The Two-Point Visual Control Model of Steering - New Empirical Evidence

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Abstract. Formal models of human steering behavior can enhance our understanding of perceptual and cognitive processes involved in lateral control. One such model is the two-point visual control model of steering proposed by Salvucci and Gray [8]. An experiment was conducted to test one of its central assumptions, namely that people use information coming from only two locations, a near region about 8m in front of the car and a far region 0,9s down the road, for lane keeping. 42 subjects completed a simulated driving task; road visibility was either unrestricted or reduced according to the assumptions of the two-point model. Additionally, the subjects could either freely choose where to look or had to fixate a target located in the far region. Analysis of steering precision data showed that reduced visibility did not reduce steering precision, thus lending support to the near/far region assumption of the two-point model.

Keywords: Driver Modeling, Lane Keeping, Near/Far Point, Two-Point Visual Control Model of Steering.

1 Introduction

Keeping a car on the lane is one of the fundamental tasks faced by human drivers. To gain a better understanding of the mechanisms of lane keeping, several models of steering behavior have been proposed, using control theoretic (for an overview, see [1]) or computational (e.g., [2], [3]) approaches. Most of these models cannot claim to realistically model the perceptual and cognitive processes that enable human drivers to steer around curves and generally stay on the road, though. For example, traditional control theoretic models, like the one proposed by Donges [4], tend to ignore the peculiar limitations of human perception and information processing, using variables like curvature which are difficult for human drivers to judge correctly (cf. [5], [6]). In recent years, new approaches have been submitted that explicitly use findings from perceptual psychology (e.g. [7]), thus trying to overcome the limitations of the more traditional approaches. One such model is the two-point visual control model of steering introduced by Salvucci and Gray [8] (also see [9]). In the following section, an overview of this model and its underlying assumptions is given, and it is shown that an empirical test for the model's basic premises is still lacking. The rest of this paper describes an experiment that tried to explicitly test one of its central

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assumptions. A description of the method used and the results are given in section 3. A discussion of these results can be found in section 4.

2 The Two-Point Visual Control Model of Steering

The two-point visual control model of steering (henceforth two-point model) likens human steering behavior to a tracking task and is based on two premises [8]. The first premise states that information relevant for lane keeping comes from two regions of the visual scene, one located near to the car (near point) and one further down the road (far point). The second basic assumption is derived from a study reported by Land and Lee [10], who found that human drivers tend to look at the tangent point while steering around bends.

Based on these premises, the two-point model assumes that by fixating a far point, which in curves coincides with the tangent point, the visual angle to that point can be assessed by human drivers. The visual angle towards the near point, located in the middle of the lane, can be judged likewise; see Figure 1 for an illustration of these points and their location on the road. The amount of steering is linked to these angles in a way that can be formulated as a PI-controller (cf. Formula 1): the drivers try to minimize changes in the angles to the near and far point, and additionally steer to keep the angle to the near point at zero (indicating a centered position in the lane).

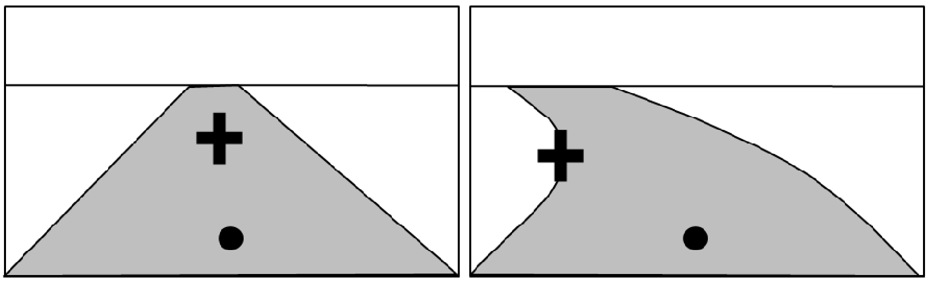

Fig. 1. Far (cross) and near (circle) point used by the two-point visual control model of steering on straights (left) and in curves (right) [8]

Formula 1 gives the equation for the described controller in its continuous form:

$$\dot{\varphi} = k_f\dot{\theta}_f + k_n\dot{\theta}_n + k_I\theta_n \,. \tag{1}$$

Here, $\dot{\varphi}$ is the change in steering angle, $\dot{\theta}_f$ and $\dot{\theta}_n$ are changes in the angles to the far and near point, respectively, and θ_n is the angle to the near point. The coefficients k_f, k_n and k_I are used to scale the contributions of each angle information. A discrete version of this controller (and thus the two-point model) has been implemented in the cognitive architecture ACT-R [11] to form a computational driver model [12].

Originally, Salvucci and Gray did not specify if the near point information is acquired through fixation of the near point or peripherally, only stating that fixation might not be necessary [8]. The implemented model[1], though, explicitly fixates only the far point, so all further discussion of the model is based on this more specific version.

2.1 Empirical Evidence Concerning the Near/Far Point Assumption

Empirical evidence for this assumption comes from a study conducted by Land and Horwood [13]. The authors used a scenario where only limited visual information was present for steering: Instead of showing the whole road, only segments subtending a visual angle of 1° were shown to the participants [13], [14]. Either one or two such segments were visible, which were varied with regard to their position. With only one segment visible, steering precision (measured as the reciprocal of the standard deviation of lane position, measured from lane center) was worse than when the full road was displayed. When an additional segment was shown, performance increased; optimal driving precision was reached when one segment was presented about 4° down from the horizon and the other near to the (virtual) car, about 7° down from the horizon. In this condition, driving performance was as good as with full road visibility. When varying speed, the optimal near segment stayed in the region 7° down from the horizon (or approx. 8.0 to 9.0m ahead); the optimal far region varied in distance, though. When measuring the preview time, this was constant at about 0.8 to 0.9s. Thus, it seems that steering requires visual information about the road trajectory from one point near to the car and another point approximately 0.8s to 0.9s down the road [13], [14], [15].

While the described finding supports the basic assumption of the two-point model, Land and Horwood report only data from three participants each conducting five drives [13]. Additionally, Chatziastros, Wallis and Bülthoff could not reproduce the results found by Land and Horwood [16]. Using a similar method, they registered no improvement of driving performance (lateral deviation) for adding a second visible road segment beyond the one near to the car. Furthermore, in the experiments reported by Land and Horwood, participants were free to direct their gaze wherever they wanted [13]. Though about 50% of all fixations were found to fall into the far region, the authors did not prevent glances to the near area, which could possibly have aided their subjects in keeping the lane. As the two-point model in its implemented form explicitly states that normal steering performance is possible even if only the far point is fixated, a rigorous test of the near/far point assumption is necessary to validate the model.

2.2 Implications of the Tangent Point Assumption

Which point in the far region is actually fixated by drivers? In this regard, the two point model builds on the results of Land and Lee's analysis of drivers' gaze during curve negotiation [10]. The authors found that human drivers tend to fixate an area of the road close to the tangent point. Land and Lee proposed that the visual angle to the tangent point can be used to estimate curvature, which then can be used to control steering behavior [10]. This proposal suffers from the same problems as some other

[1] The LISP-code for the model has been made publicly available by the author at `http://www.cs.drexel.edu/~salvucci/threads.html`

control theoretic approaches, namely that humans have difficulty judging curvature correctly [5], [6]. But according to the two-point model, there is no need to estimate curvature; the driver simply needs to fixate the tangent point and keep the visual angle to it stable in order to smoothly follow the curve (cf. the PI-controller stated above).

On the other hand, Robertshaw and Wilkie [17] (also see [7], [18], [19]), propose that for optimal steering drivers should not fixate the tangent point, but a point on the future trajectory of their car. As was shown in [20], drivers tend to steer towards the fixated point, even if instructed to stay in the middle of the lane. According to this model, fixating a point located on the lane center (center point) would be the best strategy when trying to keep the car in the middle of the lane.

The PI-controller of the two-point model could actually accommodate both tangent and center point for steering control [8]. When testing the near/far point assumption while holding drivers' gaze fixated on the far region, it is more convenient to use the center point, though. The vertical position of the fixation target should be fixed to that of the far region; as the tangent point's vertical position depends on curvature and the car's position in the lane, this cannot be guaranteed by experimental manipulation alone. Additionally, the implemented version of the two-point model uses the center point on straights. As there are no differences in fixation point in this instance, testing the assumptions could only be done on curves, lessening the external validity of the study.

To conclude, fixating a point located centrally on the lane (center point) might actually be the best strategy for drivers trying to keep their car located centrally in the lane, and allows for locking the fixation target to the same far point region in curves and on straights. A test of the near/far point assumption using restricted gaze could therefore use this point and not the tangent point. This would still allow for testing of the near/far point hypothesis, though it does not allow for testing the tangent point assumption of the model.

3 Testing the Near/Far Point Assumption of the Two-Point Model

The experiment reported in the following section had the goal of testing the assumption that two visible road segments are indeed sufficient for normal steering performance (defined as driving precision and measured by the reciprocal of SD of lateral deviation and SD of heading error) when the gaze is exclusively directed at the "far" segment, compared to a free gaze baseline condition.

To independently assess the impact of reduced visibility and restricted gaze, a 2 (visibility restricted vs. unrestricted) x 2 (center point fixation vs. free gaze) experimental design was chosen. The hypothesis derived from the two-point model assumptions combined with the evidence concerning gaze direction [19] was as follows:

> Reducing road visibility does not lead to decreased driving precision (i.e. significantly higher SD of lateral deviation and heading error).

If drivers show impaired steering precision in the limited visibility condition, this would directly invalidate the two-point model.

3.1 Method

A simulator study analogous to the Land and Horwood experiment [13], [14] was devised to test the stated hypothesis. A Logitech G27 steering wheel mounted on a table was used as car mockup, with participants sitting in a real car seat in front of the table. The simulation was displayed on a projection screen (2m width by 2m height) located approximately 2.5m in front of the steering wheel. For projection, an Acer P1165 projector set to 1280 x 1024 pixel resolution was used. This was located 2m behind and above the driver's seat, with the experimenter and computer for running the simulation software located to one side.

The simulated single-lane road had a length of 1360m, a width of 3m and was created using the driving simulation software SILAB. Only white road edge markings of 0.1m width on a black background were visible. The road was either displayed in its entirety (full visibility condition) or with only two horizontal segments visible (reduced visibility condition). Those segments were adjusted to be 1° high and were located at heights corresponding to the near point (8.3m in front of the car) and far point (0.85s ahead of the car). Thus the positions of the visible bars were set to the values (as derived from [15]) allowing optimal performance. The track consisted of a series of four left and four right curves of 135m length, with 50m of straight road in between the bends, and straights 150m long at the start and the end of the track. A radius of 47m was chosen for the curves, resulting in a challenging driving task. Gaze fixation was regulated by the use of pink, circular fixation targets displayed at the lane center in the far region. The road configuration for all conditions is displayed in Figure 2.

In order to test compliance with fixation instructions, point of gaze was recorded using a Dikablis eye tracking system, synchronized with the simulation so each logging step of the simulation recorded the corresponding information about gaze direction. To allow for automated mapping of eye tracker gaze coordinates to simulation window coordinates, two geometric markers positioned to the left and right of the lane were displayed along with the road (see Figure 2).

Participants were 42 students of Otto-von-Guericke-Universität Magdeburg. After a welcome by the experimenter, each subject signed an informed consent form and completed a questionnaire to assess demographic variables (age, gender), driving experience (time since the driving license was acquired, yearly mileage), and familiarity with driving games. This was done to exclude novice drivers from the study. In the next step, the participants were briefed about their task in the experiment followed by four practice trials of 5 minutes duration. Those included all visibility and fixation conditions, but the track differed from that used in the experimental trials. The practice trials were followed by calibration of the eye tracking device. After the calibration, each participant drove all four experimental tracks, which were preceded by a repetition of the relevant instructions. The trials were presented in random order to avoid systematic bias due to additional practice. Questions about the study could be asked at the end of the experiment. The whole process took less than one hour per participant.

All subjects were explicitly told to keep as close to the lane center as possible. As dependent variables three lane keeping performance measures were used (cf. [20]):

mean lateral position (relative to the lane centerline), standard deviation of lateral position, and standard deviation of the heading error. For computation of mean lateral position, the absolute deviation from the centerline was used. This was done to avoid lateral deviation in left and right curves cancelling each other out due to sign differences, resulting in a mean lateral deviation near zero even in subjects showing marked cutting of curves. The relevant data (lane position in m, heading error in rad) was logged automatically by the simulation software at a rate of 60 Hz.

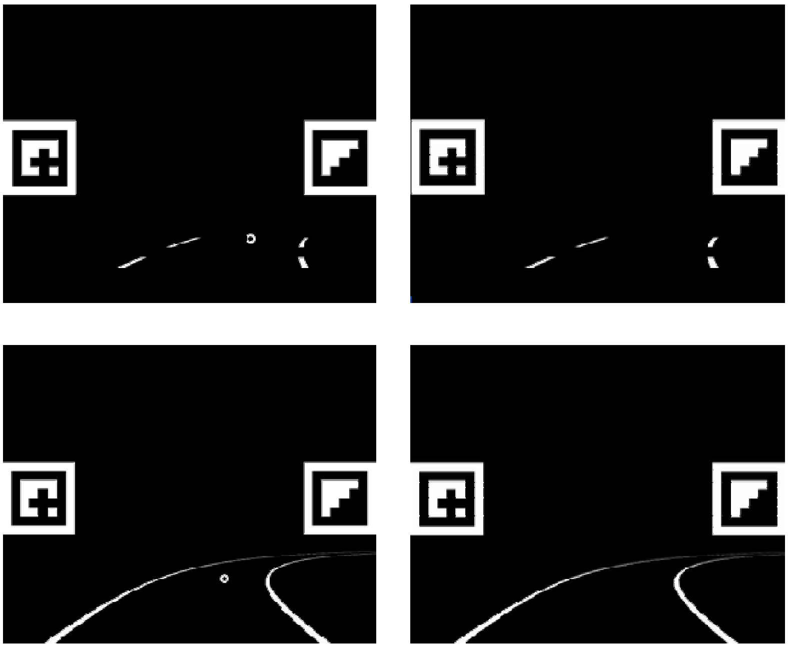

Fig. 2. Road configuration including two markers for the eye tracker and fixation circles for the two fixation conditions center point (left) and free gaze (right). The top row shows the reduced, the bottom row the full road visibility conditions. Note that the fixation targets originally were displayed in pink color to increase their saliency.

3.2 Results

The data from 8 participants had to be excluded from the analysis due to lane exceedances (resulting in extreme values for the lane deviation and/or loss of the fixation point) or failure to comply with fixation instructions. The remaining sample consisted of 19 male and 15 female subjects (total N = 34, mean age = 25,62 years (SD = 4,29) with a range of 19 to 39 years), all of whom reported at least two years of driving experience and only passing familiarity with computer racing games. The first and last 100m of the track were excluded from the analysis because the car needed some time to accelerate to 15m/s after each trial start and the imminent end of the road might have resulted in odd steering behavior from the participants. To test the stated hypothesis, two repeated measures ANOVAs were conducted on the remaining data. Table 1 gives the mean steering precision measures for the four experimental conditions and their standard deviations (SD). Precision descriptively increased both with reduced visibility and in the center point fixation condition.

Table 1. Mean and SD of steering precision (reciprocal of the SD of lateral deviation in m and heading error in rad), listed separately for each of the four experimental conditions

Fixation	Visibility	1/SD lateral deviation		1/SD heading error	
		Mean	SD	Mean	SD
free gaze	unrestricted	3.577	1.162	57.214	9.045
	restricted	3.888	1.335	74.991	19.076
center point	unrestricted	3.844	1.381	68.156	13.186
	restricted	3.955	1.366	77.085	16.992

For the reciprocal of SD of lateral deviation, the ANOVA revealed neither significant main effects for fixation, $F(1, 33) = 1.44$, $p = .24$ ($\eta2 = .04$), nor for visibility condition, $F(1, 33) = 1.39$, $p = .25$ ($\eta2 = .04$). The interaction yielded no significant effect either, with $F(1, 33) < 1$, $p = .56$ ($\eta2 = .01$).

For the reciprocal of SD of heading error, the repeated measured ANOVA showed significant main effects for fixation, $F(1, 33) = 17.35$, $p < .001$ ($\eta2 = .35$), and visibility, $F(1, 33) = 36.17$, $p < .001$ ($\eta2 = .52$). The interaction effect was significant, too, with $F(1, 33) = 9.49$, $p < .01$ ($\eta2 = .22$). As can be seen in Figure 3, the significant effects resulted because of the better steering precision in restricted visibility and center point fixation conditions, with the worst performance shown in the baseline condition (full visibility, free gaze).

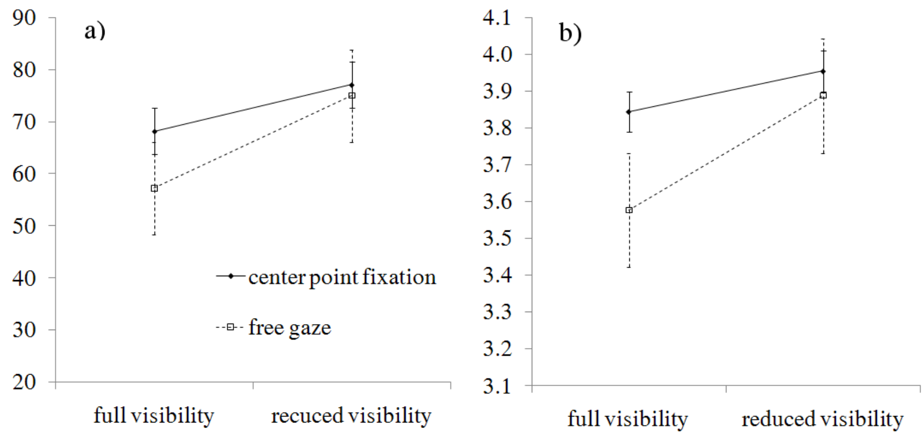

Fig. 3. Steering precision results for the four experimental conditions. In a), the marginal means for the reciprocal of the SD of heading error are reported (in 1/rad) with standard error bars shown; in b), the marginal means of the reciprocal of the SD of lateral deviation (incl. standard error bars; in 1/m) are reported.

4 Discussion

The reported experiment was conducted to test the central assumption of the two-point visual control model of steering, namely, that lane information coming from one region near to the car and one approximately 0.9s down the road is sufficient for precise steering, even with eye fixations only falling into the far region. The results indeed support this hypothesis, as the steering precision (as measured by the reciprocal of the SD of lateral deviation and heading error) was descriptively (in the case of lateral deviation) or even significantly (in the case of heading error) better with reduced visibility than with the whole road visible. This replicates the data reported by Land and Horwood [13], and additionally shows that even when fixating the far region, sufficient information about road position can be gleaned peripherally from the near area. The contradictory findings reported by Chatziastros et al. [16] could be the result of different curvature: in the Chatziastros et al. experiment, curve radius varied between 114.6m and 916.7m, as opposed to 47m in this study. Drivers probably benefit more from the far road region information when curvature is high, necessitating a faster steering response. Additionally, Chatziastros et al. used steering accuracy (lateral deviation) as their dependent measure, and not steering precision as Land and Horwood [13] and this study did. Having only near region information might be sufficient to keep approximately in the middle of the lane, but steering becomes much more stable when a second, far road segment is added. This hypothesis is supported by the steering wheel instability index reported by Land and Horwood, showing that the normalized number of peak steering responses is reduced to baseline levels when two visible segments are displayed instead of one [13].

One limiting factor to the generalizability of this study is that the reported results are only based on those participants who did not exceed the lane boundaries by more than half the car's width. Eight subjects failed to do so; two thirds of all lane exceedances were observed in the reduced visibility, center point fixation condition, with almost every other exceedance occurring in the reduced visibility, free gaze condition. This shows that about one fifth of the subjects had difficulties with the basic lane keeping task when road visibility was limited. Though the data indicate that reduced information is sufficient for most drivers to steer precisely and keep in the middle of the lane (a post hoc analysis of mean lateral deviation showed no detrimental effect of reduced visibility, either), there might be some people who use different information for steering than that available in the reported experiment, e.g. by relying more on optical flow than visual angle information (cf. [21]). As the current study does not hint at the underlying mechanisms, further research is definitely needed in this regard.

Lastly, the second important assumption of the two-point model, namely that drivers are using the tangent point as fixation target, was not tested in this experiment at all. Fixation was directed at a target located at the lane center, in accordance with theories positing that drivers should look where they steer (e.g. [7]). Though the PI-controller of the two-point model works with any fixation point located in the far region [8], a thorough test of the implemented two-point model should include a tangent point fixation condition. Additionally, eye tracking data was only used to control for compliance with the fixation instruction. The eye tracking data recorded during the free gaze trials could be checked for evidence concerning the tangent point usage. Further analysis and experiments examining the role of the tangent point as fixation target in human drivers' steering maneuvers will be the next step in our examination of the viability of the two-point visual control model of steering.

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