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Image Parameters for Driving With Indirect Viewing Systems

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Abstract

In 3 experiments, we measured driving performance when a driver had only a mediated view on the outside world. A mediated view can be provided when direct view is insufficient, for example in trucks and busses, armoured vehicles, and remotely operated vehicles. Generally, a mediated view results in image degradation compared to direct view. Data on the effects of relevant parameters such as field size and resolution on driving performance are mostly indirect. Our results show that camera location is of minor importance. A 100° diagonal field of view results in better performance than a field of view of 50° on tasks that need lateral viewing. A magnification factor of 0.5 leads to a decreased course stability and an overestimation of speed compared to a magnification of 1.0. Spatial and temporal resolution affect tasks related to foveal and peripheral vision, respectively.

Image Parameters for Driving With Indirect Viewing Systems

Introduction

In some driving situations, such as driving under armour, a limited view imposes restrictions on driving performance. In these situations an additional viewing system, like a camera-monitor system, can give a wider view on the world than the one provided by a direct view. The applications are evident. For example, to overcome view restrictions, camera-monitor systems are nowadays installed on buses and trucks. Furthermore, future concepts of armoured vehicles are based on closed cockpit principles, in which a mediated (i.e., electronically sensed and displayed) view is the primary view and periscopes serve as a backup viewing system only. As a final example, recent technological advances give impulses to the development of remotely controlled vehicles, in which the operator has no direct view at all.

However, an indirect viewing system provides images that differ in several ways from direct view, for example, in viewpoint and spatial resolution. An important human factors aspect of driving with mediated view is how driving performance is affected by system parameters such as field of view (FOV), image resolution and viewpoint. Because this has not been studied systematically, we are dependent on indirect evidence. Of the parameters that possibly influence vehicle driving, only for FOV more than incidental literature is available. A major effect of a restricted FOV is the disabling of peripheral vision, which is expected to have an effect on three aspects of driving behaviour. First, the results of Riemersma (1987), Mourant and Rockwell (1972), and Summala, Nieminen and Punto (1996) all suggest that peripheral vision plays a role in lane keeping or lateral control in general. Second, the lack of peripheral vision affects speed perception, for example, Osaka (1988) found that when the horizontal visual field is reduced the subjective speed estimation is lower. Also, Salvatore

(1968) discovered that verbal estimates of speed were lower when the driver's field of view was restricted. However, Brown and McFaddon (1986) mentioned a number of field studies in which a substantial lower speed choice is reported instead of an increase of speed. Finally, according to a number of authors, horizontal FOV affects the accuracy of time to contact estimates. Groeger and Brown (1988) and Cavallo and Laurent (1988) found less accurate estimations with a field restriction of 10°. Apart from disabling the use of peripheral vision, a limited FOV may hinder the perception of objects or locations, such as the start of a sharp curve, because they will disappear from view before they are reached. A general finding with a limited FOV is that steering into curves is initiated too early. Driving performance in a curve may also be affected if the tangent point of the curve falls outside the FOV (Land & Lee, 1994).

The FOV is sometimes enlarged at the expense of a magnification smaller than 1.0 (e.g. in convex rear mirrors). However, magnification smaller than 1.0 may lead to errors in speed and distance estimations ("objects are closer than they appear"). Therefore, the result of the trade-off between field size and magnification factor is important. We investigated the confounding of both parameters in Experiment 1, whereas the separate effects were investigated in Experiment 2. Apart from the field size and magnification factor, viewpoint may be an important parameter. Differences between eye point and camera viewpoint may result in lateral and longitudinal position estimation errors, and may induce motion sickness. Therefore, we investigated the effects of two extreme camera positions on the vehicle, and the effect of artificial spatial orientation aids in Experiment 1. Finally, Experiment 3 focusses on the effect of spatial resolution and image update rate on driving performance. Both parameters are relevant for driving with computer generated imaging and in remote control situations with a limited data link capacity.

Experiment 1

In Experiment 1 we investigated the effect of the following image parameters on driving performance: field size confounded with magnification factor, camera viewpoint, and spatial orientation aids. The spatial orientation aids consisted of transparent sheets attached to the monitor, providing information on lateral position, heading direction, and longitudinal distance on the road.

Method

Participants.

Eight male military driving instructors (age 23 to 38 years) participated in the experiment. They had a driving experience of at least 150.000 km, normal visual acuity and normal stereo vision.

Apparatus.

The experiment was run with an instrumented Dodge Caravan with automatic transmission. The accelerator pedal of the car could be blocked in any position to enforce a fixed speed. The experimenter sat in the passenger seat and had at his disposal: a speedometer, an emergency stop that switched off all electronic equipment, a braking pedal, and an event marker. The following parameters were digitally recorded with a 20 Hz sampling frequency: speed, distance travelled, lateral distance to the right hand road marking, event markings, and steering wheel angle. The terrain was a cracknel-shaped, paved driving circuit (covering 350 × 120 m, road width 6.7 m) with no other traffic. Along right hand side of the road, a 15 cm wide, white road marking was painted. The indirect viewing system was based on the PAL video system and consisted of a video camera (black and white, JVC type TK-S310 EG) and a video monitor (Phillips LDH 2152/00) mounted above the steering wheel. The size of the monitor screen was 186 × 137 mm, the fixed viewing distance was 25 cm, thus covering an area of 40° × 30° of visual angle. The drivers looked with both eyes. The driver's head was fixated by a head rest. When driving with mediated view, the outside view was obstructed by a large piece of black cloth.

Image parameters.

We varied the following image parameters:

1. The camera viewpoint. The camera was positioned over the car's longitudinal midline, either 1.7 m behind the driver and at a height of 2.8 m (called viewpoint high) or at the longitudinal position of the driver at a height of 1.8 m (viewpoint low). In both positions, the elevation of the camera was adjusted so that the horizon was at one fifth below the upper edge of the monitor.

2. The field size of the camera image. By using lenses with different focal lengths, the field size was either 50° diagonal (resulting in magnification 1.0 in the present set-up) or 100° diagonal with magnification 0.5.

3. The presence of spatial orientation aids. On a transparent sheet--attached to the monitor screen--spatial orientation aids were presented, consisting of a horizon, markings of the distance on the road to the front bumper (m), and tracks of the wheels' outer edges when driving straight.

Figure 1 shows the monitor images in the different camera conditions with the spatial orientation aids present.

Taskbattery and performance measures.

The taskbattery, designed to cover a range of driving skills on paved roads, contained tasks related to either foveal or peripheral vision. The battery was divided in lateral control and longitudinal control tasks.

The basic instruction for the lateral control tasks was to follow the road markings at a lateral distance of 0.5 m. For each task two performance measures were calculated: a task-dependent measure for the lateral position and the course instability (defined as the standard deviation of the lateral speed (m/s), which is at fixed longitudinal speeds analogue to the standard deviation of the heading angle [Blaauw, 1984]). Four tasks were included:

1. Driving an 8-shaped circuit at a fixed speed of 40 km/h. Curve radius was 53-56 m, the lateral position performance measure was the mean lateral distance (defined as the right wheels' outer edges to the road marking (m), e.g., Harms, 1993).

2. Turning sharp curves at a fixed speed of 20 km/h. Curves radius was 11-31 m, the lateral position performance measure was the mean lateral distance.

3. Performing a lane change according to ISO (1975) standard (changing from the right lane to the left lane and back) at fixed speeds of 20 and 40 km/h. The lateral position performance measure was the standard error from the midlane (m).

4. Rounding a curve with a radius of 10.5 m driving backwards. No target speed was enforced in this task. Lateral control performance measure was the distance travelled (m).

The three longitudinal control tasks were:

1. Estimating speed with the instruction to pull up to a target speed of 25 or 50 km/h and maintain that speed for 5 s (the speedometer was covered). Performance measure was the percentage off target speed, with positive values defined as a speed underestimation.

2. Longitudinal positioning, that is, aligning the front bumper with a transverse line on the road. Performance measures were the mean stopping distance (m) (negative when the car was positioned over the line), and the standard deviation of the stopping distance over repetitions (m).

3. Braking in front of a transverse line with approach speeds of 30 and 60 km/h. The transverse line was marked with beacons placed beside the road. The drivers were instructed to brake as they would normally do approaching a red traffic light. Performance measures were the time to collision (TTC) (s) at the onset of braking (defined as the distance to the transverse line divided by the momentaneous speed), and minimal TTC (s) during the braking manoeuver.

Statistical design and data analysis.

Each participant drove ten runs. The first and last runs were baseline runs with direct view, in between were eight mediated view runs, divided over the three camera parameters in a full factorial design. The order of these runs was balanced using a digram balanced design (Wagenaar, 1968). Each experimental run consisted of performing each task three times in a row. The data of each performance measure were tested on sphericity and homogenity of variance and consequently analysed by a Viewpoint (2) × Field size (2) × Spatial orientations aid (2) × Repetition (3) within-subjects ANOVA. This statistical design could be extended with a task-dependent variable: curve direction (left/right) in the sharp curves task, speed (2) in the lane change task and the braking task, and target speed (2) in the speed estimation task. To analyse the differences between the two direct view runs and the eight mediated view runs, a Camera (direct view / mediated view) × Repetition (3) within-subjects ANOVA was performed. Post-hoc Tukey HSD tests with α set at .05 were applied when applicable.

Procedure.

The participants worked in pairs, one participant drove while the other could rest. After arrival on the test site they received a general instruction on the goals of the experiment and the features of the car, followed by an instruction run with direct view, aimed to teach car handling and performing the taskbattery. During this run, instructions and feedback were provided. In the experimental runs, the complete taskbattery was run, lasting about one hour. After each task in a run, comments from the drivers on the task were recorded. Each run with mediated view was preceded by a familiarization run, consisting of driving the 8-course, the sharp curves, and driving straight backwards. The experiment lasted five weekdays for each pair of participants.

<u>Results and Discussion</u>

We will present the results of the lateral control tasks first, followed by the longitudinal control tasks.

In none of the lateral control tasks the main effects of camera viewpoint or the presence of the spatial orientation aids were significant. Field size, however, showed main effects in all the lateral control tasks. An overview is presented in Table 1.

As can be seen in Table 1 the effect of a wider FOV on the course instability was task dependent. A wide FOV was only beneficial when the driver needed an enlarged lateral view as is the case in turning sharp curves. In tasks where a smaller lateral view is sufficient to perform the task (as in driving straight or curves with a large radius, and performing a lane change), enlarging the FOV resulted in performance degradation. This may be explained by the fact that the wider FOV was confounded with magnification 0.5, resulting in smaller visual effects of vehicle swaying. An enlarged FOV had a beneficial effect on the control of lateral position in sharp curves (forward and backward).

The interaction between camera viewpoint and field size was significant on controlling the lateral position in the 8–shaped circuit, in turning sharp curves, and in driving backwards, $F(1, 7) = 26.60, p < .01$; $F(1, 7) = 16.03, p < .01$; and $F(1, 129) = 5.24, p < .03$, respectively, see Figure 2. The interactions showed a performance improvement with the 100° FOV mainly at high camera viewpoint, and worse performance with the 50° FOV at the high camera viewpoint. Examining Figure 1 makes this interaction somewhat plausible: at low camera viewpoint the vehicle, visible in the image with the wide field only, gives an overestimation of the vehicle width and thus an underestimation of lateral distance, whereas at high camera viewpoint the wide field provides a better lateral reference.

In the speed estimation task, no main effects of camera viewpoint, presence of the spatial orientation aids, and target speed were present. The latter indicates that speed estimation errors were proportional to the target speed. However, there was a main effect of field size, $F(1, 7) = 51.11$, $p < .01$, that indicated a relative overestimation of speed with a 100° FOV (mean -4.3%), compared with 50° (mean 14.0%). The interaction Camera viewpoint × Field size showed a trend, $F(1, 7) = 5.27$, $p < .06$), that indicated that for the 50° FOV there was a speed underestimation, mainly at high camera viewpoint (20.4% and 7.8% for high and low viewpoint, respectively). For the 100° FOV there was relative overestimation of speed, not significantly dependent on viewpoint (-3.1% and -5.5% for high and low viewpoint, respectively). These effects were in accordance with the idea that optic flow in the image contributes to speed perception (e.g., Van der Horst, 1991). With the 50° FOV, the main flow came from the nearest road structures, which decreased at camera viewpoint high. At 100° FOV, the image minification decreased the flow from the road, but there was more flow from eccentric structures (immediately near the course was woodland), both at low and high camera viewpoint. The results suggest that the peripheral flow is a more effective speed cue than the flow from the road. This is in accordance with the results reported by Salvatore (1968). In his experiments participants had to estimate their speed with only peripheral or only foveal view on a highway. In the peripheral view conditions, estimated speed was higher and closer to the target speed. Effects of field size as found in our experiment were also reported previously (e.g., Osaka, 1988). The condition that best resembles the direct view situation, both regarding the visual flow and the speed estimation error, was normal field at the low camera viewpoint.

In the longitudinal positioning task, there were no main effects of field size and the presence of the spatial orientation aids. There was only a main effect of viewpoint on the stopping distance, $F(1, 7) = 10.10$, $p < .02$. The means for viewpoint low and high were 1.40 and 0.69 m, respectively. In both conditions, drivers stopped too early which is a common finding, for example, Holzhausen, Pitrella and Wolf (1993) found that participants halted too early when they had to stop in front of a wall. Relatively early stopping can be caused by underestimation of distance to the line, or overestimation of approach speed, or both. The error in the 'viewpoint high' condition was smaller, which is in accordance with the relative underestimation of speed in the 'viewpoint high' conditions, as found in the speed estimation task. The importance of speed estimation is confirmed by the fact that the distance markers of the spatial orientation aids did not enhance performance, and the fact that the drivers mentioned the strategy of some form of mental counting after the disappearance of the transverse line or another characteristic point.

Compared to the 50° FOV, the 100° FOV reduced the variance over repetitions by 40% from 0.55 m to 0.32 m, $F(1, 7) = 33.56$, $p < .01$. This was probably caused by the presence of reference points in the 100° FOV image, including the car itself.

In the braking task, camera viewpoint showed a significant effect on the minimal TTC ($F(1, 7) = 10.80$, $p < .02$): In the low viewpoint condition, minimal TTC was 1.2 s, compared to 1.0 s in the high viewpoint condition. The order of this difference is the same as may be expected on the basis of the difference in longitudinal position of the viewpoint in both conditions (1.7 m). The only other significant effect was the Field size × Approach speed interaction, $F(1, 7) = 13.01$, $p < .01$. The post hoc test showed that an effect of field size was only present for approach speed 30 km/h. Means for the 50° and 100° FOV were 1.3 s and 1.1 s, respectively; for approach speed 60 km/h, the means were 1.0 and 1.0, respectively. In comparable experiments, Van der Horst (1990) found a minimal TTC of 1.3 s for approach speed 30 km/h and 1.0 s for approach speed 60 km/h, irrespective of instructions or occlusion. Compared to these results, the present experiments show that drivers had normal control over the braking process with mediated view.

For the TTC at the onset of braking, there was an approach speed dependent difference between direct and mediated view ($F(1, 7) = 14.35$, $p < .01$): At 60 km/h approach speed the means were 3.8 s and 3.4 s for direct and mediated view, respectively; at 30 km/h approach speed the means were 3.2 s and 3.4 s, respectively. Thus at 60 km/h, participants braked later with mediated view than with direct view. Given the absence of an overall camera effect in the speed estimation task, this suggests that with mediated view relative overestimation of distance occurs at higher speeds. The 0.5 magnification and the halved resolution reduced the availability of details of objects at a distance, which possibly resulted in overestimation of larger distances relevant for the onset of braking at higher speeds. Overestimation of larger distances is not contrary to the underestimation of short distances found in the longitudinal positioning task. This hypothesis was confirmed by strategies mentioned by the participants, namely estimating the distance to the beacons, but (in the camera view conditions) none mentioned taking into account the factor speed.

Regarding the participants' remarks, the following was noteworthy. In the lateral control tasks, the drivers used a point of reference for lateral position whenever possible, preferring reference points on the car's image. Only when there were no such points (as in the 50° FOV conditions) they made use of fixed points on the monitor. It was surprisingly that only a few drivers mentioned the use of the spatial orientation aids, even in the longitudinal positioning task, in which the aids precisely indicated the distance from the transverse line to the bumper.

Conclusions

Spatial orientation aids placed on the monitor, although designed to provide cues for lateral position, course, and distance, do not result in performance improvements. This can be caused by the limited number of instruction runs, which might have been insufficient to teach proper use of the markings. More plausible is that the markings in the present design do not have a surplus value over cues that are also available, for example, reference points on the car.

Camera viewpoint and field size are the most important parameters. A main effect of camera viewpoint was present in the positioning task only, showing an advantage of the high viewpoint, probably caused by the better overview. Also important to notice is the fact that only two participants complained on moderate effects of motion sickness, and only during the first run with camera view. This indicates that even placement of the camera at the back of the vehicle, more than 1 m higher than the driver's eyes, and at a different lateral position, induces no serious problems with motion sickness. More evident are the effect of field size and the combined effect of viewpoint and field size. The direction of the effect of field size is task dependent. A 100° FOV results in better performance in the sharp curves task, backwards driving, and the positioning task, but also leads to speed overestimation. The 50° FOV results in better performance in the 8–shaped circuit, and the lane change task. Apparently, the advantages of the wide field (better lateral view; vehicle reference in the image) outweigh its disadvantages (image distortion, lower resolution), especially if combined with camera viewpoint high. Since in both conditions the images were presented to the same retinal location, the use of different vision systems (foveal vs. ambient) is not relevant in this respect. This will be addressed in Experiment 2, in which the effects of FOV and magnification are disentangled.

Taskbattery.

One of the objectives of Experiment 1 was to come to a concise taskbattery that includes both lateral and longitudinal control tasks. Based on the present results, we conclude that driving the 8-shaped course and driving backwards have no additional value over the sharp curves and the lane change tasks. Concerning the longitudinal control tasks, speed estimation and braking are more sensitive tasks. However, the latter task does not allow to determine the effects of speed and distance estimation, while speed estimation errors are often given as explanations for effects on TTC estimation. Therefore, in Experiment 2, estimating longitudinal distance is included instead of braking. Finally, there are no indications that it is useful to include different speed levels in the lane change and speed estimation tasks.

Experiment 2

An important goal of Experiment 2 was to unconfound the effects of FOV and magnification factor. Furthermore, the experiment was conducted in a driving simulator without mechanical motion information. This situation resembles a remote control situation. It is important to know if and how the lack of mechanical motion information affects the relative effects of image parameters on driving performance. If the effects of parameter manipulations are the same, it means that it is allowed to generalize conclusions from simulator experiments to field settings, and that conclusions are valid for both driving and remote control.

Compared to Experiment 1, in Experiment 2, we tested only the critical parameters (camera viewpoint and field size), and we reduced the taskbattery to turning sharp curves, performing a lane change, and speed and longitudinal distance estimation. The experimental design was chosen to separate the effects of FOV and magnification factor, but also allowed a comparison with Experiment 1 in which both variables were confounded.

Method

Participants.

The eight drivers of Experiment 2 did not participate in Experiment 1, but were chosen from the same population of military driving instructors. Their age ranged from 34 to 48 years, and their driving experience was at least 400,000 km. All of them had normal or corrected-to-normal vision. None of the participants had experience with driving simulators.

Apparatus.

The experiment was run in a fixed-base driving simulator. The visuals were generated with a three-channel Evans & Sutherland Esig 2000 image generator. For the simulated direct view conditions the image was projected on a cylindrical screen with a field size of 120° (H)× 40° (V) by means of three Barco graphics 800 projectors with a resolution of 1024 × 1024 pixels each and a refresh rate of 60 Hz. The dynamic vehicle model was based on the characteristics of the vehicle used in Experiment 1, including automatic gear shifting, automatic speed limitation in fixed speed tasks, and haptic feedback in the steering wheel and the braking and acceleration pedals (Godthelp, Blaauw & Van der Horst, 1982). To eliminate the use of sound cues in the speed estimation task the simulated sound of the engine could be switched off.

For the camera view conditions a monitor (Mitsubishi colour display monitor, HL7955SBK) was placed in the mock-up, while the cylindrical screen was left blank. The monitor was placed directly above the steering wheel, and at a right angle with the line from eye to the image of the horizon. The participants' head was supported by a head rest. Refresh rate of the monitor was 60 Hz, with a resolution 1024 × 1024 pix. To keep conditions similar to the field experiment, the colour monitor was used as a black and white monitor. Viewing distance, screen size, and aiming could easily be adjusted to the specific conditions.

The 8-shaped circuit of Experiment 1 was modelled in the visual database of the simulator, including the 15 cm wide white line marking painted on the right side of the road, and the woodland besides the road. During the runs the primary measures were digitally recorded as a function of time (30 Hz sampling frequency), including: lateral and longitudinal position, speed, heading, and steering wheel angle.

Image parameters.

Three image parameters were varied: camera viewpoint, field size, and magnification factor. The levels of the former two were equivalent to those in Experiment 1. The latter indicates the ratio between field size (dependent on camera / surrounding parameters) and monitor size (dependent on observer / image parameters). Magnification 1.0 was the result of combining field size 50° with monitor size 50° and field size 100° with monitor size 100°; magnification 0.5 was the result of combining field size 100° with monitor size 50°, see Table 2.

Taskbattery.

Based on the conclusions of Experiment 1, the following four tasks were included in the taskbattery: turning sharp curves at 20 km/h, performing a lane change at 40 km/h, estimating a target speed of 50 km/h, and estimating longitudinal distance in a dynamic setting. The instructions and the performance measures of the first three tasks were the same as in Experiment 1. Estimating longitudinal distance was implemented by instructing the driver to drive with a fixed speed of 50 km/h towards a stationary car, and push a button at an estimated distance of 100 m and 50 m. Performance measure was the distance estimation error as a percentage of the target distance, and the standard deviation of the estimated distance over three repetitions.

Statistical design.

The experiment consisted of eight runs: the first and last were baseline conditions with (simulated) direct view. In between the baseline runs were six camera view runs. These were divided over three primary variables with two levels each; viewpoint: low and high (see Experiment 1), field size: 50° and 100° diagonal, and magnification factor 0.5 and 1.0. Since we considered the combination of field size 50° with magnification 0.5 not useful, the three parameters were not varied in a complete factorial design. To disentangle the effects of field size and magnification factor, field size was analysed by comparing the four conditions with magnification 1.0, and magnification factor by comparing the four conditions with field size 100°. ANOVAs were run for each image parameter and performance measure with the following within subjects design: camera factor (2) × repetition (3). The design could be extended with a task–dependent subtask (2): curve direction in the sharp curves task, and target distance in the distance estimation task. Post–hoc Tukey tests with α set at .05 were applied when applicable.

Procedure.

After arrival at the simulator, the participants received a general instruction on the goals of the experiment and the features of the simulator, followed by an instruction run to familiarize them with the taskbattery and the driving circuit. Extended instructions and feedback on performance were given. This run was always in (simulated) direct view. During the first five minutes the instructor sat next to the participant in the mockup.

Following the first instruction run, the chauffeurs drove the eight experimental runs. Each of these runs was preceded by a short instruction run in order to become familiar with the particular viewing condition (driving only the 8-course and the sharp curves clockwise). An experimental run consisted of performing each task of the battery three times consecutively, taking about 30 minutes. When one participant drove, the other rested. Before starting each of the six runs in the camera conditions, location and orientation of the camera for that specific condition were shown to the participant using a schematic side view of the simulated car.

Results and Discussion

Lateral control.

In the sharp curves task, there was a main effect of camera viewpoint on the mean lateral distance ($F(1, 7) = 6.76$, $p < .04$), showing a higher mean with a high camera viewpoint. We expected that in the 'high viewpoint' condition lateral distance would be underestimated compared to 'viewpoint low'. A post-hoc Tukey test on the interaction Viewpoint × Field size, $F(1, 7) = 28.73$, $p < .01$, revealed that viewpoint high with 50° FOV differed from all other conditions, see Figure 3. The fact that the effect of viewpoint was only present in the 50° FOV conditions may be explained by the difficulties in determining the correct lateral position with a small FOV, because of the restricted lateral view and the lack of reference points in the image. The beneficial effect of these cues was substantiated by the main effect of field size on both the mean lateral distance, $F(1, 7) = 37.10$, $p < .01$, and the course instability, $F(1, 7) = 13.46$, $p < .01$. On both measures, performance improved with a 100° FOV. Reference points are important cues in determining the correct lateral position (Thomas, 1991; Van Erp & Padmos, 1994). The significant interaction Field size × Curve direction on the course instability, $F(1, 7) = 15.63$, $p < .01$, showed that performance decline was mainly present in the 50° FOV turning the right curves (mean course instability was 2.7 times higher). Turning right curves in right hand road driving results in a shift of the road markings and the tangent point (Land & Lee, 1994) to the right on the monitor, and eventually off the monitor, while in turning left curves the markings and the tangent point come more centrally in the image. With a 50° FOV, the tangent point, which is an important cue in negotiating curves (Land & Lee, 1994; Land & Horwood, 1998), will be out of view in the right curves, resulting in performance decline.

The magnification factor resulted in substantial and significant differences on mean lateral distance, $F(1, 7) = 147.51$, $p < .01$, and course instability, $F(1, 7) = 19.72$, $p < .01$. On both measures, performance was degraded with magnification 0.5: 65% and 72%, respectively. This may be caused by the underestimation of lateral speed and distance with magnification 0.5, resulting in larger lateral distance and course instability. The results confirm Schulz-Helbach, Donges and Rothbauer (1973) who found that a magnification of 0.4 increased the standard deviation of lateral position on a straight road with 30 %.

In the lane–change task, the effects of viewpoint and field size were not significant. There was only a trend of field size on the standard error from midlane, $F(1, 7) = 3.73$, $p < .10$, which indicated a twice as high standard error in the 50° FOV conditions. This better performance with 100° FOV may have been caused by the possibility of using the car as reference point, which could have been helpful in determining the lateral position of the vehicle in each lane. Magnification factor caused large and significant effects on the lateral position control $F(1, 7) = 22.57$, $p < .01$, which showed a performance that was lower by a factor of six when the magnification was 0.5. The effect on the course instability is in the same direction, but smaller (30%) and only marginally significant, $F(1, 7) = 4.69$, $p < .07$.

Longitudinal control.

The variable camera viewpoint indicated a trend of relative underestimation of speed with a high camera viewpoint (mean 23.6%) compared to a low viewpoint (mean 16.0%),

$F(1, 7) = 5.24$, $p < .06$. With the high camera viewpoint the visual flow from the road is less compared to camera viewpoint low. Magnification factor was highly significant, $F(1, 7) = 13.70$, $p < .01$, which yielded a 27% overestimation of speed in the conditions with magnification 0.5, as compared to a 6% overestimation with magnification 1.0. There are only a few experiments in which magnification factor is systematically varied. Unfortunately, confounding of magnification and field size occurs in many experiments. We have no clear-cut explanation for the overestimation with magnification 0.5. Based on the reduced visual flow in the middle 50° FOV, we expected speed underestimation. The speed overestimation might have been the result of distance overestimation (see distance estimation task below). However, Evans (1970) reported a similar effect of magnification factor. In his experiment magnification was accomplished by changing the viewing distance to the projection screen, so magnification was not confounded with field size. We found no effect of field size on speed estimation.

In the distance estimation task, viewpoint and field size showed no effects. Only the magnification factor had a significant effect on the distance estimation error. Compared to direct view with an estimation error of 24%, the results showed a small overestimation with magnification 1.0 (11%), and a large overestimation of distance with magnification 0.5 (-18%). The results indicated that a magnification larger than 1.0 was needed to find the same results as in the direct view control conditions. As expected there was no main effect of target distance on distance estimation error, so distance estimation error is a fixed proportion of the target distance, in accordance with for example Kraft (1989).

Comparison of Experiment 1 and 2

To compare Experiment 1 and 2, the four camera conditions that were used in both experiments were analysed, which implies the confounding of field size and magnification factor. This comparison resulted in one interesting incongruence, namely the effect of field size in the sharp curves task. In Experiment 1, the 100° FOV with magnification 0.5 resulted in better performance, while in Experiment 2, the 50° FOV with magnification 1.0 resulted in better performance. There were two factors involved which may each account for one of the effects. The wider field gave a better lateral view and provided reference points in the image which may have improved performance. The flip side of the coin was the minification of the images, causing underestimation of lateral distance and speed, which may have lowered performance. Only in Experiment 1, the positive effects of the wider field outweighed the negative effects. The latter can be explained by the fact that in Experiment 1, the driver had visual as well as mechanical motion information, while in Experiment 2, the driver had no redundant mechanical motion information to compensate for the degraded visual information on lateral motion.

Discussion

We investigated three camera factors. Of those, camera viewpoint appears to be less critical than field size and magnification. Important characteristic of the present experiment is the fact that field size and magnification were varied independently. Performance with the 100° FOV is substantial better than with the 50° FOV for taking sharp curves. Magnification appears to be an important camera factor as well. The results show that a magnification of 0.5 of the outside world may lead to performance deterioration in taking sharp curves and performing a lane change, but also results in a decreased speed underestimation found with a magnification of 1.0. Magnification of 0.5 also leads to an overestimation of distance. In Experiment 1, where field size and magnification factor were confounded, the explanation for the relative speed overestimation in the wide field conditions was that of extended (peripheral) visual flow. However, the present experiment indicates that varying field size in the range 50° - 100° does not affect the estimation of speed.

Overestimation of distance combined with underestimation of speed compared to direct view, may cause problems in tasks where both estimations are combined, for example braking for an obstacle, or making speed adjustments for an oncoming curve. This result is striking considering the fact that magnification is often tolerated to acquire a larger field size. Roscoe (1984) already suggested that there is an optimum magnification for every imaging system. Present results indicate that an optimum magnification factor might be larger than 1.0.

Comparing the results of Experiment 1 and 2 reveals only one inconsistent effect that can be explained by the lack of redundant mechanical motion information on lateral vehicle motion in Experiment 2. This means that one should be cautious when generalizing results of field and simulator experiments, and when generalizing results between driving and remote control situations.

Experiment 3

Experiment 3 focusses on two other important system parameters, namely spatial and temporal resolution. Apart from field size, the literature identifies image quality (often expressed in terms of contrast and resolution) as an important parameter. Acuity-mediated foveal vision is expected to affect tasks such as performing a lane–change and distance estimation (e.g. Leibowitz & Owens, 1977; Higgins, Wood & Trait, 1998). Image update rate, however, is expected to affect peripheral vision, and thus tasks as course control and speed estimation. Furthermore, spatial and temporal resolution are both important parameters in situations in which the images are relayed by means of a data link with a limited capacity, which is common in remote control. We chose to vary both parameters in the same experiment to investigate a possible trade–off between both, which is not expected because of their different effects on foveal and peripheral vision.

Method

Participants.

Eight experienced military driving instructors participated in the experiment (mean age 44). All had normal, or corrected-to-normal vision, only two of them had prior experience with driving simulators (between 15 and 30 minutes). They had not participated in the previous experiments.

Apparatus.

The apparatus was the same as used in Experiment 2, with the following extension to manipulate the spatial resolution. After generation of the images with a resolution of 512 × 484 pix. (comparable to PAL tv images with 625 lines), the images were put through a Datacube MV200 image processor system. The images were successively convolved with a square kernel of variable dimensions (1×1 up to 8×8 pixels, configured to yield the average value of the area around each pixel), sub–sampled according to the size of the kernel, repeated to generate the original number of pixels, and low–passed filtered by convolving with a sinc function (Harmon & Julesz, 1973). The images were generated with a viewpoint 1.7 m behind the driver and 2.8 m above the ground (camera viewpoint high in the preceding experiments), a 100° diagonal FOV, and a magnification 1.0.

Image parameters.

Two image parameters were varied: the update rate and the spatial resolution. The update rate was manipulated through the dynamic vehicle model, which generated the parameters for the image generator at 30, 10, 5, or 3 Hz. The spatial resolution was manipulated by varying the dimension of the square kernel in the Datacube MV200.

Dimensions of 1×1, 2×2, 4×4, and 8×8 yielded an image resolution of 512×484, 256×242, 128×121 pix., 64×60 pix., respectively.

Taskbattery.

Based on the experience gained from the previous experiments, the following five tasks were included in the taskbattery: turning sharp curves at 20 km/h, performing a lane change at 40 km/h, estimating a target speed of 50 km/h, estimating longitudinal distances of 100 and 50 m, and braking with an approach speed of 60 km/h. The performance measures were those described in Experiment 1 and 2 The taskbattery was performed in a fixed order, each task three times consecutively.

Statistical design.

Due to constraints on the availability of the participants, we could not vary both independent variables in a complete factorial design. Based on a pilot study, we expected no or only small performance changes in the higher range of both variables. Therefore, only the lower three levels of update rate (10, 5, and 3 Hz) and spatial resolution (256×242, 128×121, and 64×60 pix.) were combined in a full factorial design. This design was analysed by a within-subjects ANOVA: update rate (3) × spatial resolution (3) × sub-task (2). The variable sub-task was present in turning sharp curves: left and right curves, and in estimating distance: 100 m and 50 m target distance. The combination of update rate 30 Hz and resolution 512×484 pix. was considered as baseline condition, and driven as first and last run. The performance on these baseline runs was tested against the 10 Hz combined with 256×242 pix. condition. Post-hoc Tukey tests with α set at .05 were applied when applicable.

Procedure.

Participants came in pairs on two consecutive days. After arrival and introduction, they were familiarized with the experimental environment for 30 minutes, including car handling, and tasks instructions with feedback on performance. During the experiment, one participant performed the taskbattery which lasted about 20 minutes, while the other rested. After finishing each taskbattery, participants were asked to give comments. No feedback on their performance was given.

Results and discussion

In accordance with our expectations, we did not find significant differences between the baseline and the 10 Hz / 256×242 pix. condition.

Lateral control.

In the sharp curves task, update rate showed an effect on the course instability, $F(2, 14) = 4.25$, $p < .04$, and the mean lateral distance, $F(2, 14) = 11.1$, $p < .01$, see Figure 5. The largest deterioration occurred between 5 and 3 Hz. Spatial resolution showed no significant main effects.

Figure 6 shows the significant effects of update rate in the lane change task on the standard error from midlane, $F(2, 14) = 3.79$, $p < .05$, and the course instability, $F(2, 14) = 7.28$, $p < .01$). Spatial resolution showed a significant effect on the course instability, $F(2, 14) = 11.40$, $p < .01$). The results showed that both variables caused performance decline, update rate mainly in the range below 5 Hz, spatial resolution already below 512×484 pix. Apparently, a high resolution was required, probably because the pylons--which mark the different lanes--were an important lead, and lower resolution decreased their visibility.

Longitudinal control.

The speed estimation task showed no effect of update rate or spatial resolution, although the task proved to be sensitive to varying viewing conditions in the previous experiments. Because sampling and blurring do not effect the flow generated by the low spatial resolutions (taken over the whole screen), lowering the spatial resolution was not expected to affect speed estimation.

There was no main effect of update rate on the distance estimation error. The main effect of spatial resolution, $F(2, 14) = 9.54$, $p < .01$, indicated a relative overestimation of distance with lower spatial resolutions (see also Roscoe, 1984). This may be explained by the fact that an important cue participants used in determining target distance to the object was the visibility of (small) details. Therefore, in the low–resolution conditions a shorter target distance was needed. Comparing performance with the baseline condition showed that only with a resolution of 256×242 pix. the estimation was adequate.

In the braking task, the main effects of update rate and spatial resolution were significant for the TTC at the onset of braking: $F(2, 14) = 5.42$, $p < .02$ and $F(2, 14) = 4.72$, $p < .03$, respectively. Both main effects were also significant for the minimal TTC during braking: $F(2, 14) = 2.92$, $p < .09$ and $F(2, 14) = 8.25$, $p < .01$, respectively. The means indicated that with lower update rates or lower resolutions, participants started braking later: TTC at the onset of braking decreased gradually from 3.0 s to 2.4 s. Furthermore, participants reached a lower TTC during the braking process: Minimal TTC during braking decreased gradually from 2.3 s to 1.9 s. The effects of spatial resolution were consistent with the relative overestimation of distance with low resolution if observers processed distance and speed separately.

Ad hoc analysis of the data revealed that the number of collisions was low and did not differ between conditions, thus participants were able to control the braking process in conditions with lowered spatial and temporal resolution as well as in the baseline condition.

Conclusions

No differences were found between the baseline and the condition with 10 Hz update rate and a resolution of 256×242 pix. The main effects that were present largely agree with the hypothesised effects on foveal and peripheral vision related tasks. This means that requirements on spatial and temporal resolution are task dependent. The sharp curves and the lane change tasks typically require a minimum update rate of 5-10 Hz. In the braking, speed estimation, and distance estimation tasks, update rate may be as low as 3 Hz. The lane change task and the distance estimation task require at least a resolution of 256×242 pix., for turning sharp curves, estimating speed, and braking, the resolution may be as low as 64×60 pix. for a 100° diagonal FOV.

In none of the tasks a significant interaction of update rate and spatial resolution was present. This finding indicates that, if there is only one main effect, a higher level on one variable can not compensate for a lower level on the other. If data link reduction is an important issue as it is in, for instance, remote control, a system with adjustable levels for update rate and spatial resolution may reduce the required data link capacity without affecting driving performance.

General Conclusions

The effects of the investigated parameters are summarised in Table 3. First conclusion is that drivers are able to steer their vehicle with a mediated view on the outside world alone. The differences between mediated view and direct view (Experiment 1), or simulated direct view (Experiment 2), if present, are small. Of the investigated image parameters, providing artificial spatial orientation aids is of minor importance. This indicates either that the drivers do not need such aids to determine position and course, or that they prefer 'natural' aids such as vehicle reference points. The parameter camera viewpoint shows small effects on driving performance. This indicates that choosing the camera viewpoint to optimally compensate for view restrictions, might be possible without large implications on driving performance. For driving on the road, FOV and magnification factor are important parameters. Enlarging the field size from 50° to 100° diagonal improves driving performance on tasks affected by peripheral vision (e.g. turning sharp curves). Experiment 2 shows that performance degrades when the magnification is 0.5 compared to 1.0. This degradation is especially prominent in tasks dependent on foveal vision, e.g. performing a lane–change. When field size and magnification are confounded, the choice for a smaller FOV or magnification 0.5 is task dependent. Another task dependency related to foveal and peripheral vision is present in Experiment 3. Spatial resolution affects task related to foveal vision and temporal resolution tasks related to peripheral vision. Main effects show that, dependent on the driving task, the level of one of the parameters can be reduced without negatively influencing driving performance. This implies that in remote control settings, data link restrictions do not necessarily result in performance degradations when the levels of the parameters are optimally chosen.

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Table 1

Overview of the Effects of the Field Size on the Lateral Control Tasks. Means are Presented in the Order 50° - 100°

Task:	8-course	Sharp curves	Lane change	Backwards
Course instability (m/s):	0.11 - 0.13*	0.20 - 0.17**	0.10 - 0.14**	0.06 - 0.06
Lateral position (m):	0.55 - 0.55	0.64 – 0.53**	0.13 - 0.14	32.0 - 28.4**

* denotes $.01 < p < .05$, ** denotes $p < .01$.

Table 2

Screen Size, Viewing Distance, and Resolution (Pixels per Degree of Visual Angle) for 50° and 100° Monitor Size. Values of Experiment 1 are Given as Comparison

Monitor size[1]	Screen size[2]	Viewing distance	Average resolution
50^0	219 × 164 mm		
	606 × 604 pix	293 mm	14.8 × 19.3 pix/^{0}
100^0	370 × 278 mm		
	1024 × 1024 pix	194 mm	11.7 × 14.4 pix/^{0}
Experiment 1	186 × 137 mm		
	700 × 525 pix	250 mm	17.5 × 17.5 pix/^{0}

[1] visual angle of the depicted image for the observer

[2] size of the camera image on the monitor

Table 3

Overview of the Investigated Parameters and Their Effects, Combined Over the Three Experiments

Parameter	Effects
direct vs. mediated view	small effects only
artificial spatial orientation aids	no effects, drivers probably prefer existing reference points on the car
camera view point	small advantage of a higher viewpoint in the positioning task, a higher viewpoint may also enlarge the positive effects of a wider field size
field of view (FOV)	a 100° FOV results in better performance in turning sharp curves, driving backwards and positioning, a 50° FOV leads to better performance in the 8–shaped circuit and the lane change. There is no difference between 50° and 100° on speed estimation.
magnification factor	magnification of 0.5 compared to 1.0 results in worse performance in turning sharp curves and in the lane change, leads to distance overestimation, but also reduces speed underestimation.

(table continues)

Factor	Effects
spatial resolution	for a 100° FOV, spatial resolutions below 256×242 pix. result in performance degradation. For turning sharp curves, braking, and the estimation of speed, the resolution may be lower.
temporal resolution	a minimum temporal resolution of 5–10 Hz is required for the sharp curves and the lane change tasks. Temporal resolution may be lower for braking and speed and distance estimations.
mechanical motion information	the presence of mechanical motion information can possibly compensate for the reduced visual cues on vehicle swaying caused by a magnification factor smaller than 1.0.

Figure Captions

<u>Figure 1.</u> Images showing the four camera conditions in which the spatial orientation aids were present. The car was aligned with the right hand road marking. For the 100° diagonal field of view, the car is partly visible.

<u>Figure 2.</u> Interactions between camera viewpoint and FOV on the lateral position performance.

<u>Figure 3.</u> Interaction of camera viewpoint and field size on the lateral position performance in the sharp curves task.

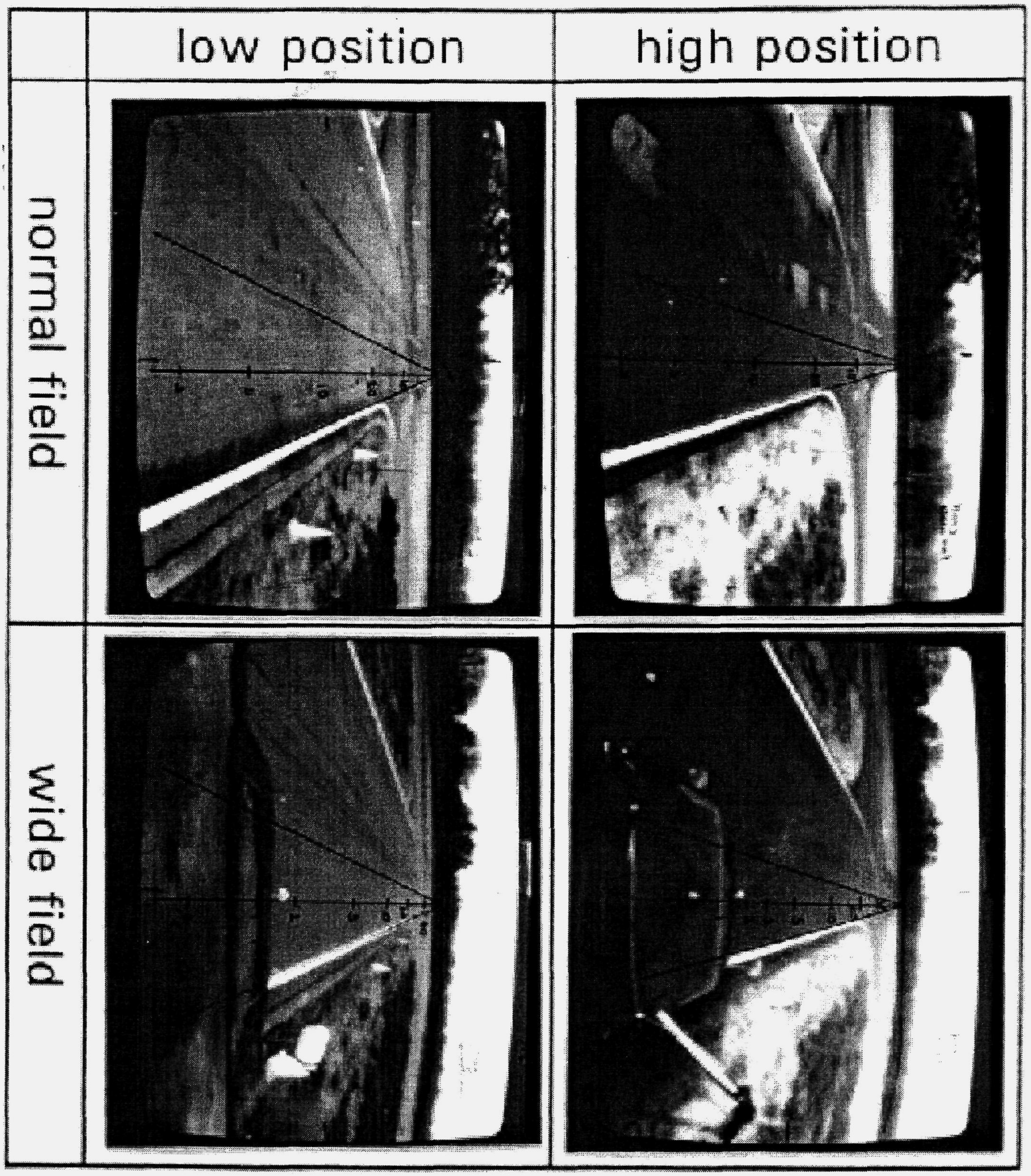
<u>Figure 4.</u> Interaction of field size and curve direction on the course instability in the sharp curves task.

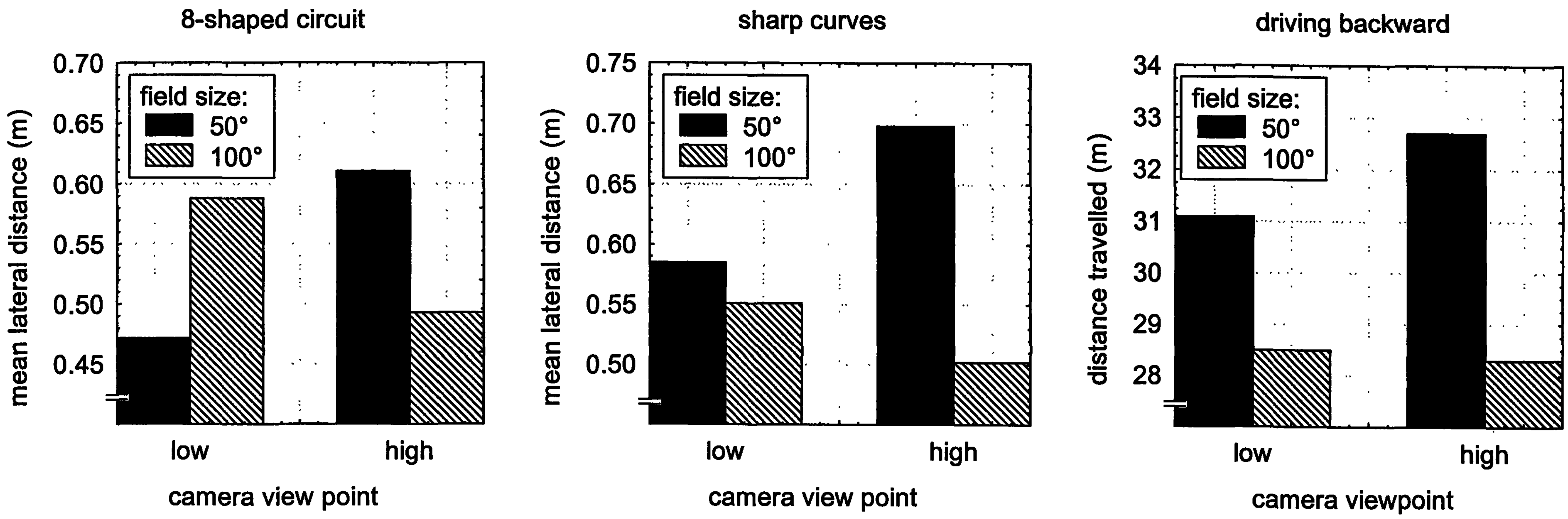
<u>Figure 5.</u> Main effect of update rate in turning sharp curves on the lateral position performance (circles and left axis), and the course instability (squares and right axis).

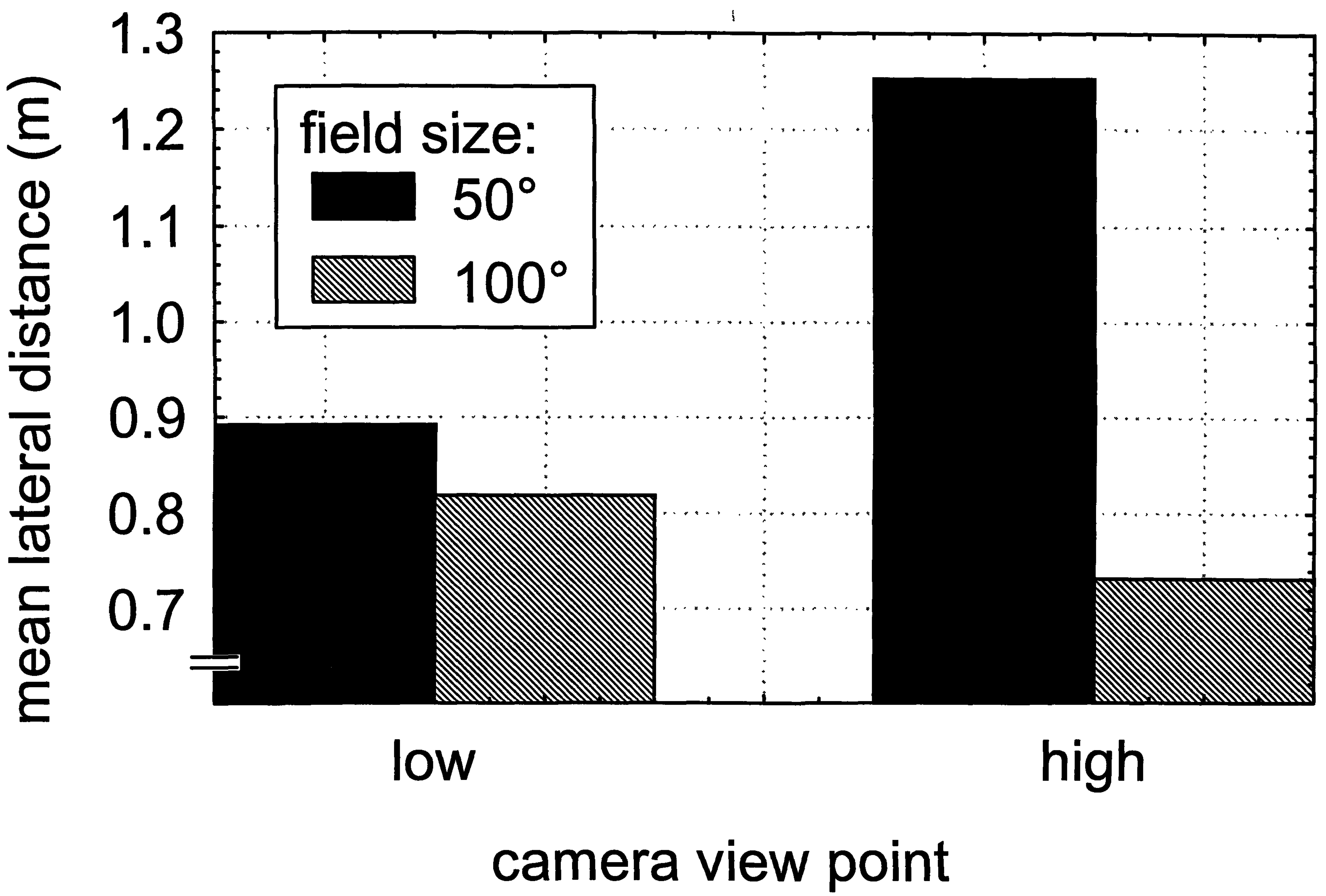
<u>Figure 6.</u> Main effect of update rate in the lane change task on the lateral position performance (circles and left axis), and the course instability (squares and right axis).

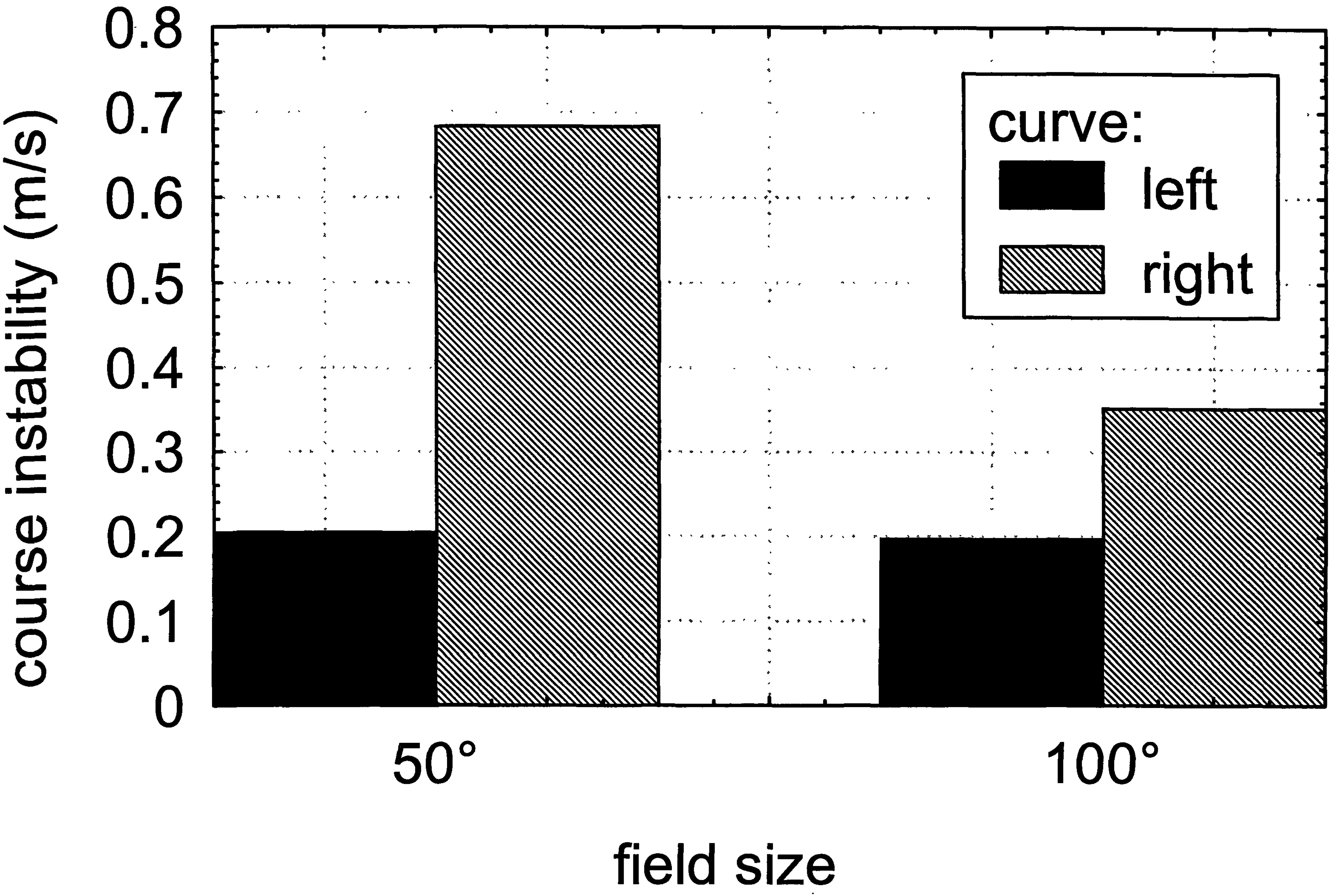
<u>Figure 7.</u> Main effect of spatial resolution in the lane change task on the lateral position performance (left bars and axis, not significant), and the course instability (filled bars and right axis).

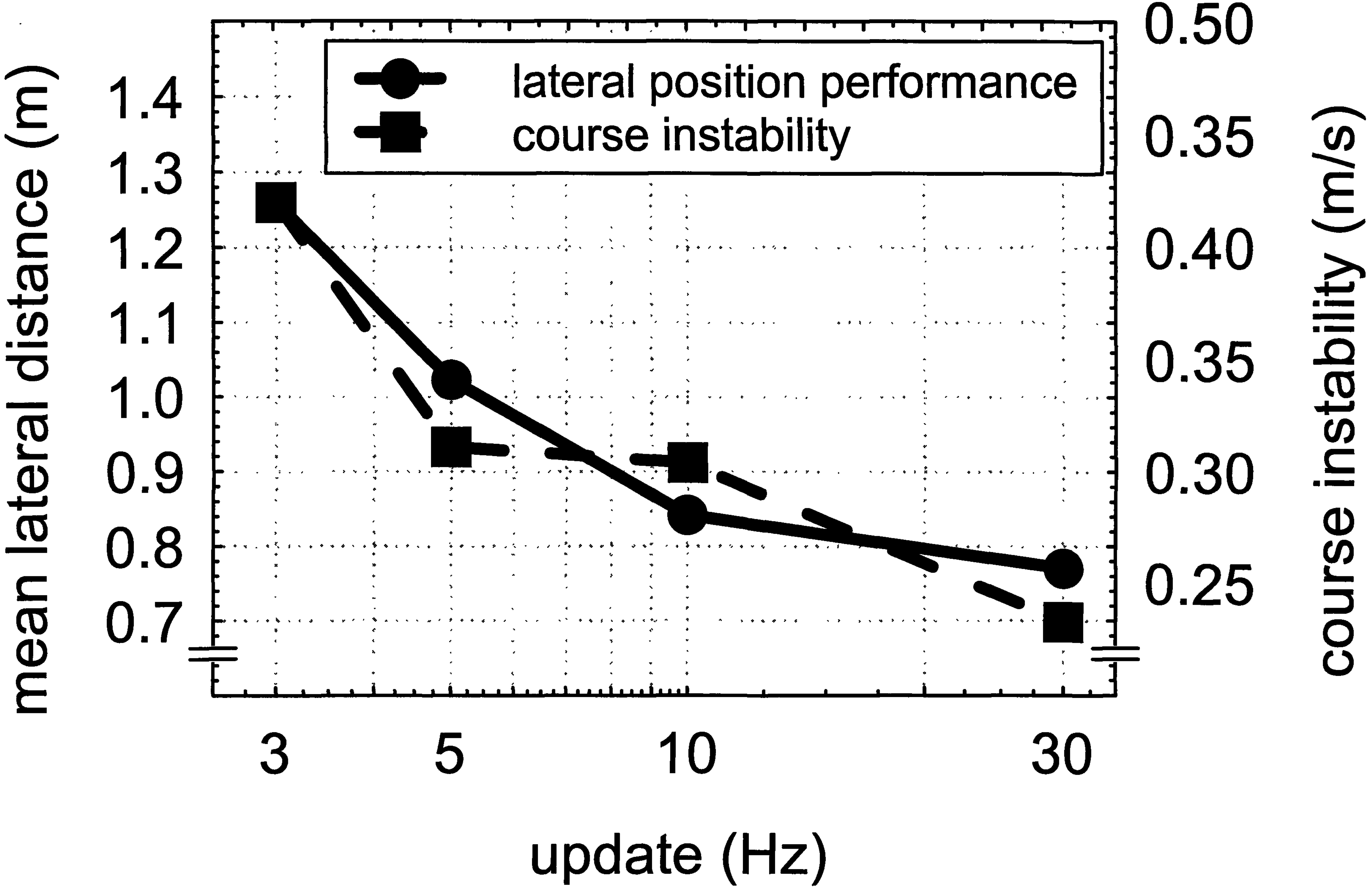
Figure 8. Effect of spatial resolution on the distance estimation task for target distance 50 m (filled bars) and 100 m (open bars).

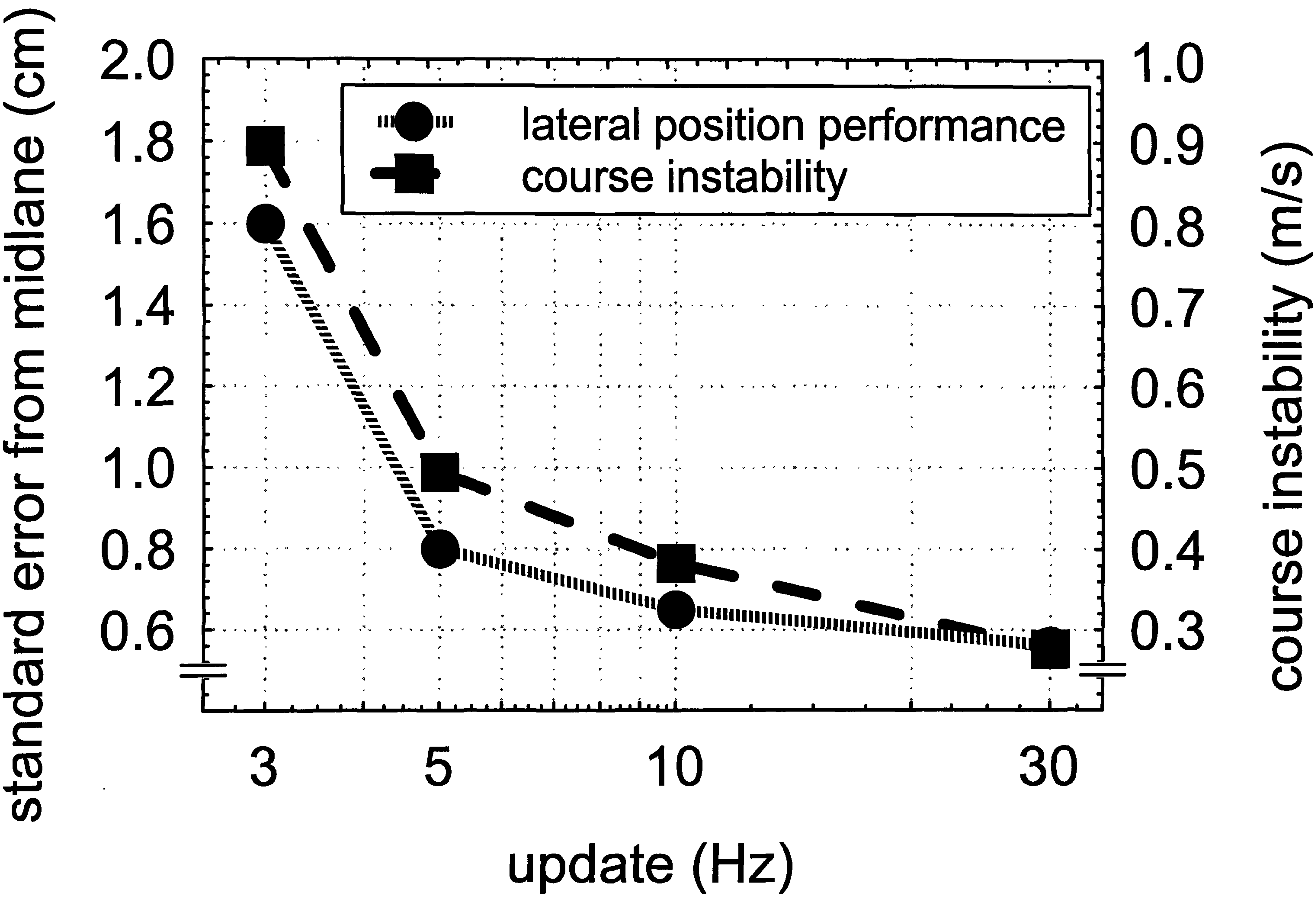

low position
high position
normal field
wide field

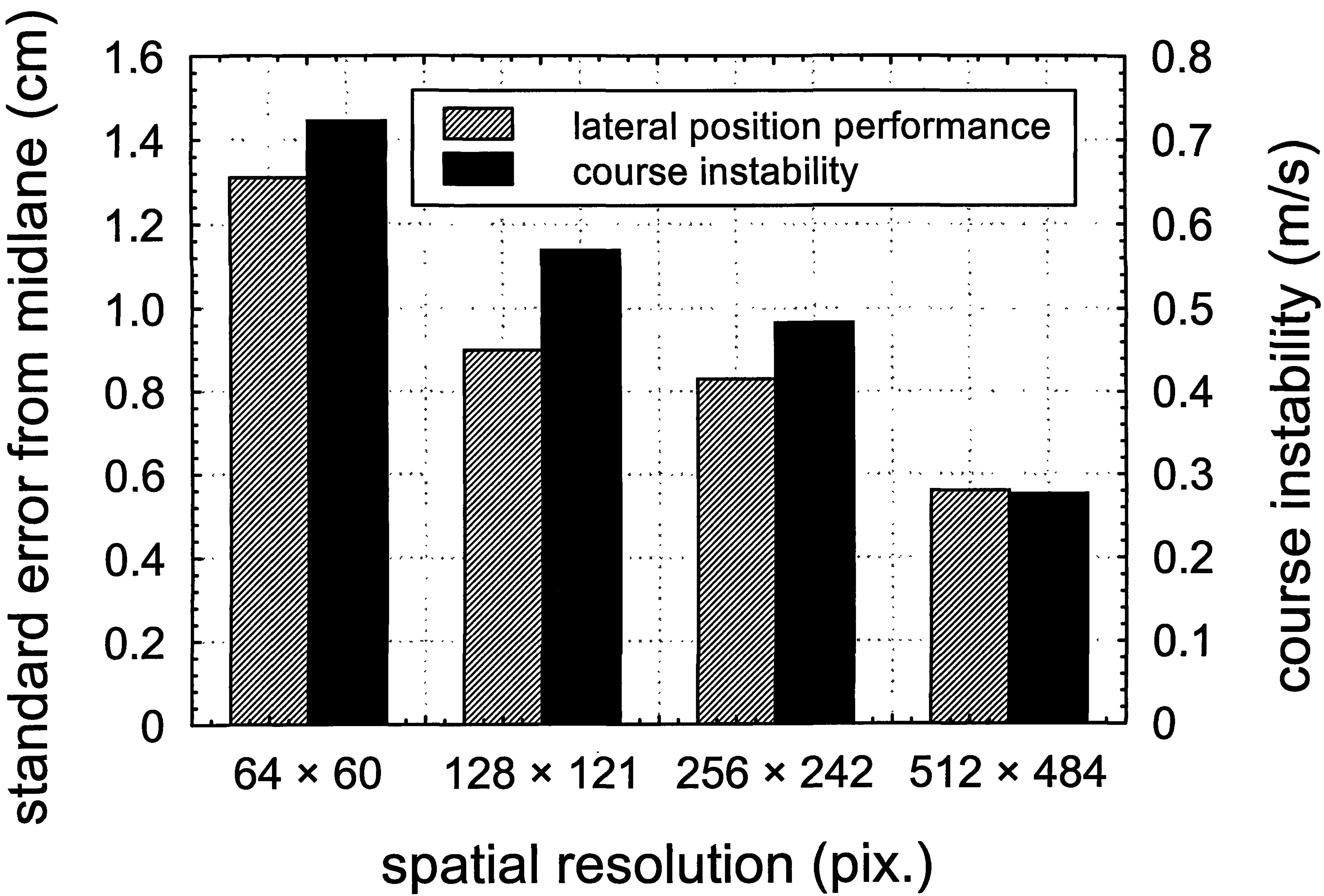

8-shaped circuit
mean lateral distance (m)
0.70
0.65
0.60
0.55
0.50
0.45
field size:
50°
100°
low
high
camera view point
sharp curves
mean lateral distance (m)
0.75
0.70
0.65
0.60
0.55
0.50
field size:
50°
100°
low
high
camera view point
driving backward
distance travelled (m)
34
33
32
31
30
29
28
field size:
50°
100°
low
high
camera viewpoint


mean lateral distance (m)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
field size:
50°
100°
low
high
camera view point

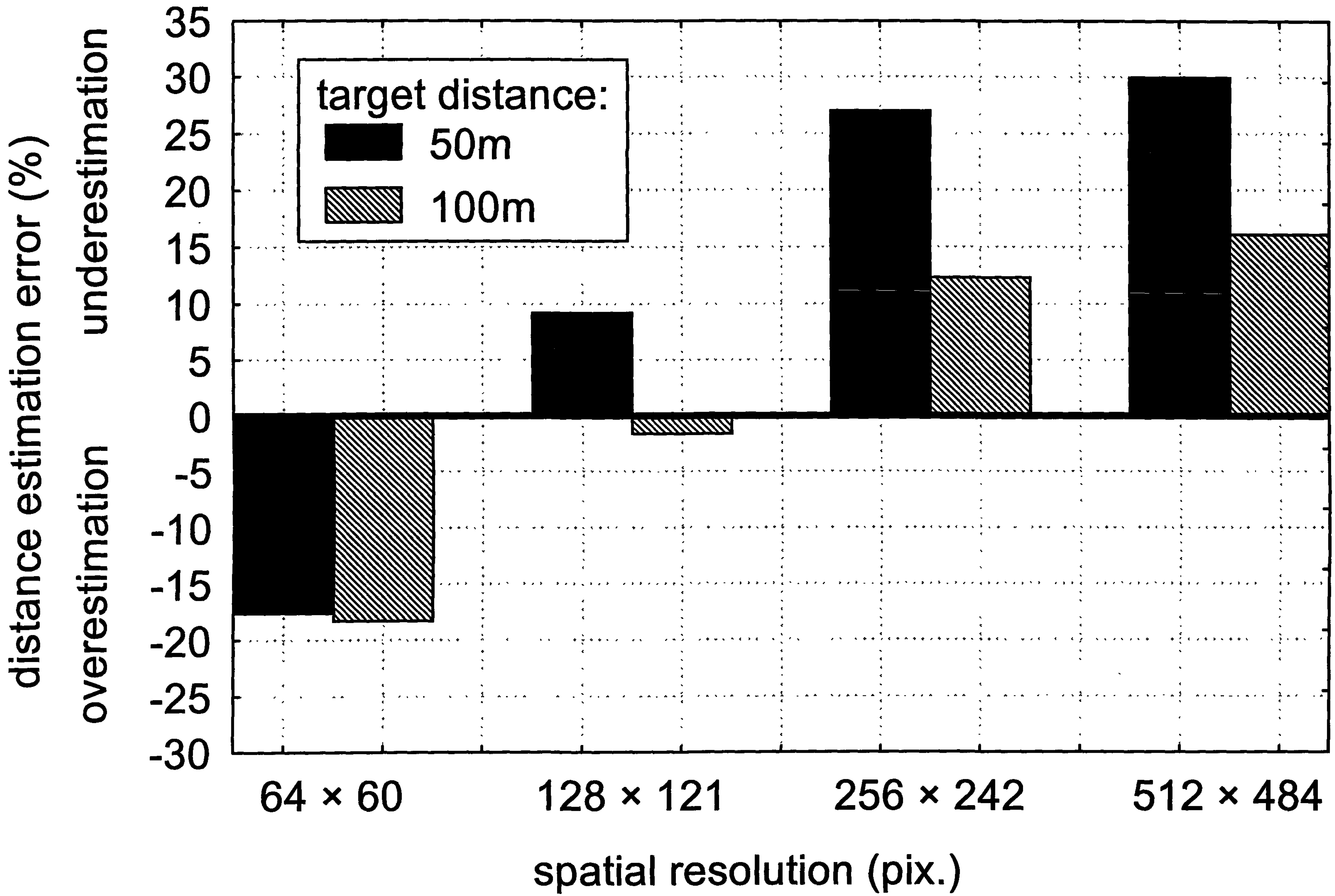

course instability (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
curve:
left
right
50°
100°
field size


lateral position performance
course instability
mean lateral distance (m)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.50
0.35
0.40
0.35
0.30
0.25
course instability (m/s)
3
5
10
30
update (Hz)


standard error from midlane (cm)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
lateral position performance
course instability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
course instability (m/s)
3
5
10
30
update (Hz)



standard error from midlane (cm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
lateral position performance
course instability
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
course instability (m/s)
64 × 60
128 × 121
256 × 242
512 × 484
spatial resolution (pix.)


distance estimation error (%)
underestimation
overestimation
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
target distance:
50m
100m
64 × 60
128 × 121
256 × 242
512 × 484
spatial resolution (pix.)