Role of Visual Cues from the Environment in Driving an Agricultural Vehicle

D. Karimi and D.D. Mann*

Department of Biosystems Engineering, University of Manitoba, Canada

Abstract: Driving is an interactive process in which the driver receives information regarding the state of the vehicle and the environment in which the vehicle is moving through visual, motion, haptic and auditory cues. The driver needs this information for successful guidance or navigation of the vehicle. A good understanding of this process requires knowledge of the sensory cues used by the driver in performing different driving tasks. This knowledge is also necessary in the development of driving simulators which are emerging as useful research tools. The goal of this research was to test whether drivers of agricultural vehicles use visual cues from the environment when performing common driving tasks such as parallel swathing and simple turning maneuvers. Experiments were performed using a tractor in the field and using a tractor driving simulator in the laboratory. The results show that in straight line driving with a lightbar guidance system, the steering behavior and performance of most drivers does not change with varying level of visual information from the environment. However, it seemed that approximately 33% of the subjects in our experiment used an aiming cue on the field boundary, when available. Visual cues from the environment played a significant role in maneuvers which included more than one phase of steering input. Drivers were able to successfully complete those maneuvers that consisted of only one phase of steering input, such as turns, even when complete visual cues from the environment were not provided. However, maneuvers which required multiple phases of steering input could not be completed when the visual information from the environment was incomplete. A driving simulator for agricultural vehicles, therefore, should include these cues. Also, cabs of agricultural vehicles should be designed in such a way that these features can be easily seen by the operator.

Keywords: Visual perception, steering, driving, driving simulator, agricultural vehicle.

INTRODUCTION

It is generally believed, and has been shown by some experiments, that visual cues are the single most important cues in automobile driving [1]. Although the exact contribution of the visual cues to the driver's perception is not clear [2], it is known that in the absence of visual cues, drivers are unable to perform some basic driving tasks [3]. Visual perception of motion is made possible primarily by what is usually referred to as "peripheral vision", which originates from the rod-shaped receptors in the retina [4]. Changes in the locations of the surrounding objects as the observer moves in the environment is the source of information for detecting self-motion. This phenomenon is called optic flow and was first described by Gibson [5]. He proposed the notion of the Focus of Expansion (FOE), which is the point out of which the arrays of optic flow expand, and suggested that a moving observer estimates his/her heading by identifying this point. Other sensory cues (i.e., vestibular, proprioceptive, haptic, and auditory cues) have less importance and generally provide redundant information to reinforce the visually perceived information [6]. In fact, many of the existing models of the steering behavior of a human driver are based solely on the driver's visual perception [7].

Previous research on the automobile driver's steering behavior has shown that drivers look at the tangent point on the inside of each bend when approaching a turn in the road [8]. Moreover, at low vehicle speeds, drivers only need visual information from parts of the road that are close to the vehicle, while at higher speeds visual information is needed from both near and distant parts of the road [9]. A model of driver control behavior has been developed that uses "near visual cues" for maintaining the car's position in the lane and "distant visual cues" to deal with the approaching curves in the roadway [10]. A more recent study has shown that when traveling on straight paths drivers are able to judge their heading quite accurately whereas on curved paths the error in judgment of heading is very large (approximately 13°). Since the subjects were able to identify and track a point on the upcoming path with much higher accuracy, the study concluded that it is the path, rather than the heading, that is the main source of control information provided by the visual system [11]. Extensive experimental studies have been performed to investigate the automobile driver's eye glance behavior under different conditions and for various driving tasks. These studies have provided additional insight into which parts of the visual scene are used by the human driver and how this information is utilized. It has been observed that on straight roads most of the eye fixations are very close to the focus of expansion while on a curved road, eye fixations follow the road geometry [12]. Other experiments have shown that peripheral vision is used to monitor vehicle position in the lane, other vehicles on the road, and road signs while the central vision is used for closer examination of the situation in front of the vehicle [13]. Previous studies have also shown that a driver's use of different features in the

*Address correspondence to this author at the E2-376 EITC, University of Manitoba, Winnipeg, Manitoba, R3T5V6, Canada; Tel: (204)-474-7149; Fax: (204)-474-7512; E-mail: Danny_Mann@umanitoba.ca

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visual scene can be significantly affected by a driver's experience [14, 15] and the driving task at hand [16].

Visual perception through optic flow can be considered as the most important source of information for estimating self motion. However, this information can be ambiguous because head and eye rotations occur during self-motion. This will change the image that is formed on the retina [17]. In fact, different eye and head rotations and body motions can result in similar flow patterns on the retina. Non-visual information (i.e. vestibular and proprioceptive cues and efferent copy) are needed to disambiguate the visual information. Experiments have shown that all these three non-visual cues are essential to ensure accurate perception of self-motion [18]. The exact role of visual and non-visual cues for different driving tasks is still being researched [19].

Sophisticated driving simulators have opened new research opportunities in this area. On the one hand, successful driving simulation requires a good understanding of human perception and the characteristics of the information that the driver needs to perform different driving tasks. On the other hand, driving simulators have been used to research the same questions in a safe and easily controllable environment [20, 21].

Although there has been extensive research on the role of visual cues in automobile driving, no similar research has been reported for agricultural vehicles. This is despite the significant differences that exist between the two types of vehicles and the driving tasks involved: agricultural vehicles have different dynamics and operate at lower speeds in straight lines through fields (called parallel swathing). Moreover, the source of visual information in automobile driving is different than the source in driving an agricultural vehicle; in automobile driving, visual information is derived from road edges and features or objects in the visual scene (i.e., other vehicles on the road) that do not exist in driving an agricultural vehicle in a field. Driving of an agricultural vehicle consists mostly of parallel swathing and simple maneuvers such as turns of various angles. The goal of this study was, therefore, to see whether drivers of agricultural vehicles use visual cues from the environment in performing these tasks and whether a driving simulator for these vehicles should include visual cues. Based on the reviewed literature on automobile driving (for example [3]), our null hypothesis is that drivers do need visual cues from the environment for successfully performing turns and maneuvers. Previous research has shown that when driving in straight lines in the presence of crosswind, automobile drivers do not depend on visual cues to a great extent and, instead, increase their use of motion cues such as yaw motion and lateral acceleration cues [22]. Moreover, drivers of agricultural vehicles use a guidance system in straight-line driving. Therefore, our hypothesis is that drivers of agricultural vehicles do not depend on visual cues from the environment in straight line driving.

MATERIALS AND METHODS

Field Experiments

Field experiments were performed in the summer of 2007 in southern Manitoba, Canada. Ten experienced tractor drivers participated in the experiments. Subjects were selected from among the staff and students of the Department of Plant Science of the University of Manitoba based on their previous tractor driving experience, availability and willingness to participate in the experiment. Three of the subjects were students and the other seven were staff members. All subjects were male and 27 to 55 years old (average 39). Before the start of the experiment, the subjects were provided with a detailed written description of the experiment and were asked to sign a consent form after reading the information provided. Each subject was paid Can$25 after the completion of the experiment. The experimental procedure, including the written information provided to the subjects and the consent forms for the field experiment and the simulator experiment (described later) had been previously reviewed and approved by the Education/Nursing Research Ethics Board of the University of Manitoba.

The experiments consisted of two parts: 1) parallel swathing with a lightbar guidance system, and 2) performing a selected number of turning maneuvers. A John Deere 5425 tractor was used in the field experiments.

In the parallel swathing experiments, an Outback S® lightbar guidance system was used to provide information to the operator to enable the tractor to be driven in a straight line. Because some of the drivers had never used this system before, each driver was given some time to drive using the lightbar until he became familiar with the system. Then each driver drove seven or eight passes along the field. The exact position of the tractor was recorded using an RTK GPS system (Leica GPS1200). The mean error in measurements of the RTK system was approximately 2 cm (the range of this error was 1.5 to 4.0 cm). The mean of the lateral deviations of the tractor from the straight line, measured by the RTK system, was approximately 29 cm, with a standard deviation of approximately 15 cm. Therefore, the measurement error of the RTK system was ignored.

In the second experiment, each driver was asked to perform a selected number of maneuvers (Fig. **1**). The maneuvers included turns of 45, 90, and 180° to both the left and the right and two maneuvers which resembled single and double lane changes on a road. The subjects were provided with a printed copy of Fig. (**1**) and were asked to perform the maneuvers. The same RTK GPS system was used to record the exact position of the tractor.

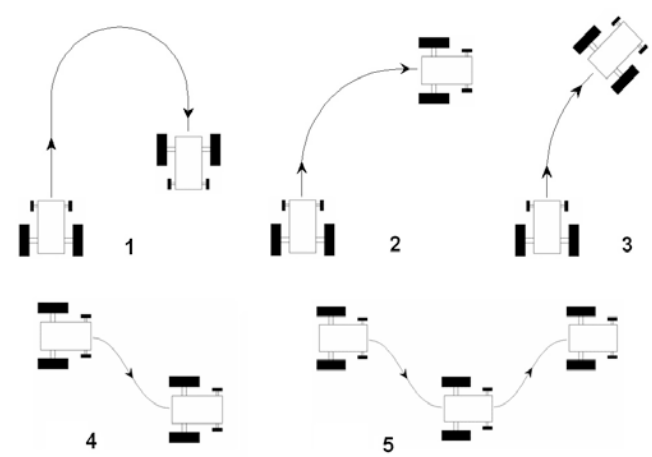

Fig. (1). Maneuvers that were performed in the field and simulator experiments.

SIMULATOR EXPERIMENTS

Simulator experiments were performed using a tractor driving simulator located in the Department of Biosystems Engineering, University of Manitoba. This is a moving-base simulator which uses three projectors to provide a forward field of view of approximately 65° (Fig. **2**).

The simulator also provides realistic torque feedback on the steering wheel. Fifteen experienced tractor drivers, including the ten drivers who participated in the field experiments, participated in the simulator experiments. All subjects in this experiment were either student or staff members of the Plant Science and Biosystems Engineering Departments of the University of Manitoba. Four of the subjects were students and 11 of them were staff members. All of the subjects were male and 20 to 55 years old (average 38). Before the start of the experiment, each subject was provided with a written description of the experimental procedure. The subjects were also asked to sign a consent form before starting the experiment. After the completion of the experiment, each subject was paid Can$60 as an honorarium.

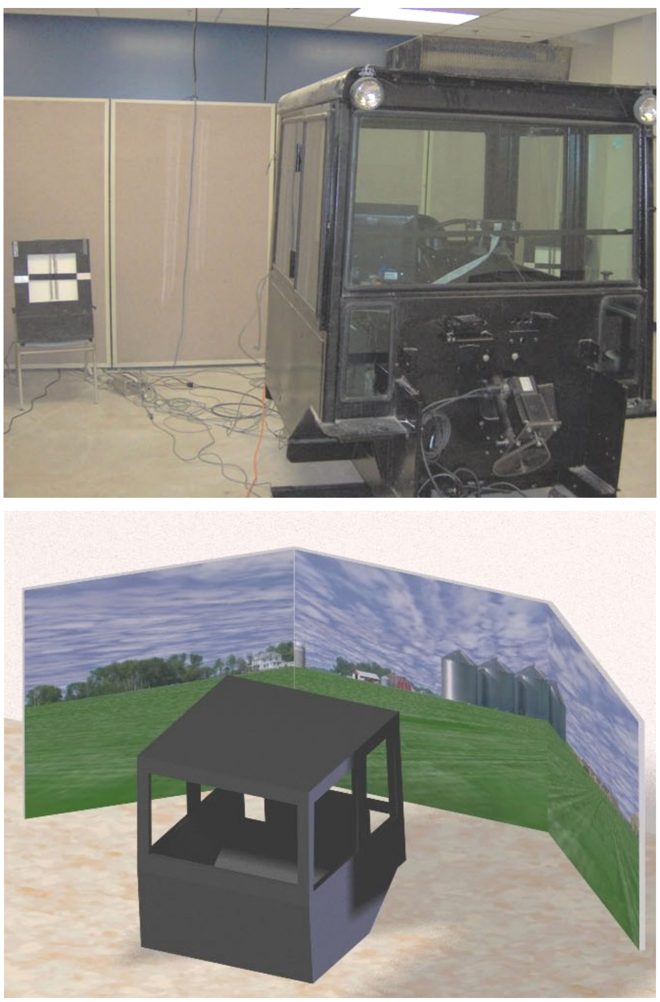

Fig. (2). The front view of the simulator (top) and a schematic representation of the simulator and the visual display during operation (bottom).

The type of driving tasks performed in the simulator experiments were the same as those performed in the field experiments explained previously. The experiment consisted of three sessions: 1) full visual information was provided (referred to as SE1), 2) visual information only from the simulated field boundary was provided (referred to as SE2), and 3) visual information only from the simulated field surface was provided (referred to as SE3). Fig. (**3**) shows part of the simulated visual scene during each of these sessions. In each of the three sessions, the driver first drove in parallel swathing mode for 15 min. Then the driver was asked to perform steering maneuvers identical to those performed in the field experiments. Images of the maneuvers were shown to the driver on an LCD monitor inside the simulator cab. Exact location of the simulated tractor and steering wheel angle were recorded by the main computer at a rate of 20 Hz.

Fig. (3). Snap shots from the simulated visual scene in the three driving simulator experiments: SE1 (top), SE2 (middle), and SE3 (bottom).

Data Analysis

A record of the tractor location obtained from the RTK GPS system in the field experiment was used to calculate the deviation of the tractor from the straight line. Root-mean-square (RMS) of lateral deviations was calculated. Fourier transform of lateral tractor deviations was then computed using the following formula:

$$Y(j\omega) = \int_{-\infty}^{+\infty} y(x)\, e^{-j\omega x}\, dx \qquad (1)$$

where y(x) is the tractor lateral deviation. Using this transform, the energy of the signal for different frequency ranges can be obtained from the following equation [23]:

$$\text{energy} = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} \left| Y(j\omega) \right|^2 d\omega \qquad (2)$$

We computed the energy for three frequency regions:

T= 8 to 16, the high-frequency region

T= 16 to 32, the medium-frequency region

T= 32 to 45, the low-frequency region

where $T = 2\pi/\omega$ is the period. The energy in each of these regions was then divided by the total energy to obtain the fraction, expressed in percentage, of energy of the lateral deviations in each frequency band.

The same procedure was followed using the position data collected using the simulator. In addition, the RMS of the steering wheel angle was also computed for the simulator experiments to obtain a measure of the control activity of the driver.

RESULTS AND DISCUSSION

Straight Line Driving

Table **1** shows the RMS of the lateral deviations and their frequency composition averaged for all drivers (10 drivers in the field experiment and 15 drivers in the simulator experiments). The numbers in Table **1** show that, on average, the results are very close for the field experiment with the three simulator experiments. Analysis of variance did not show any significant differences between any of the experiments and in terms of any of the four parameters. Therefore, on average, the steering behavior and performance of drivers in straight line driving with a lightbar guidance system does not change as a function of different levels of visual information from the environment. This means that in performing this task, the majority of drivers mostly depend on the lightbar guidance information and other information such as yaw motion cues. Changing the visual cues from the environment does not affect the behavior of these drivers as they can compensate for the missing or incomplete visual cues from the environment with other information such as the lightbar signal or motion cues. Our conclusion is consistent with the findings of similar studies for automobile driving that suggest that, when driving on a straight road in the presence of crosswinds, the driver's dependence on visual cues decreases and, instead, drivers increase their use of motion cues.

However, one-third of the drivers (5 out of 15) changed their steering behavior with varying levels of visual information from the environment. These drivers significantly increased their control activity, which is reflected by higher RMS of steering wheel angle, when field boundary cues were eliminated (experiment SE3). Table **2** shows the results of the three simulator experiments for these five subjects in terms of the RMS of driving error (a measure of task performance) and the RMS of steering wheel angle (a measure of driver effort). In experiment SE3, when the field boundary was removed from the visual scene, the RMS of steering wheel angle was 20 to 130% (61% on average) larger than in experiments SE1 and SE2. Analysis of variance showed that the RMS of steering wheel angle in experiment SE3 is significantly different from experiments SE1 and SE2 (Pr(>F)=0.026). It is a common practice for drivers of agricultural vehicles to use an object on the field boundary as an aiming cue when driving in parallel swathing mode. This is particularly true when they do not use a guidance system. However, it is likely that even when a guidance system, such as a GPS lightbar system, is used, the driver does not spend all of his time looking at the guidance system and still uses an aiming cue as an extra source of guidance information. Our results tend to support this hypothesis for this selected group (one-third) of the drivers. For these drivers, the use of an aiming cue on the field boundary (i.e., experiments SE1 and SE2) resulted in smaller steering movements which is an indication of a more relaxed driving style. As can be seen from the table, the RMS of lateral deviations of the tractor was lower for experiment SE3 compared to experiments SE1 and SE2. Although this difference was not statistically significant (Pr(>F)=0.50), it indicates that lateral deviations from the desired straight line increase when using an aiming cue on the field boundary instead of fully concentrating on the guidance system.

Table 1. Summary of the Results from Straight-Line Driving Experiments in the Field and Simulator; Indicating the RMS of Lateral Deviations (RMSL), and the Amount of Energy of the High-Frequency (HF), Medium-Frequency (MF), and Low-Frequency (LF) Portions of the Spectrum

Experiment	RMSL (m)	HF (%)	MF (%)	LF (%)
Field (n=10)	0.32	30	40	31
SE1 (n=15)	0.35	29	43	29
SE2 (n=15)	0.35	29	42	30
SE3 (n=15)	0.34	31	42	27

Overall, these results indicate that when driving in straight lines with the help of a guidance system, drivers are able to steer the vehicle in the absence of visual feedback from the environment without a decrease in performance. In other words, the task difficulty and performance of the driver are functions of the accuracy and dynamics of the guidance system rather than the amount of visual feedback from the environment. Therefore, we can conclude that our null hypothesis was true and drivers do not significantly depend on visual feedback from the environment in straight line driving mode.

Table 2. The Results of the Simulator Experiments for Five Subjects that Seem to Change their Control Strategy in Straight Line Driving Depending on the Visual Cues. The Table Shows the RMS of Lateral Deviations (L) in m and the RMS of Steering Wheel Angle (W) in Degrees

Subject	SE1		SE2		SE3	
	L (m)	W (°)	L (m)	W (°)	L (m)	W (°)
1	0.40	10	0.39	15	0.42	23
2	0.41	18	0.45	15	0.30	26
3	0.38	12	0.37	10	0.28	18
4	0.25	7	0.30	10	0.26	12
5	0.40	17	0.25	12	0.32	22
mean	0.37	13	0.35	12	0.32	20

Turning Maneuvers

Field experiments showed that drivers were able to perform all of the steering maneuvers shown in Fig. (**1**) with acceptable accuracy. Fig. (**4**) shows examples of how the drivers performed maneuvers 1 and 5. The error in performing each of the maneuvers was quantified in terms of the difference between the observed final tractor heading and the desired heading for that maneuver. For maneuvers 1 to 5, the error averaged across all drivers was 5, 7, 5, 10, and 12°, respectively. Table **3** shows this error for field experiments and for the simulator experiments.

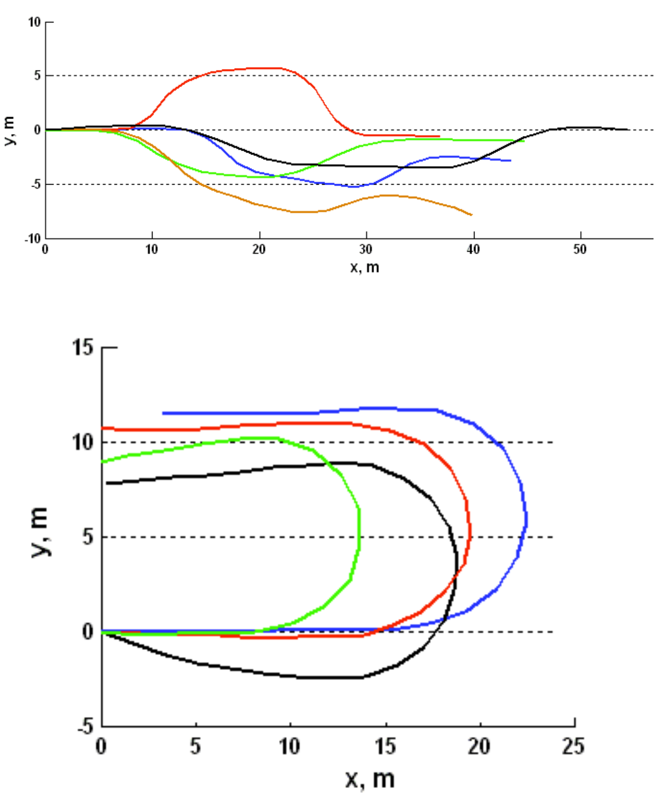

Fig. (4). Typical tractor trajectories as the tractor operator performed maneuvers 1 and 5 in the field.

Table 3. Error in the Final Tractor Heading for Maneuvers 1 to 5, Averaged Across All Drivers

Experiment	M 1 (°)	M 2 (°)	M 3 (°)	M 4 (°)	M 5 (°)
Field (n=10)	5	7	5	10	12
SE1 (n=15)	10	6	5	15	17
SE2 (n=15)	58	38	24	33	43
SE3 (n=15)	16	15	12	11	20

In the first simulator experiment (SE1), the drivers were able to perform the assigned maneuvers with acceptable accuracy although the average errors in the final heading were slightly higher than for the field experiment: 10, 6, 5, 15, and 17°, respectively, for maneuvers 1 to 5.

In the second simulator experiment (SE2), the drivers performed maneuvers 1, 2, and 3 with much larger errors (58, 38, and 24° for maneuvers 1, 2, and 3) and most of them were unable to perform maneuvers 4 and 5. For maneuver 4, for example, drivers produced steering wheel inputs that were needed for a turn. To understand the difference, it is instructive to consider Fig. (**5**) which shows the steering wheel movements required for both a simple turn and for maneuver 4. Heading angle and lateral deviations shown in this figure were computed using the tractor dynamic model used in the tractor driving simulator which can be represented by the following transfer functions [24]:

$$\frac{\psi(s)}{\delta(s)} = \frac{6.47(s+14.8)}{s(s+13.6)(s+7.31)}$$
$$\frac{Y(s)}{\psi(s)} = \frac{0.86(s+11.5)(s+3.33)}{s(s+14.8)} \qquad (3)$$

where:

δ: steering angle input (steer angle of the front wheel of the tractor), rad

ψ: tractor heading, rad

Y: tractor lateral deviation, m

The steering inputs in Fig. (**5**) are sine waves, but the exact shape of this input is immaterial. As can be seen from this figure, for a simple turn to the left, for example, the driver should turn the steering wheel to the left and then back to the center. For a maneuver similar to maneuver 4, however, the driver must repeat the same steering wheel movement in the opposite direction to make the total change in the tractor heading equal to zero. In fact for a zero change in the final heading, the net area under the steering wheel angle curve (the upper right curve in Fig. (**5**)) should be zero. However, in experiment SE2, all but one of the drivers performed only the first part of the steering wheel movement (i.e., they made a turn instead of a lane change maneuver). Fig. (**6**) shows examples of the drivers' performance for maneuver 4.

As can be seen from Fig. (**6**), the second phase of steering wheel movement is either very small or completely ignored. Therefore, according to Fig. (**5**), the steering wheel movement generated by the driver is representative of the steering wheel input required for a turn. This is confirmed by the trajectory of the tractor, also shown in Fig. (**6**).

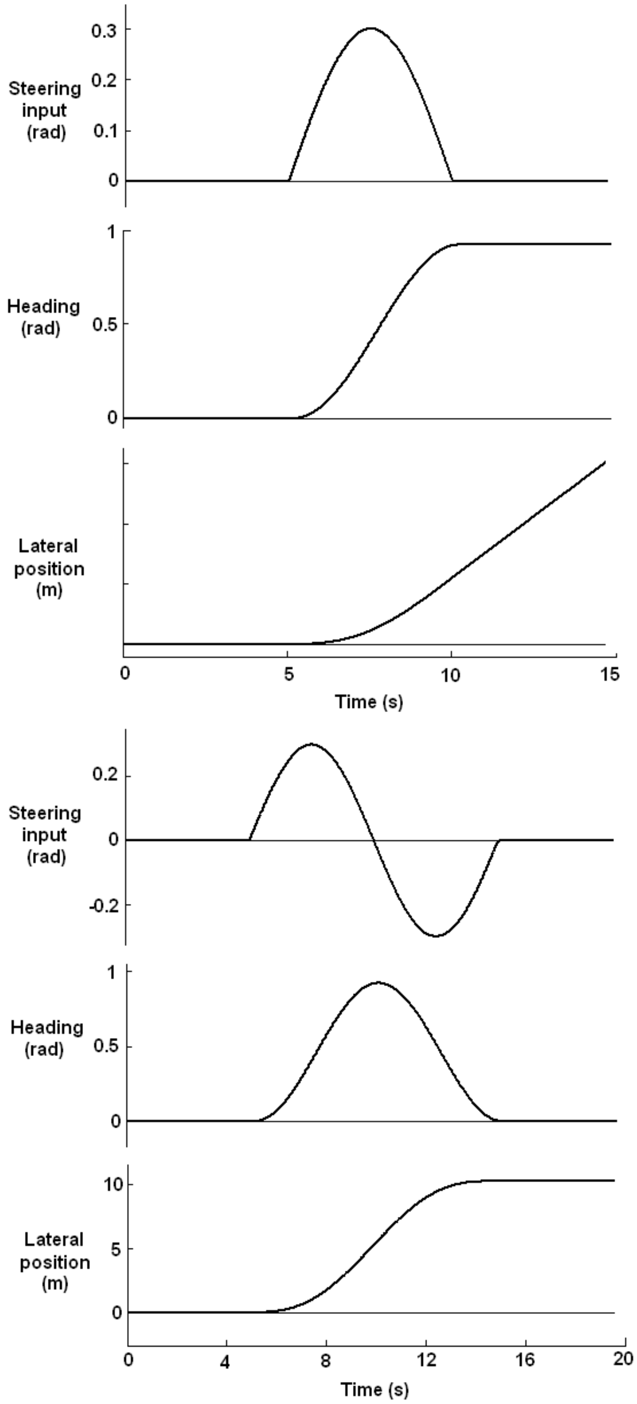

Fig. (5). Steering wheel inputs necessary to perform a simple turn (top) and a lane change (bottom).

Our results are similar to the observations made by Wallis [25]. They asked several experienced automobile drivers to perform a lane change maneuver on a steering wheel in the absence of any visual cues. None of the participants performed the right steering wheel movements. In fact, in their experiment, similar to our observations in experiment SE2, the participants performed only the first phase of the steering wheel movement necessary for the lane change, effectively making a turn instead of a lane change. Observations from experiment SE2 show that in the absence of visual cues from field surface, drivers are able to complete one-step maneuvers such as turns but when the maneuver includes two or more steps (maneuvers 4 and 5) the drivers do not initiate the second part of the steering movements. Since motion and haptic cues were provided in our experiments, it can be said that motion and haptic cues do not replace the visual cues for these maneuvers. Also, it should be noted that in this experiment (SE2), drivers were able to see the field boundary. Therefore, we might be able to conclude that the drivers use visual cues from the field surface for this maneuver.

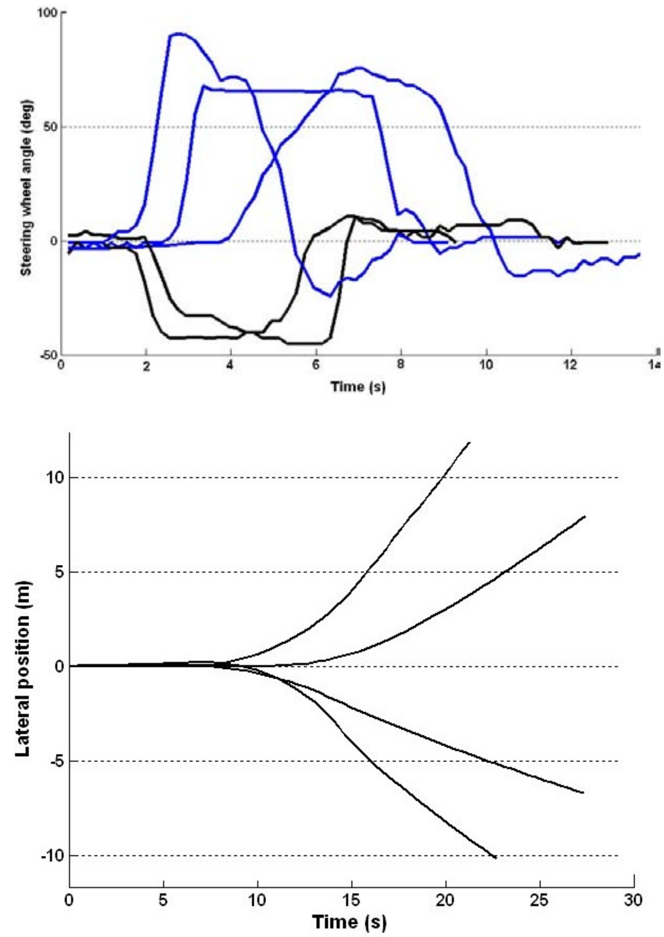

Fig. (6). Steering wheel angle and lateral deviation of the tractor in experiment SE2 as the drivers performed the maneuver 4 in Fig. (**1**).

In experiment SE3, the drivers were able to perform those maneuvers that consisted of only one steering step (i.e., maneuvers 1, 2, and 3). The errors in the final tractor heading were slightly higher than, but comparable with, those of experiment SE1 and the field experiment. The averages of the errors were 16, 15, and 12° for maneuvers 1 to 3. However, for maneuvers 4 and 5, a small number of the drivers performed incorrect steering inputs quite similar to the ones that were observed in experiment SE2. In other words, for maneuver 4, drivers performed only the first phase of the required steering input and ignored the second phase, therefore, effectively making a simple turn. This happened for 3 drivers only; 12 drivers performed the second phase of steering input. As mentioned before, only one driver made the right steering input in experiment SE2.

These results, therefore, clearly indicate that drivers of an agricultural vehicle need visual cues from the environment to perform maneuvers as simple as maneuvers 4 and 5. They do not know what steering inputs are required for such simple maneuvers. Full visual cues, from both the field surface and the field boundary, are required to ensure drivers are able to navigate the tractor. Therefore, we can conclude that our null hypothesis was true. As mentioned in the Introduction, previous studies have shown that automobile drivers use both near and distant visual cues, depending on the vehicle speed and the driving task being performed. Our results show that, when driving in an agricultural field, tractor drivers use different parts of the visual scene when performing different driving tasks. For straight line driving with a guidance system, one third of the drivers used field boundary cues. For performing turns and maneuvers, however, drivers needed visual feedback from the field surface.

Limitations

The major limitations of our experiments were related to the simulator tests in which subjects performed turns and maneuvers. Field of view angle of the simulated visual scene was 65°. In real driving in the field, drivers may use wider fields of view in performing maneuvers. Moreover, motion cues were limited to high-frequency yaw motion. It is likely that lateral acceleration or constant yaw velocity provides additional cues that the drivers may use, particularly when the visual information is not sufficient. Another limitation of this study was the sample size in terms of the number of subjects that participated in the experiments. Ten drivers participated in the field experiment whereas 15 drivers took part in the simulator experiments. This relatively small number of subjects might raise questions regarding the generalizability of the findings. Generalizability of our results may be further limited considering the fact that our subjects were not actual tractor drivers, rather university students or staff members with significant tractor driving experience. Also, straight line driving experiments, both in the field and in the simulator, were relatively short in duration. It is likely that the driver's behavior changes over time.

CONCLUSION

For the majority of the drivers in this study, and for all drivers on average, steering performance and behavior in straight line driving with a lightbar guidance system did not depend on the level of the visual cues from the environment. This may indicate that most of the drivers did not use visual feedback from the environment in performing this task. Alternatively, drivers may successfully change their control strategy and use other sensory information such as yaw motion cue or the lightbar guidance signal so that their performance is unaffected by the lack of certain features in the visual feedback from the environment. One third of the drivers changed their steering behavior when the visual feedback from the field boundary was removed. This may be an indication that these drivers use an aiming cue on the field boundary as additional source for guiding information when driving with a lightbar system, resulting in significantly lower steering activity. Visual cues from the environment are also needed by the driver of an agricultural vehicle for performing maneuvers which consist of two or more steering inputs. Any model proposed for the behavior of a driver of an agricultural vehicle should, therefore, include the use of visual cues. For straight line driving with a guidance system, this contribution should probably appear as a feedback loop that can be closed or open, depending on whether the driver actually uses visual cues from the environment. For performing maneuvers, the driver model should explicitly show that the driver needs visual feedback from the environment to start a new steering input. The results of this study also emphasize the essential role of visual cues from the environment in driving simulation for agricultural vehicles. The drivers in our study used optic flow from the field surface and aiming cues on the field boundary for the driving tasks considered; a driving simulator for an agricultural vehicle must include these features.

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