite a range (roughly from infinity to less than 800 mm) without causing distance overestimation.

The differences between these results and previous findings underline the importance of further research on mirror perception. Perception in mirrors, especially in convex mirrors, is more complex than meets the eye. Conceivably, the findings of Higashiyama and colleagues are special cases that are compatible with the present results. Perceived size could have played a role and might have been attributed to convexity rather than to size. To be sure, convex mirrors do pose a challenge to perception and they are to be used with caution.

Concerning the perception of moving objects in mirrors, collision times were consistently judged to be later than specified by the stimulus. However, not curvature seemed to be the critical factor but the size of the stimulus in terms of its visual angle subtended for the observer. This study was able to show the supreme importance of visual angle by introducing a number of control conditions including a remote viewing condition in which participants sat 3.73 m away from the screen. Small visual angles caused large delays in TTC reactions. This finding contradicts the tau theory (Lee 1976), which bases TTC estimation on relative sizes independent of visual angle. A global size-arrival effect was found that is not limited to the target stimulus itself (DeLucia 1999) but rather seems to apply to the whole visual field.

However, a reduction of the mirror radius between the planar and the convex mirror should have caused even more errors in TTC estimation, which it did not. It is speculated that some knowledge about the effects of convex mirrors may have been advantageously employed. A replication with even smaller radii of curvature while maintaining visual angle will have to verify this conjecture.

5. Human factors implications

Manufacturers of rear view mirror systems for vehicles should keep in mind that the use of convex mirrors has its price. Whereas the reduction of mirror curvature enlarges the visual field and thereby reduces the blind area, it comes at a cost: distance judgements become more variable and, more seriously, TTC is systematically overestimated. In traffic, exact estimations of the positions of other vehicles are fundamental. The pay-off point between seeing more of the surrounding area and being able to judge the positions of other vehicles must be chosen with great care. Furthermore, convex mirrors make it advisable to better educate drivers about the effects caused by these mirrors. In particular, drivers should be acquainted with the perils of overestimating TTC.

Regulations concerning rear mirrors for cars do not specify admissible mirror size or visual angles. Instead, they specify the visual field. It was possible to show here that the visual angle does have a strong impact on mirror perception. Thus, a minimum size of the image that is displayed in rear mirrors must be regulated to enhance safety (see also Flannagan *et al.* 1997). It was found that without a mirror a visual angle of 25° provides rather accurate TTC estimations. Experiment 2 suggests that the critical mirror size is somewhere between 15° and 5° of visual angle. The performance decrement between 25° and 15° was rather modest, while the smaller image sizes produced substantial error in TTC estimation. If the decision to move into the overtaking lane were entirely based on the driver-side rear view mirror image, the small mirror image creates the dangerous impression that considerably more time is available than is actually the case. The exact minimum mirror size for convex mirrors should be determined in deliberate experiments with convex mirrors of different curvature to test stationary and moving stimuli.

Luoma *et al*. (1995, 2000) emphasized that convex rear mirrors enhance safety during lane change manoeuvres. They found that convex driver-side mirrors reduced accidents, at least in cities. Potential problems were deemed to be of minor concern. The authors suggested that the beneficial effect of multi-focal and convex mirrors is due to reduced response times. The larger field of view causes a car in the overtaking lane to come into view earlier and thus the driver can respond to such traffic earlier. This is not to be confused, however, with TTC estimation. Once the car is detected, convex mirrors cause an overestimation of TTC, thus deceiving the driver about the time he/she has available to move into the overtaking lane. The advantage of seeing a car in the overtaking lane at all stands in opposition to the disadvantage of misjudging the car's speed once it has been detected. A multi-focal mirror with the radius of its inner area being close to infinity might be the most useful combination of increasing detectability without compromising TTC estimation.

An interesting complication is the influence that adaptation has on mirror perception. Mirrors are used in traffic every day without causing accidents all the time. Presumably, observers adapt to some extent to the specifics of the mirror they are using, but they may never do so entirely. For distance estimates of objects that were up to 40 m behind a rear view mirror, Flannagan *et al*. (1996) reported results to this effect. It might be revealing to replicate the present experiments with moving stimuli after participants have received extensive training with a given mirror. On the basis of experiment 2, showing that the effects of mirror convexity haven been taken into account to some degree, such calibration training is promising. Being used to the convex driver-side mirror of a German car, when switching to a US rental car, one of the authors (H.H.) had considerable difficulty adjusting to the larger image and the decreased field of view. After a few days this difficulty had been entirely overcome. This indicates that the risk of accidents due to rear view mirrors might be highest immediately after switching from one type of mirror to another.

The current experiments show that the field-of-view advantages of convex rear view mirrors come at a price. The general proposal by the EU commission to reduce the radius of convex rear mirrors from 1800 mm to 1200 mm should not be implemented before further tests with 1200 mm mirrors have been conducted. The pay-off matrix between all risks and benefits that accompany a reduction in curvature must be considered. It might be advisable to mandate multi-focal mirrors.

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