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A Study of the Effects of Lens Focal Length on Remote Driver Performance

Monica M. Glumm
Patricia W. Kilduff
Amy S. Masley

ARL-TR-25

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M. M. Glumm; P. W. Kilduff; A. S. Masley

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The effects of three lens focal lengths on remote driving performance were measured. The three focal lengths and their corresponding horizontal fields of view (FOVs) were 12 mm (29°), 6 mm (55°), and 3.5 mm (94°). On-board driving performance (direct view) was also measured. The study was conducted on an indoor test course consisting of six segments: straightaways, right-hand turns, left-hand turns, serpentine, figure 8, and obstacle avoidance. The findings indicate that for the first five segments of the course, driving speed and accuracy were significantly greater ($p < .05$) with the 6-mm lens than with either the 12-mm or the 3.5-mm lens. In the last course segment (obstacle avoidance), speed and accuracy were significantly less ($p < .05$) with the 12-mm lens than with either the 6-mm or the 3.5-mm lens. Differences between the latter two lenses in speed and accuracy were not statistically significant. For the first five segments of the course, significantly greater speed and accuracy ($p < .05$) was achieved during on-board operations than during operations in the remote mode using the 6-mm lens. In the obstacle avoidance segment, speed was also significantly greater in the on-board mode ($p < .05$), but there was no significant difference in speed between the 6-mm and the 3.5-mm lens. In this analysis, the 6-mm lens was found to be less accurate ($p < .05$) than the 3.5-mm lens or the on-board driving mode, but the significance of this difference was considered marginal. No significant difference in accuracy was found between on-board driving and remote operations using the 3.5-mm lens. Overall, in five of the six course segments, the 6-mm lens resulted in significantly greater speed and accuracy than either of the other two focal length conditions. The results of this investigation indicate that the 6-mm lens focal length offered a more acceptable trade-off among FOV, resolution, and image distortion than either the 12-mm or the 3.5-mm lens.

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A STUDY OF THE EFFECTS OF LENS FOCAL LENGTH ON REMOTE DRIVER PERFORMANCE

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APPROVED: ROBIN L. KEESEE
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CONTENTS

EXECUTIVE SUMMARY

This was the first in a series of investigations conducted by the Human Research & Engineering Directorate (HRED) of the U.S. Army Research Laboratory (ARL) in support of the program manager for unmanned ground vehicles (PM-UGV). The primary objective of this study was to measure the effects of three lens focal lengths on remote driving performance (i.e., speed and accuracy). The three focal lengths chosen for assessment and their corresponding horizontal fields of view (FOVs) were 12 mm (29°), 6 mm (55°), and 3.5 mm (94°). On-board driving performance was also measured and compared with data obtained during the remote driving phase. The study was conducted on an indoor test course consisting of six segments, which included straightaways, right-hand turns, left-hand turns, serpentine, figure 8, and obstacle avoidance. For the first five segments of the course, the measure of accuracy was the absolute deviation from the centerline of the road. For the last segment (obstacle avoidance), accuracy was based on obstacles hit. Data obtained in this latter segment were analyzed separately from those obtained in Segments 1 through 5. The findings indicate that for the first five segments of the course, speed and accuracy were significantly greater ($p < .05$) with the 6-mm lens than with either the 12-mm or 3.5-mm lens. In Segment 6 (obstacle avoidance), speed and accuracy were significantly less ($p < .05$) with the 12-mm lens than with either the 6-mm or 3.5-mm lens. The results also indicated that differences between the latter two lenses in speed and accuracy were not statistically significant

Follow-on analyses compared performance in the remote mode with those achieved during on-board operations. In Segments 1 through 5, significantly greater speeds and accuracy ($p < .05$) were achieved during on-board operation than during operations in the remote mode using the 6-mm lens. In Segment 6, higher speeds ($p < .05$) were also achieved during on-board driving. There was no statistically significant difference in speed between the 6-mm and the 3.5-mm lenses. Remote operations using the 6-mm lens were less accurate than on-board driving. In contrast to the results of the previous analysis of differences in performance among the three lens focal length conditions, the findings indicated that the 6-mm lens was also less accurate than the 3.5-mm lens. The significance of this difference, however, was suggested by analysis to be marginal. There was no statistically significant difference in accuracy between on-board driving and remote operations using the 3.5-mm lens.

The results of this investigation indicate that the 6-mm lens offers a more acceptable trade-off among FOV, resolution, and image distortion than either the 12-mm or the 3.5-mm lens focal lengths. There is evidence to suggest that FOV and visual distortions were the major contributors to degradations in remote driving performance. The findings of this study support the selection of a lens focal length that causes minimum optical distortion and most accurately depicts the size, distance, and speed of objects as they would normally be seen when viewed directly by the human eye.

A STUDY OF THE EFFECTS OF LENS FOCAL LENGTH ON REMOTE DRIVER PERFORMANCE

INTRODUCTION

Although the technology for constructing remotely operated military systems exists, the knowledge base needed to support cost-effective design decisions is still lacking. The Human Research & Engineering Directorate (HRED) of the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, Maryland, in support of the program manager for unmanned ground vehicles (PM-UGV), is conducting research to identify visual display and control device design characteristics required for teleoperation, particularly as they apply to the quantity and quality of sensory input needed by the remote operator to perform a given task effectively.

The current focus of this research is on the task of remote driving and associated vision requirements. The video image transmitted to the teleoperator is provided by a single, black-and-white camera fixed on the chassis of the remote vehicle. Initial investigations try to optimize this configuration and derive a baseline suitable for follow-on experimentation that will quantify the effects of system enhancements and provide the data needed to support cost-benefit trade-off analyses.

The first in this series of investigations, which is the subject of this report, was conducted to select a lens focal length for the baseline camera configuration.

The focal length of the camera's lens will affect several important aspects of the image provided to the remote driver. Unfortunately, a positive effect in one area may induce a negative effect in another. Lens focal length will determine the horizontal and vertical fields of view (FOVs) provided to the remote operator. The shorter the focal length, the wider the FOV. Although wider FOVs supply more visual information to the driver regarding his or her environment, peripheral distortion may occur as focal length is reduced. Objects may also appear farther away than they actually are; the converse is true for longer focal lengths. As focal length is reduced, so is resolution. McGovern (1987) notes that with a high resolution camera (750 horizontal pixels) a 6.5° FOV is required to provide normal (20/20) vision to the operator, whereas the visual equivalent for a 90° FOV is worse than 20/150.

A number of studies have been conducted during the past years examining remote driver performance using various size vehicles on both indoor and outdoor test courses, but few have addressed the issue of lens focal length. Although Silverman (1982) used a fixed camera, his evaluation was limited to lenses that provided one narrow (31°) and one wide (96°) FOV. His indoor test course was composed of numerous turns. Difficulty was controlled by varying the width of the course. Silverman found a significant reduction in the number of times the vehicle contacted obstacles (which defined the course boundaries) and in control (joystick) movement for the wider FOV condition. McGovern (1980) also found that the remote operator, while driving a Jeep Cherokee on normal roads and parking lots, was not comfortable turning corners using a single camera with a narrow FOV (40°). Installation of two additional cameras to provide a total of 120° FOV resulted in much easier operation.

The data and information derived from these earlier investigations were insufficient to support the selection of a lens focal length for the baseline configuration. The study, which is the subject of this report, examines the effects of three focal lengths toward identifying the focal length that maximizes remote driving performance.

OBJECTIVES

The study was conducted in three phases. The primary objectives of each of these phases were as follow:

Phase 1 - to measure and compare the effects of three lens focal lengths on driver performance during remote operation of a small, four-wheel, electrically powered vehicle on an indoor test course consisting of five course segments. These five course segments include straightaways, right-hand turns, left-hand turns, serpentine, and a figure 8.

Phase 2 - to measure and compare the effects of the same three lens focal lengths on driver performance during remote operation of the vehicle on an obstacle avoidance course.

Phase 3 - to measure driver performance during on-board operation of the same vehicle on the same indoor test course and to compare these data with speeds and accuracies of the lens focal length(s) that yielded the best performance during Phases 1 and 2.

METHOD

Subjects

Nine military and nine civilian personnel participated in the investigation. All were males who ranged in age from 18 to 35 years with an average age of 27. The subjects were licensed drivers with 1 to 11 years of experience. All were screened to meet physical qualifications for visual acuity of the target user group of 20/20 vision in one eye and at least 20/100 in the other eye (corrected or uncorrected). The military occupational specialty (MOS) of six of the nine military volunteers was armor crewman (19K). The MOSs of the remaining three soldier participants were infantry officer (11A), artillery officer (13A), and ammunition specialist (55M). Most of the civilian subjects were employed as engineers and psychologists.

Apparatus

Research Platform

A four-wheel, teleoperated golf cart served as the research platform (see Figure 1). The golf cart (Model X-444) was built by E-Z-GO Division of Textron, Inc., and converted for remote operation for HRED by Tooele Army Depot in Tooele, Utah. The vehicle was approximately 1.2 m (4 ft) wide by 2.4 m (8 ft) long. Power was supplied by six 6-volt rechargeable batteries. The vehicle was capable of attaining a maximum speed of 22 kph (14 mph). The control station consisted of a steering wheel, brake, and accelerator pedals. Information about vehicle speed, wheel direction, and system voltage was transmitted from the vehicle and displayed on dial-type gauges at the operator's remote control panel. The vehicle was capable of being operated from an on-board driving position as well as remotely using the same control station. In the remote driving mode, the vehicle's control station was seated within a frame containing a 12-volt battery pack and electrical connector. The control station was attached to the frame by four bolts and a power hook-up cable. The station was easily removed as a unit from the frame and reinstalled on board the vehicle. This unique design feature enabled the researcher to measure and more reliably compare on-board versus remote driving performance.

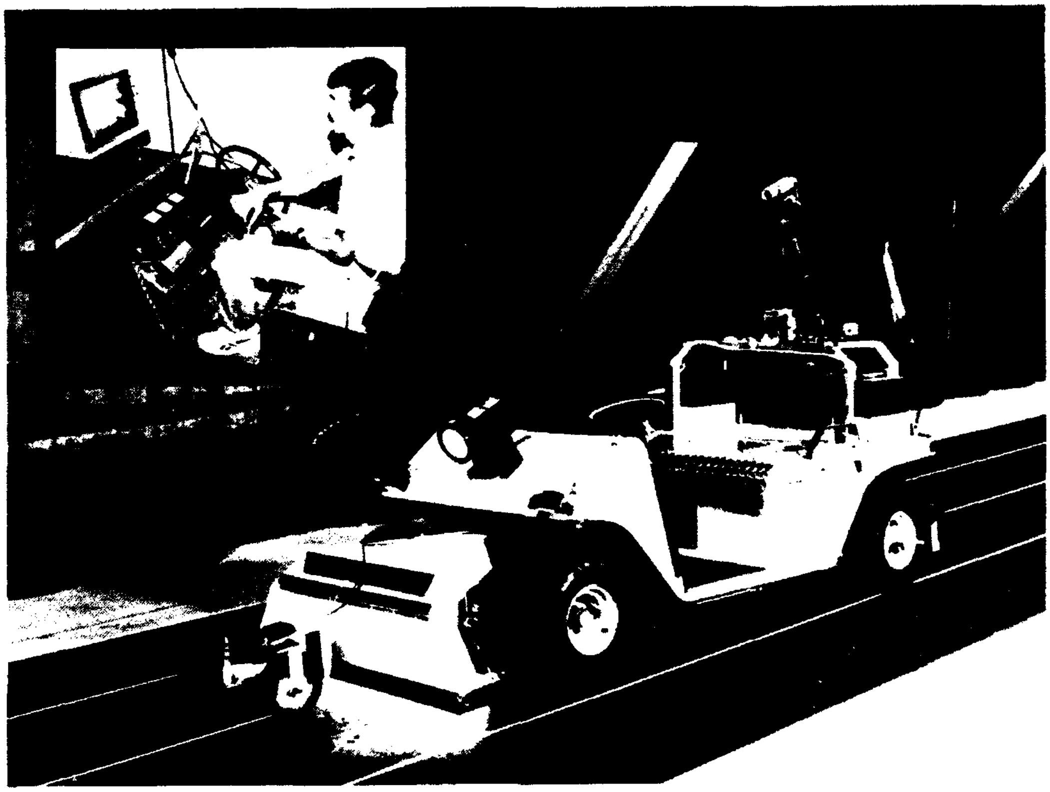

Figure 1. Teleoperated research platform and remote control station.

Video Camera

A PULNIX black-and-white, charged couple device (CCD) video camera (Model TM440) was fixed along the center of the y-axis (side to side) of the vehicle so that the horizontal FOV was equally distributed to either side of the vehicle's centerline. Camera location and orientation along the x (fore and aft) and z (vertical) axes were based upon an assessment of the adequacy of the sky-to-ground ratio for each lens focal length, close-in vision, and vehicle reference point accommodations.

Lenses

The three camera lenses used during the investigation were fixed focal lengths manufactured by Fujinon, Inc. Table 1 provides additional information about FOVs and resolutions of the camera lens and display system as defined by three different measuring techniques.

Table 1

Camera Lens Descriptions

Focal length	FOV Horizontal	FOV Vertical	Resolution: TV resolution chart (lines)[a]	Resolution: Armed forces visual acuity chart[b]	Resolution: Edmund resolving power chart (arc min)
12 mm	29°	22°	400	20/50	5.50
6 mm	55°	43°	400	20/100	12.35
3.5 mm	94°	75°	400	20/200	22.00

[a]Horizontal and vertical
[b]Calibrated; equivalent to Snellen eye chart

Transmitter

The video image was transmitted by a COHERENT Communications, Inc., UHF channel video transmitter (Model VT-250) to a VIDTECH tuner/receiver (Model RS-2001).

Monitor

The video image was displayed to the remote driver on a black-and-white DAGE-MTI, Inc., monitor (Model HR 2000) with 13-inch screen. The monitor was situated approximately 76 cm (30 inches) forward of the operator. The center of the monitor was 15° below the operator's (50th percentile male) horizontal line of sight.

Test Course Instrumentation

The following lists the major items of equipment used in measuring and processing driver performance data on the robotic test facility's indoor test course:

On-board Instrumentation:

Video camera (monochrome), PULNIX America, Inc., (Model TM440), with 4.8-mm lens, COSMICAR

UHF video transmitter, COHERENT, (Model VT-400)

Off-board Instrumentation:

TV receivers, VIDTECH, (Model RS-2001)

Video contrast trackers, DBA Systems, Inc. (Model 606-3A)

Monitor (13-inch), Sony TRINITRON (Model PVM-1342Q)

Video recorder (S-VHS), Panasonic (Model AG 7400)

Data Processor System:

Microcomputer, Compaq (Model Deskpro 386)

Digital interface for PC, Real-Time Systems (Model DG 96)

Video graphics array (VGA) monitor, Compaq (Model 420)

Procedures

Indoor Test Course

The study was conducted on an indoor test course at Aberdeen Proving Ground (APG), Maryland. The course, which is housed in a former aircraft hangar, was jointly developed by the U.S. Army Combat Systems Test Activity (USACSTA) and ARL (see Figure 2). Its black macadam roadway is 2.7 m (9 ft) wide and approximately 400 m (1/4 mile) long. The area surrounding the road is painted a lighter shade to define path boundaries. The course consists of six segments that include straightaways, right-hand turns, left-hand turns, serpentine, figure 8, and an obstacle avoidance segment. Driving performance on each of these segments is scored automatically, and summary statistics are available immediately after each run. These performance data include vehicle speed and accuracy.

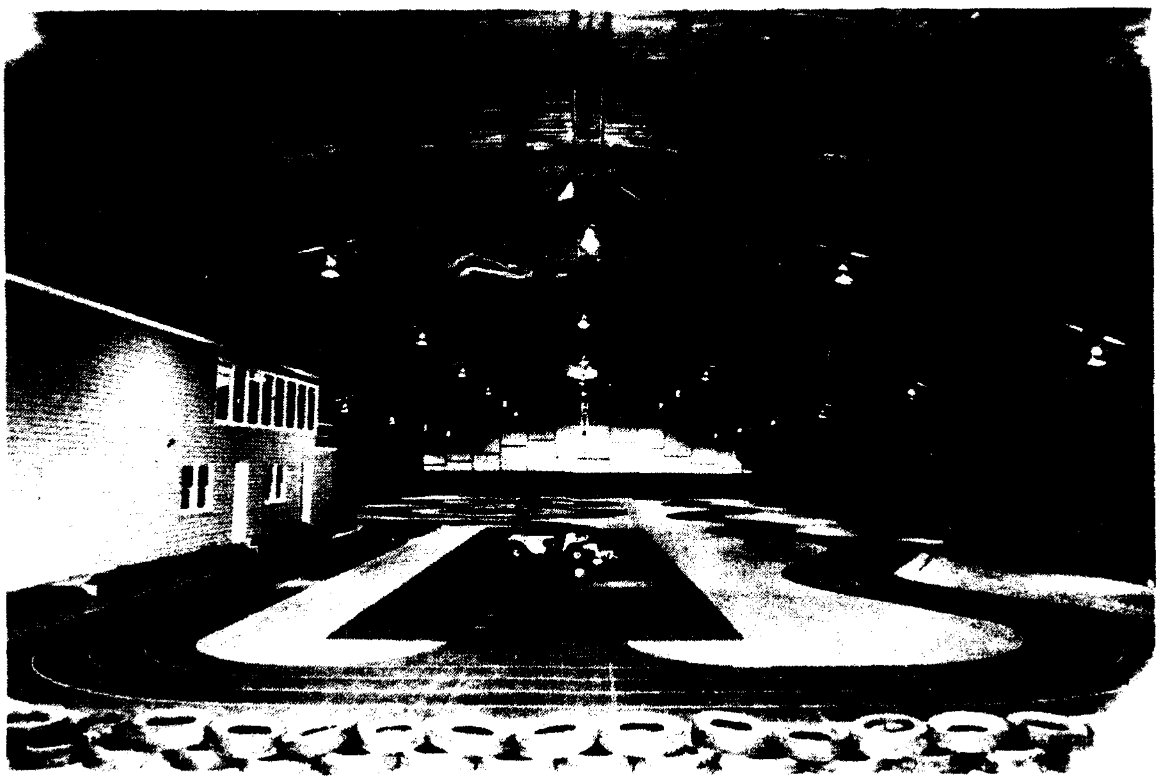

Figure 2. USACSTA-ARL robotic test facility's indoor test course.

The measure of accuracy for all course segments, except for the obstacle avoidance segment, is the amount of absolute deviation from the centerline of the road. This centerline, along with four other stripes, is painted on the roadway's surface. Each stripe is approximately 1.3 cm (1/2 in.) wide. The stripes are spaced 68.5 cm (27 in.) apart and run parallel along the length of the course. A fluorescent light, video camera, and transmitter are mounted within a hood attached to the front of the vehicle. The fluorescent light illuminates the stripes on the road directly beneath the hood for the video camera (see Figure 3). The video image of these stripes is transmitted to the data acquisition center for processing by two contrast trackers. These trackers lock onto the right edge of the right-most stripe in the FOV of the camera and compute the position of that stripe relative to the camera's horizontal FOV. Data pertaining to deviations from road centerline are collected at a rate of 60 times a second.

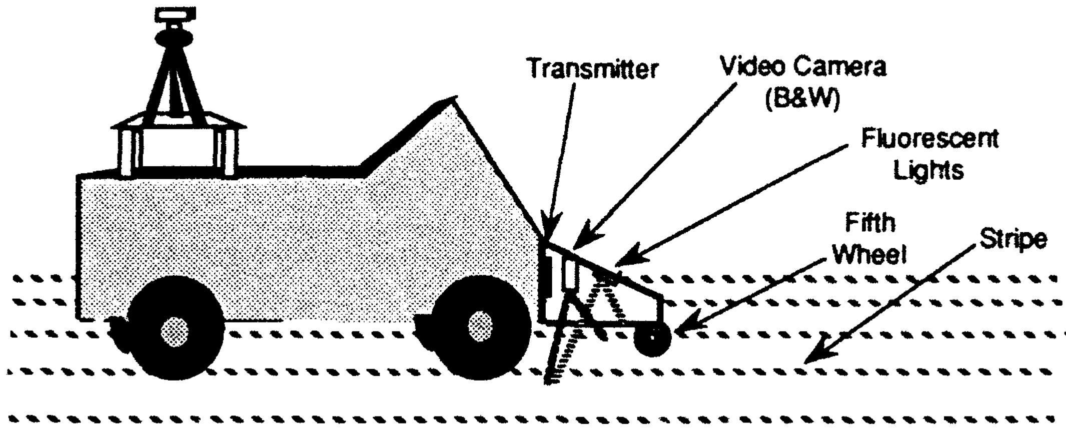

Figure 3. On-board instrumentation for measuring deviations from road centerline.

The obstacle avoidance segment, located at the end of the course, is the last maneuver to be performed. In this segment, the vehicle is driven between and around traffic cones spaced approximately 4.9 m (16 ft) apart. The number of traffic cones hit is used to determine the level of accuracy for this segment. These data are provided by normally open contact switches, which are incorporated into each pylon and linked to the computer. Failure to maneuver the vehicle between any two traffic cones is also counted as a hit.

A microswitch, located at the start of the course, senses the commencement of a run, and data collection is initiated automatically. Data collection is terminated in a similar manner. Microswitches are also located at the beginning and end of each course segment. If the vehicle temporarily strays off the course to a point where there are no stripes within the FOV of the camera, microswitches located every 4.9 m (16 ft) within each segment identify the vehicle location upon its return and resume data collection. Vehicle speed is computed within each of these intervals based on time and distance traveled. The revolutions of a fifth wheel are converted into digital pulses that correspond to the actual distance traveled by the research platform.

Minimum Performance Requirements

Before the subject investigation, a pilot study was conducted to determine the following:

- the minimum levels of performance the subjects must attain during training in remote and on-board driving, respectively.

- an estimate of the number of trials required to train the subjects to these minimum performance levels.

- the independence of the speed and accuracy data over a segment.

During the pilot study, each of five subjects was trained until they achieved an asymptote in both speed and accuracy (i.e., deviations from road centerline) over all course segments. A minimum level of performance was first established for remote operations using the mid-size 6-mm lens. The mean performance of the five subjects in speed and accuracy was used to determine the minimum level of performance subjects were to attain during subsequent training periods in remote driving. Similar procedures were followed in establishing a minimum level of performance for on-board driving.

On the average, subjects attained asymptote after 12 completions of the course during remote operations compared to six when driving from the on-board position. Overall mean speed and accuracy are shown in Table 2. A bivariate correlation indicated that speed and accuracy over a course segment were not highly correlated ($r = .401$, $p > .05$). Because speed and accuracy were assumed to be independent, separate repeated measures multivariate analyses of variance (MANOVAs) were performed for each.

Table 2

Minimum Performance Requirements

Driving mode	Speed (kph)	Accuracy (cm)
On board	8.5	13.0
Remote	6.5	16.0

Subject Screening and Pretest Questionnaires

An acuity test, at far and near distances, was administered to each of the 18 volunteers to ensure 20/20 corrected or uncorrected vision in one eye and at least 20/100 in the other eye. This requirement was based on physical qualifications for visual acuity of the target user group. All subjects completed a questionnaire to obtain pertinent demographic and background information (see Appendix A).

Training and Test

To minimize potential bias in the evaluation of remote operator performance, the remote phase of the investigation preceded on-board driving. Each subject was seated at the remote control station and was asked to perform a successive number of trials or runs through the entire course until the established minimum performance levels in speed and accuracy were reached over all course segments and maintained for three trials. The subjects then completed two trials for each of the three lens focal length conditions. Lens focal length presentation was counterbalanced randomly (see Table 3), whereas the presentation of course segments was not. Each subject traveled the same course segments in the same order during all trials. When the remote driving phase of the investigation was completed, the control station was mounted on the vehicle chassis for on-board driver training. As in remote training, the subject was trained to a minimum level of performance established for on-board driving. The subjects then completed two trials in the on-board driving mode. As in the remote driving phase of study, each subject traveled the same course segments in the same order during all trials. Throughout each phase of the study, the subjects were reminded that speed and accuracy were equally important. They were instructed to drive as fast and as accurately as possible.

Table 3

Counterbalancing Scheme

Subject	Focal length Order of presentation		
1	1	2	3
2	2	3	1
3	3	1	2
4	1	2	3
5	2	3	1
6	3	1	2
7	1	2	3
8	2	3	1
9	3	1	2
10	1	2	3
11	2	3	1
12	3	1	2
13	1	2	3
14	2	3	1
15	3	1	2
16	1	2	3
17	2	3	1
18	3	1	2

Motion Sickness Questionnaire

A motion sickness questionnaire was administered to the subjects before, during, and after training and test in both the remote and on-board phases of study (see Appendix B). The purpose of the questionnaire was to ensure that symptoms related to motion sickness did not exert a significant influence on the results of the investigation.

EXPERIMENTAL METHODOLOGY

The design matrix is shown in Figure 4. The study was a full factorial, within subjects (repeated measures) design. The independent variables were lens focal length and course segment. The three focal lengths and their corresponding horizontal FOVs were 12 mm (29°), 6 mm (55°), and 3.5 mm (94°). The six course segments were (1) straightaways, (2) right-hand turns, (3) left-hand turns, (4) serpentine, (5) figure 8 and (6) obstacle avoidance. The dependent variables were vehicle speed and accuracy. The measure of accuracy for all course segments, except for obstacle avoidance (Segment 6), was the amount of absolute deviation from the centerline of the road. The obstacle avoidance segment, located at the end of the course, was the last maneuver to be performed. These data were analyzed separately from data obtained on course Segments 1 through 5. The number of traffic cones hit was used to determine the level of accuracy for this segment. Speed and accuracy data obtained during the on-board driving phase of the investigation provided a baseline for assessment of remote driving performance.

STATISTICAL ANALYSES

Phase 1

Repeated measures MANOVAs (Wilks' λ) were performed on speed and accuracy data obtained for each of the three lens focal lengths on course Segments 1 through 5. Tukey's multiple comparison test was used to determine where statistically significant differences lay among the three lens focal lengths.

Phase 2

A repeated measures MANOVA was used to assess the effect of focal length on vehicle speed in course Segment 6 (obstacle avoidance). Tukey's multiple comparison test was used to determine where differences in speed and accuracy lay among the three focal lengths. A chi-square test was performed to assess the effect on accuracy (traffic cones hit).

Phase 3

Repeated measures MANOVAs were performed on speed and accuracy data for those focal lengths that achieved the best performance during remote operations and those data obtained in the on-board driving (Baseline) mode for course Segments 1 through 5. A repeated measures MANOVA was also used to determine the significance of differences in speed among these focal lengths and the Baseline condition on course Segment 6. A chi-square test was performed to assess the effect on accuracy in this latter segment. Tukey's multiple comparison tests were used to determine where significant differences lay.

Remote Driving					
Course Segments			Focal Length (horizontal field of view)		
			12 mm (29°)	6 mm (55°)	3.5 mm (94°)
Phase 1	1	Straightaway			
	2	Right Turns			
	3	Left Turns			
	4	Serpentine			
	5	Figure 8			
Phase 2	6	Obstacle Avoidance			

Driving Mode						
Course Segments			Remote			On Board
			12 mm	6 mm	3.5 mm	Direct View
Phase 3	1	Straightaway				
	2	Right Turns				
	3	Left Turns				
	4	Serpentine				
	5	Figure 8				
	6	Obstacle Avoidance				

Figure 4. Design matrix.

RESULTS

Driving performance

Phase 1

Table 4 shows mean speed and accuracy data for each of the three lens focal length conditions over course segments 1 through 5. The results of the MANOVAs, presented in Tables 5 and 6, indicated that there was a statistically significant difference among the three focal lengths and course segments in both speed and accuracy ($p < .05$). There was also a significant interaction between focal length and segment for both speed and accuracy.

Table 4

Mean Speed and Accuracy by Lens Focal Length

Speed (kph)

Segments 1 through 5			Significance	Segment 6 (obstacle avoidance)			Significance
12 mm (29°)	6 mm (55°)	3.5 mm (94°)		12 mm (29°)	6 mm (55°)	3.5 mm (94°)	
6.3*	7.0	6.5*	<.05 / *NS[a]	3.4	4.9*	5.1*	<.05 / *NS[a]

Errors: (cm) for Segments 1 through 5; (hits) for Segment 6

Segments 1 through 5			Significance	Segment 6 (obstacle avoidance)			Significance
12 mm (29°)	6 mm (55°)	3.5 mm (94°)		12 mm (29°)	6 mm (55°)	3.5 mm (94°)	
40.4	16.7	23.7	<.05	1.5	0.17*	0.08*	<.05 / *NS[a]

[a]Differences between asterisked items are not statistically significant, but differences between asterisked and non-asterisked items are significant at the level indicated.

Table 5

MANOVA Results of Accuracy on Course Segments 1 Through 5

Source	Equivalent F	df	Wilks' λ	P
Focal length	23.608	2,16	0.2531	<.05
Segment	30.284	4,14	0.1036	<.05
Focal length x segment	5.559	8,10	0.1836	<.05

Table 6

MANOVA Results of Speed on Course Segments 1 Through 5

Source	Equivalent F	df	Wilks' λ	P
Focal length	23.119	2,16	0.2571	<.05
Segment	44.698	4,14	0.0726	<.05
Focal length x segment	9.099	8,10	0.1208	<.05

Tukey's multiple comparison tests for focal length revealed that speed and accuracy were significantly greater ($p < .05$) with the 6-mm (55°) lens than with either the 12-mm (29°) or 3.5-mm (94°) lens. The 3.5-mm lens was significantly more accurate ($p < .05$) than the 12-mm lens, but differences in speed between the two focal lengths were not significant.

A breakdown of mean speed and accuracy data for each of the three focal length conditions by course segment is provided in Appendix C. As can be seen, the main effect for segment could be attributed to the significantly greater speeds and accuracy achieved on course Segment 1 (straightaway) as compared to any of the other course segments. The interaction effect of focal length by segment was attributed to the significantly greater speed and accuracy achieved by the 6-mm lens which was most readily noticeable on course Segment 1.

Phase 2

Table 4 above also shows mean speed and accuracy data for each of the three focal length conditions for course Segment 6 (obstacle avoidance). A repeated measures MANOVA and chi-square test were used to assess the effects of focal length on speed and accuracy (number of cones hit), respectively. The results of these analyses, presented in Tables 7 and 8, indicated statistically significant differences in both speed and accuracy among the three focal lengths.

Table 7

MANOVA Results of Speed on Course Segment 6

Source	Multivariate F	df	Wilks' λ	P
Focal length	12.724	2,16	.3860	<.05

Table 8

Chi-square Test Results of Accuracy for Course Segment 6

Source	Chi-square	df	P
Focal length	63.27	2	<.05

Tukey's multiple comparison test revealed that speed and accuracy were significantly less ($p < .05$) with the 12-mm lens than with either the 6-mm or 3.5-mm lens. In this analysis, differences between the 6-mm and the 3.5-mm lens in speed and accuracy were not found to be significant.

Phase 3

During Phase 1, in course Segments 1 through 5, the 6-mm lens focal length achieved significantly greater speed and accuracy than did either the 12-mm or the 3.5-mm lens. During Phase 2, no significant differences were found between the 3.5-mm and the 6-mm lens in performance on course Segment 6. Therefore, during Phase 3, in course Segments 1 through 5, on-board driving performance (baseline) was compared with performance with the 6-mm lens, and in course segment 6, performance in the on-board mode was compared with that of both the 6-mm and 3.5-mm lens. Mean speed and accuracy data for these lens focal lengths and the baseline condition are shown in Table 9. The significant differences in speed and accuracy among the remote and on-board driving modes reflect the results of the MANOVAs presented in Tables 10 through 12.

The results of the MANOVA test (Wilks' λ) of accuracy data obtained on course Segments 1 through 5 are shown in Table 10. There was an approximate 4-cm difference in accuracy between remote driving performance with the 6-mm lens and performance in the on-board driving mode. This difference was statistically significant ($p < .05$). The results also show a significant main effect for course segment on accuracy ($p < .05$) between remote driving (6-mm lens) and on-board operation. There was no significant interaction effect between driving modes and course segment on accuracy.

The results of the MANOVA of speed data obtained in course Segments 1 through 5 are shown in Table 11. The results show a significant main effect ($p < .05$) and a significant interaction effect ($p < .05$) for focal length and course segment. Tukey's multiple comparison test revealed that this latter interaction effect was attributable to the significantly greater speeds ($p < .05$) achieved on course Segments 1 and 5 (straightaway and figure 8) and the significantly lower speeds ($p < .05$) achieved on Segment 4 (serpentine) by comparison with performance on Segments 2 and 3 (right- and left-hand turns).

A repeated measures MANOVA was performed on speed data obtained on course Segment 6 (obstacle avoidance). The results shown in Table 12 indicate that there was a statistically significant difference in speed ($p < .05$) among the two lens focal lengths (6 mm and 3.5 mm) and the baseline (on-board driving) condition. Tukey's multiple comparison test revealed that these significant differences lay between the baseline and each of the remote driving conditions (i.e., 6-mm and 3.5-mm lens focal lengths). There was no statistically significant difference in speed, however, between the 6-mm and 3.5-mm focal length conditions.

Table 9

Mean Speed and Accuracy for Those Focal Lengths Achieving the Best Performance During Remote Operation and Performance in the On-board Driving (baseline) Mode

Speed (kph)

Segments 1 through 5		Significance	Segment 6 (obstacle avoidance)			Significance
6 mm (55°)	Baseline		6 mm (55°)	3.5 mm (94°)	Baseline	
7.0	9.1	<.05	4.9*	5.1*	7.3	<.05 / *NS [a]

(cm) Errors (hits)

Segments 1 through 5		Significance	Segment 6 (obstacle avoidance)			Significance
6 mm (55°)	Baseline		6 mm (55°)	3.5 mm (94°)	Baseline	
16.7	12.7	<.05	0.17	0.08	0.08	NS

[a]Differences between asterisked items are not statistically significant, but differences between asterisked and non-asterisked items are significant at the level indicated.

Table 10

MANOVA Results of Accuracy for Course Segments 1 Through 5

Source	Equivalent F	df	Wilks' λ	P
Focal length/ baseline	19.326	1,17	0.467	<.05
Segment	13.823	4,14	0.202	<.05
Focal length x segment	1.574	4,14	0.689	NS

Table 11

MANOVA Results of Speed for Course Segments 1 Through 5

Source	Equivalent F	df	Wilks' λ	P
Focal length/ baseline	220.687	1,17	0.071	<.05
Segment	77.031	4,14	0.043	<.05
Focal length x segment	25.058	4,14	0.877	<.05

Table 12

MANOVA Results of Speed for Course Segment 6

Source	Multivariate F	df	Wilks' λ	P
Focal length/ baseline	10.387	2,16	0.230	<.05

A chi-square test was used to assess the effects of focal length on accuracy in course Segment 6. The results, shown in Table 13, indicate statistically significant differences in performance ($p < .05$) among the baseline and the two lens focal length conditions.

Table 13

Chi-square Test Results of Accuracy for Course Segment 6

Source	Chi-square	df	P
Focal length	85.5	2	<.05

Tukey's multiple comparison test was used to determine where these differences in accuracy lay. The results showed that the 6-mm lens was significantly less accurate ($p < .05$) than either the 3.5-mm lens or the baseline condition. There was, however, no significant difference in accuracy between the 3.5-mm lens and the baseline conditions.

Motion Sickness

In their responses to the pretest questionnaire (see Appendix A), 50% of the subjects claimed that they were not at all susceptible to motion sickness. The remaining 50% indicated that they were minimally susceptible, but only 28% claimed that they had experienced some form of motion sickness in the past. An examination of the subjects' responses to the motion sickness questionnaire indicated that two subjects experienced symptoms related to this syndrome after operation in the remote mode. One of the two subjects, who had considered himself to be minimally susceptible, reported "slight" disorientation and sweating after both training and test in the remote driving mode. No symptoms had been reported by this subject before commencement of either training or test, nor had any symptoms been noted during the on-board driving phase which followed. The disorientation was described as a "dizzy" and "spacey" feeling. The second subject, who had indicated no susceptibility to motion sickness, reported that he was "somewhat" disoriented and experienced "quite a bit" of general discomfort after testing in the remote mode. No symptoms had been reported by this subject during training in the remote mode or before commencement of test, nor had any symptoms been reported later during either training or test in the on-board driving phase.

The two subjects who experienced the symptoms described above represent a relatively small percentage of the total subject group. Only one of the two subjects was among the nine who had indicated susceptibility to motion sickness. Although the above symptoms may have been induced by factors associated with operations in the remote mode, there is no evidence to indicate that any of the test conditions influenced their onset. There is also no evidence to indicate that the symptoms reported by these subjects had a significant effect on their remote or on-board driving performance.

DISCUSSION

Changes in lens focal length will result in changes in FOV, resolution, and image distortion. During this study, in five of the six course segments, remote drivers achieved greater speed and accuracy with the 6-mm lens focal length than with either the 12-mm or 3.5-mm lens. Some evidence suggests that FOV and distortions in the size, speed, and distance of objects within the remote driver's visual field were among the major contributors to degradations in remote driving performance among these focal lengths.

Visual distortions were most apparent at both focal length extremes. Subjects made no mention of differences in picture clarity (resolution) among the three lenses but frequently commented about differences in object size and distance when transitioning from one focal length to another. Objects within the narrow FOV of the 12-mm lens appeared to be closer than they actually were. The converse was true for the 3.5-mm lens. These distortions may have also affected the remote drivers' perceptions of distance from path deviations. The 12-mm lens would have influenced premature steering commands, whereas the 3.5-mm lens would have caused the driver to delay input. During the study, subjects also noted a distortion between actual and perceived vehicle speed at the two focal length extremes. Vehicle response to relatively small steering adjustments was magnified by the longer 12-mm focal length. With the 3.5-mm lens, such inputs appeared to have no effect. In both instances, the remote driver was compelled to take "corrective" action.

Subjects favored the wider FOV of the 3.5-mm lens when negotiating the obstacle avoidance segment but were uncomfortable with the "bird's eye view" caused by this shorter focal length on other course segments. Visual distortions distanced the remote driver from the vehicle and the roadway, obscuring smaller shifts in vehicle response and position. The 3.5-mm lens also exhibited the fish-eye effect characteristic of shorter focal length lenses. Although this effect was not extremely pronounced, it created an illusion of course motion around the periphery of the image. One subject commented that if he were to become motion sick, it would be with the 3.5-mm lens.

The 6-mm lens offered less resolution and FOV than the 12-mm or 3.5-mm lenses, respectively, but the optical distortions caused by this mid-size lens were not as apparent as those induced by either of the two focal length extremes. The ratio of perceived to actual size and distance was closer to 1:1 for the 6-mm lens. Most subjects, when asked if they had a lens preference, selected the 6-mm lens. Some considered it to be an even choice between the 6-mm and the 3.5-mm focal lengths but added that if they were forced to select one of the two, they would choose the mid-size lens.

The results of this investigation suggest that the 6-mm focal length lens offered a more acceptable trade-off among FOV, resolution, and image distortion than either the 12-mm or the 3.5-mm lens. Although the FOV of the 3.5-mm lens was significantly wider than that of the 6-mm, the latter consistently demonstrated greater speed and accuracy in five of the six course segments. In the obstacle avoidance segment, driving speed and accuracy using the 3.5-mm lens was better than that with the 6-mm lens, but these differences were small. Advantages offered by the wider FOV of the 3.5-mm lens may have been diminished by the visual distortions induced by this shorter focal length. Similarly, performance with the 6-mm lens was far superior to that with the 12-mm even though the resolution of the 12-mm lens was twice that of the 6-mm. It is suspected that the restricted horizontal and vertical FOVs of the 12-mm lens compounded the effects of optical distortions induced by this longer focal length. The remote driver's view of the course surrounding the immediate path of travel and impending deviations was severely limited. Unlike the 6-mm and 3.5-mm focal lengths, the narrow FOV of the 12-mm lens did not capture the front edges of the vehicle or the adjacent lines that defined the road's boundaries. Subjects often used these two references to gauge the vehicle's distance from the edges of the road just as they would when operating from an on-board driving position. Without this visual information, the subjects' only resort was to track the centerline of the road using a central reference point on the vehicle. This technique was inadequate for judging vehicle position relative to the road's centerline when negotiating turns.

In course Segments 1 through 5, significantly greater speed and accuracy were achieved during on-board operations than during operations in the remote mode using the 6-mm lens. Losses in accuracy, however, caused by the 6-mm lens focal length were not dramatic, particularly by comparison with those of the 12-mm or 3.5-mm lenses. In Segment 6, the 6-mm lens was less accurate than either the 3.5-mm or the on-board driving conditions, but these differences were small. In this segment, as for all other course segments, the most notable differences between on-board and remote driving performance occurred in speed. Higher speeds might imply a higher level of driver confidence. As above, it is theorized that FOV and image distortion were among the major contributors to these differences, but it is also suspected that other sensory motor feedback provided the on-board driver served to complement the expansion in his visual field. Most important, this additional information was now more in line with how the driver normally perceived his world.

During the study, differences in resolution among the three lens focal lengths were not pronounced. The participants may not have considered any losses in picture clarity that they observed to be great enough to be worthy of note. When expressed in more familiar terms of visual acuity, differences in resolution among the lens focal lengths appear sizable. Losses in resolution about the same as those caused by the 6-mm and the 3.5-mm lenses would undoubtedly degrade the driver's ability to read road signs but may have minimal influence on his ability to follow a well-defined path. It is also possible, however, that these differences would become more troublesome in a more cluttered environment where drivers were tasked to detect and identify obstacles. In this instance, such subtle differences in resolution could exert a greater influence on performance. However, a recent study conducted by Holly, Schipani, Shires, and Chang (1992) suggests that the remote driver may be able to tolerate relatively large reductions in resolution. During his investigation, Holly examined the effects of four levels of pixel count (i.e., 256, 128, 64, and 32) and gray scale (i.e., 32, 16, 8, and 4) on obstacle detection. At 32 gray scales, performance degradations at 128 x 128 pixels were small and insignificant. A dramatic decline in obstacle detection occurred when pixel count was reduced to 64 x 64.

In summary, it is suspected that distortions in size, speed, and distance caused by both extremes in focal length were a major but not the sole contributor to degradations in driving performance. The restricted FOV of the 12-mm lens and possibly, to a lesser extent, the lower resolution of the 3.5-mm lens may have also aggravated performance degradations at these focal length extremes. In the on-board mode, increases in driving speed and precision are hypothesized to have been attributable to increases in the quantity and quality of visual information combined with the introduction of other customary sensory motor stimuli.

CONCLUSIONS AND RECOMMENDATIONS

The focal length of the remote camera's lens has a measurable effect on the image presented the remote driver and on remote driving performance. Lens focal length will dictate the horizontal and vertical FOVs provided by a single camera. Changes in resolution and visual distortions will also occur as focal length is manipulated. The results of this investigation indicate that the 6-mm lens offered a more acceptable trade-off among these variables than did either the 12-mm or the 3.5-mm lens focal lengths.

More controlled, systematic investigation of resolution, FOV, and image distortion will help quantify the individual effects of these variables on remote driving performance and will provide valuable input to the data base. The data and information derived from further study will assist in the selection of camera(s) and display systems and will provide insight in the assessment of low data rate operations and image compression techniques. However, presently, when the designer selects a fixed focal length lens for the remote camera, his or her options are limited. No lens focal lengths offer an optimum in both resolution and FOV. Attempts to maximize one of these variables by changing the focal length of the lens will degrade the other and aggravate distortions in the size, speed, and distance of objects in the teleoperator's visual field. In the current study, it appeared that visual distortions, which occurred at both focal length extremes, were more discomforting to remote drivers than were losses in either resolution or FOV. It would seem, based upon the results of this investigation, that extremes in lens focal length should be avoided. The data also appear to suggest that deviations beyond the mid-point toward either extreme tend in the direction of performance degradation and support the selection of a lens focal length that causes the least optical distortion and most accurately depicts the size, distance, and speed of objects as they would normally be seen when viewed directly by the human eye.

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APPENDIX A

PRETEST QUESTIONNAIRE

PRETEST QUESTIONNAIRE

Please answer the following questions. The information you provide will be kept CONFIDENTIAL.

1. Name: ____
   Last First Middle Initial

2. If you are **military**, please provide the following information:

   Rank: ________________

   Military Occupational Specialty (MOS): ______________

   Time in Service: ______years

3. If you are **civilian**, please provide the following information

   Job Title: ______________

4. Age: __________

5. Height: __________

6. Weight: __________

7. Are you left- or right-handed?

   Left-Handed [ ] Right-Handed [ ]

8. Do you wear eyeglasses or contacts?

   Yes [ ] No [ ]

9. Do you have a civilian drivers license?

   Yes [ ] No [ ]

   If YES, how many years have you been licensed to drive?

   _______years

10. Do you have a military drivers license?

    Yes [ ] No [ ]

If YES, what military vehicles are you qualified to drive?

<u>Vehicle Type</u>	How many <u>years?</u>
____________________	________ years
____________________	________ years
____________________	________ years
____________________	________ years

11. Have you ever done any high performance competitive driving (for example, drag racing, stock car racing, autocross, etc.)?

Yes [ ] No [ ]

If YES, describe ____
____
____

12. How often do you play video or arcade games? *(Check one)*

All the Time [ ]
Often [ ]
Sometimes [ ]
Rarely [ ]
Never [ ]

13. Have you ever operated a vehicle remotely (toy or otherwise)?

Yes [ ] No [ ]

If YES, describe ____
____
____

14. Have you ever been motion sick (for example: seasick, carsick, airsick, trainsick, etc.) ?

Yes [ ] No [ ]

If YES, explain ____
____
____

15. How susceptible are you to motion sickness? *(Check one)*

Extremely [ ]
Very [ ]
Moderately [ ]
Minimally [ ]
Not at All [ ]

APPENDIX B

MOTION SICKNESS QUESTIONNAIRE

MOTION SICKNESS QUESTIONNAIRE

Name: ____________

Date: ____________

Time: ____________

INSTRUCTIONS: For each item listed, place an " X " in the box to correspond to **HOW YOU FEEL AT THIS MOMENT.** PLEASE ANSWER EVERY ITEM.

	Not at All	Slight	Somewhat	Moderate	Quite a Bit	Extreme
1 Generally uncomfortable	☐	☐	☐	☐	☐	☐
2 Tired	☐	☐	☐	☐	☐	☐
3 Depressed	☐	☐	☐	☐	☐	☐
4 Sleepy	☐	☐	☐	☐	☐	☐
5 Headache	☐	☐	☐	☐	☐	☐
6 Dizzy (with eyes closed)	☐	☐	☐	☐	☐	☐
7 Dizzy (with eyes open)	☐	☐	☐	☐	☐	☐
8 Disoriented	☐	☐	☐	☐	☐	☐
9 Sweaty	☐	☐	☐	☐	☐	☐
10 Faint	☐	☐	☐	☐	☐	☐
11 Aware of my breathing	☐	☐	☐	☐	☐	☐
12 Nauseous (sick to stomach)	☐	☐	☐	☐	☐	☐
13 Burping	☐	☐	☐	☐	☐	☐

	Not at All	Slight	Somewhat	Moderate	Quite a Bit	Extreme
14 Hungry	☐	☐	☐	☐	☐	☐
15 No appetite	☐	☐	☐	☐	☐	☐
16 Chills	☐	☐	☐	☐	☐	☐
17 Blurred vision	☐	☐	☐	☐	☐	☐
18 Decreased salivation (dry mouth)	☐	☐	☐	☐	☐	☐
19 Increased salivation	☐	☐	☐	☐	☐	☐
20 Hot flashes	☐	☐	☐	☐	☐	☐
21 Clammy	☐	☐	☐	☐	☐	☐
22 Vomiting			YES ☐	NO ☐		

Thank you

APPENDIX C

MEAN SPEED AND ACCURACY BY COURSE SEGMENT

Table C-1

Mean Speed and Accuracy by Course Segment

Course segment	Speed (kph)				Accuracy[a]			
	12 mm	6 mm	3.5 mm	Baseline	12 mm	6 mm	3.5 mm	Baseline
1 Straightaway	8.3	8.8	8.2	11.7	23.5	12.3	15.1	8.5
2 Right turns	5.8	6.7	6.0	8.8	40.6	16.4	19.9	14.7
3 Left turns	6.2	6.6	5.9	8.4	41.2	18.7	31.4	13.6
4 Serpentine	5.3	5.9	5.6	7.4	45.2	18.4	24.5	15.4
5 Figure 8	5.9	7.1	6.7	9.2	51.4	17.6	27.7	11.2
6 Obstacle avoidance	3.4	4.9	5.1	7.3	1.5	0.17	0.08	0.08

[a]For course Segments 1 through 5, accuracy is reported in centimeters (cm). For course Segment 6 (obstacle avoidance), accuracy is reported in number of hits.