**Error accumulation when steering toward curves**

**Courtney M. Goodridge1,2, Jac Billington1, Gustav Markkula1,2, Richard M. Wilkie1,\***

1School of Psychology, University of Leeds

2 Institute for Transport Studies, University of Leeds   
[\*r.m.wilkie@leeds.ac.uk](mailto:*r.m.wilkie@leeds.ac.uk)

# Abstract

To steer a vehicle, humans must process incoming signals that provide information about their movement through the world. These signals are used to inform motor control responses that are appropriately timed and of the correct magnitude. However, the perceptual mechanisms that determine how drivers process visual information are unclear. Previous research has demonstrated that when steering toward a straight road-line, drivers accumulate perceptual evidence (error) over time to initiate their steering action (Accumulator framework), rather than waiting for perceptual evidence to surpass time-independent fixed thresholds (Threshold framework). However, straight road-lines are a simplified case with a constrained set of visual cues so the observed behavioural responses were perhaps biased toward evidence accumulation. The more general case of steering around bends provides richer continuously varying information, with a requirement that the trajectory is adjusted to match the curvature of the road ahead. The current experiment aims to establish whether the Accumulator framework still provides a good description of human responses when steering toward curved road-lines. Using a computer-generated steering correction paradigm, drivers (N=11) steered toward an intermittently appearing curved road-line that varied in position and radius with respect to the driver’s position and trajectory. A Threshold framework predicted that steering responses would be of fixed magnitude and at fixed absolute errors across condition regardless of the rate of error development. Conversely, the Accumulator framework predicted that drivers should respond to larger absolute errors when the error signal developed at a faster rate.  Results were consistent with an Accumulator framework in a manner that supports previous investigations as well as the computational modelling literature. We propose that the accumulation of perceptual evidence captures human behaviour in a variety of steering contexts that drivers face in the real world.

*Keywords: Sensorimotor, Control, Perception, Action, Cognition, Driving, Automation*

Public significance statement: Drivers do not respond to time-independent fixed error thresholds; rather perceptual information is accumulated over time in order to initiate an appropriate steering action. This finding is applicable when steering back onto straight and curved paths and suggests that drivers accumulate perceptual information regardless of the geometry of the target path.

## Introduction

Driving a vehicle is a highly skilled task that involves complex coordinated movements. Steering (Dinparastdjadid et al., 2018; Markkula et al., 2018; Nash & Cole, 2018; Salvucci & Gray, 2004; Wilkie & Wann, 2003) and braking (Durrani et al., 2021; Lamble, Laakso, & Summala, 1999; Markkula, Engström, Lodin, Bärgman, & Victor, 2016; Markkula et al., 2021; Xue, Markkula, Yan, & Merat, 2018) are two sub-components of driving that have been rigorously tested and modelled within the driving literature. Recent accounts have proposed that steering control is *intermittent* in nature rather than continuous. Rather than one unbroken active continuous control adjustment (Johns & Cole, 2015; Lappi & Mole, 2018), intermittent control proposes that steering is comprised of multiple discrete adjustments that are initiated upon surpassing perceived control error thresholds (Gawthrop, Loram, Lakie, & Gollee, 2011; Loram, Lakie, & Gawthrop, 2009; Markkula et al., 2018). However, the mechanism that can best model this intermittency is not yet fully understood. Two alternative frameworks – Threshold and Accumulator – have been proposed as mechanisms that could describe the intermittency involved in steering. Whilst previous research has demonstrated that steering toward *straight* road-line targets is best explained via an Accumulator framework (Goodridge, Mole, Billington, Markkula, & Wilkie, 2022), aspects of the experimental design may have made it more likely that people would accumulate perceptual information rather than rely upon fixed time independent thresholds. Therefore a specific aim of this manuscript was to build upon the work conducted by Goodridge et al (2022) to investigate whether Accumulator-predicted steering responses translate to a more general context where the optical information presented to drivers is more closely aligned to that experienced during real-world locomotor settings (i.e. steering toward curved paths).

Threshold and Accumulator frameworks attempt to explain how an input signal builds towards a threshold in order for a sensorimotor action to be initiated. The main assumption of a Threshold framework is that a sensorimotor action is triggered once an error signal indicating a need for control surpasses a fixed absolute value (Lee, 1976; Seppelt & Lee, 2015). During rear-end braking scenarios, a candidate for such an error signal is visual looming, which is generated when an object moves toward an observer (Terry, Charlton, & Perrone, 2008). The angular projection of the object on the retina is defined as with the angular expansion rate (optical expansion) being defined as (Lee, 1976; Xue, Markkula, Yan, & Merat, 2018). Hence a driver may only produce a braking response once optical expansion surpasses some fixed magnitude. Whilst it may seem intuitive that a human would initiate a sensorimotor action based directly upon the perceptual information that is presented at a particular instant, recent evidence within the driving domain has suggested that this is too simplistic to reliably replicate human performance (Durrani, Lee, & Shah, 2021; Goodridge et al, 2022; Markkula, Boer, Romano, & Merat, 2018; Markkula, Uludag, Wilkie, & Billington, 2021). When braking in response to a looming signal, it has been found that drivers do not simply respond once the looming surpasses a fixed value. Rather, drivers initiate braking at larger looming signals when the rate of change in the looming signal is higher (Lamble et al, 1999; Markkula et al, 2021). An explanation for this behavioural phenomenon is that drivers accumulate perceptual signals over time and then respond once the accumulated quantity surpasses a fixed point, known as the “decision boundary”. Figure 1 details how the time of response changes for perceived control errors () that increase at different rates. The accumulation of small perceived control errors over a long time (Figure 1, yellow shaded zone) is equivalent to the accumulation of large perceived control errors over a short time (Figure 1, purple shaded zone) (Markkula, 2014). Whilst a single fixed Threshold response occurs when the perceived control error () hits the threshold (Figure 1, rhombus symbols) responses based upon a single accumulated error decision boundary are initiated at higher perceived control errors when the rate of increase in the signal is larger (Figure 1, plus symbols). This captures findings within the braking literature where drivers initiate their braking responses at higher overall looming values when the rate of change in the looming signal is higher (Lamble et al., 1999; Markkula et al., 2021).

C:\Users\pscmgo\OneDrive for Business\PhD\Project\Experiment_Code\TvA_analysis_curves\Plots\Fig1.tiff

*Figure 1: Threshold versus Accumulator predictions for responses to perceived control error that either increases at fast (purple) or slow (yellow) rates (). The Accumulator framework predicts a response once the area below the line (integral) exceeds a certain threshold. For a Threshold framework, response onset occurs when the magnitude of the signal exceeds the fixed threshold (dashed horizontal line). The shaded portions under each line are equal in area, indicating equal error accumulation.*

Goodridge et al (2022) conducted one of the first well-controlled and targeted investigations of Accumulator and Threshold frameworks of steering action initiation. Participants were tasked with steering towards an intermittently appearing target ‘road-line’ that varied in position and orientation with respect to the driver’s starting position and trajectory. They used a simplified virtual environment to allow for more precise control and manipulation over the perceptual information that drivers could sample to inform their steering response. Furthermore, control trials that did not require steering responses were interleaved within experimental trials to ensure participants had to wait and sample the visual information rather than anticipating steering responses. This allowed the paradigm to directly exploit the key theoretical differences between Threshold and Accumulator frameworks: how a perceptual signal builds over time. Goodridge et al (2022) found that the timing and magnitude of steering behaviours were in line with Accumulator predicted responses. Drivers did not respond based upon time-independent thresholds, rather they altered their response to the rate at which the perceived control error developed.

In Goodridge et al (2022) the locomotor conditions initially simulated a linear direction of travel relative to a visible *straight* road-line that could be offset at one of a number of possible orientations. However, such a set up produced a prominent egocentric visual angle when the line was first presented when positioned on the road-line (during 0 m starting position conditions, see Figure 2A). To remove the initial egocentric signal, the camera view was counter-rotated by the same number of degrees as the orientation offset (see Figure 2B). However, this manipulation resulted in the future path and instantaneous heading of participants not being aligned, despite initially travelling linearly.

**C:\Users\pscmgo\OneDrive for Business\PhD\Project\Experiment_Code\experiment_curves\Data cleaning and modelling\Manuscript_Plots\Fig9.tiff**

*Figure 2: Bird’s-eye view of the experimental paradigm presented in Goodridge et al (2022) without (A) and with (B) the camera counter-rotation. The points (filled circles) show examples of the position of the vehicle at the start of a trial (T0) and at a later point in time (T1). The bold vertical line represents the visible road-line, the dashed lines represent the trajectories of different orientations, and the arrows represent the direction of the camera view (“camera view” refers to the viewport through which the driver observes the virtual environment and thus generates the image shown on the visual display). To create a display simulation that provides optical information similar to that produced during real-world locomotion, the camera view would be in-line with the direction of travel (panel A). To remove the initial egocentric at T0, the camera view would have to be counter-rotated by the same number of degrees as the orientation (panel B). Now the camera view always aligns with the road-line at T0 and thus nullifies initial error signals when starting from the road-line.*

One potential limitation levied against this experimental set-up is that the counter-rotation may have promoted the Accumulator-like behavioural effects that were observed. Previous research has demonstrated that errors in heading are correlated with errors in steering (Kelly, Beall, Loomis, Macuga, & Smith, 2006) and that altering the heading of an observer (within a virtual environment with sparse motion parallax) can alter the strategy used to steer toward a target (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Hence previous literature has suggested that altering an observers perceived heading can affect the strategy observer’s use to steer, and the precision with which they are able to implement their locomotor strategy. Furthermore, counter-rotating the virtual heading in the manner produced by Goodridge et al (2022) could have produced a sensation of vehicle drift. This is because the optical information participants received (specified by the camera view) had an angular offset relative to the direction they were travelling. Hence it is possible that ambiguity in the perceptual signals may have led to a decreased reliance on a single threshold of response, leading instead to behaviour more consistent with accumulation. Goodridge et al (2022) discussed the possibility that Accumulator and Threshold frameworks may both be present within the human sensorimotor response system in order to produce robust and appropriate actions depending upon the situation. If that is the case then it may have been that the methodology used by Goodridge et al (2022) facilitated information accumulation, rather than accumulation being the predominant method used by drivers independent of the steering context.

The present experiment aims to investigate whether the Accumulator framework will generalise and still capture steering behaviours when steering toward a curving road-line, when future path and instantaneous heading coincide (Adapting and extending the paradigm presented in Goodridge et al (2022), without camera counter-rotation).Rather than manipulating driver orientation relative to a straight road-line, a series of different curvedroad-lines will be presented to participants. As the driver moves linearly through the world, tangential to the curved road-line, a perceived control error () (for example, the lateral distance between the driver and the road-line) develops. By increasing the curvature of the road-line, develops more quickly. In this sense, the degree of curvature of the road-line is used in a manner equivalent to the angle of orientation manipulation in previous investigations (Goodridge et al, 2022), whereby trials with increased curvature will cause the perceived control error to develop at a faster rate. Manipulating the starting position of the driver (Figure 3, moving along the Z axis) introduces a change in initial error signal, but without a concomitant increase in accumulated error.



*Figure 3: Bird’s-eye view of the experimental set up. The black vertical arrow represents the trajectory of the driver and the dashed line represents the direction of the drivers gaze. The solid curved lines represent road-lines that were visible to participants. The star point on the 1000 m radius line represents a preview distance 10 m along the line. The angle between the direction of travel and the point on the road-line represents the visual angle . Drivers travel initially tangential to the curved road-lines. The curvature of the road-line (measured via radius) is broadly equivalent to angle of orientation in the experiments presented in Goodridge et al (2022). A smaller radius results in higher because the distance between the travelling driver and the road-line is increasing at a faster rate.*

Curved paths/trajectories changes the information provided to the observer, with the rate of change in () varying over time due to any mismatch between the curvature of the trajectory and the curvature of the road-line. If an observer is travelling tangential to the curved road-line and fixates a point through the curve on to the line that they wish to pass through (Figure 3, star symbol on 1000 m radius curve), visual angle () to that point will increase at an accelerating rate over time (and the acceleration will increase when bend curvature is greater). Whilst it is conceivable that people could use within a Threshold or Accumulator framework, the most salient signal within this paradigm will be the driver’s visual angle toward a point the road-line. Furthermore, previous research has highlighted that specifies the extent and direction of steering that is required whilst indicates whether the driver’s current trajectory will pass through the fixation point (Robertshaw & Wilkie, 2008; Wann & Land, 2000; Wilkie et al., 2008). Because of the evidence suggesting that visual direction is a prominent perceptual signal for controlling steering, (Fajen & Warren, 2003; Goodridge et al., 2022; Robertshaw & Wilkie, 2008; Wann & Land, 2000; Wilkie et al., 2008; Wilkie & Wann, 2003) for the simulations that generate the hypotheses presented in the current experiment, the perceptual input used will be the angle () between the observer’s current trajectory and a point 10 metres (approximately 1.26 s) ahead on the road-line. As per Goodridge et al. (2022) three steering metrics were taken: i) the timing of the first steering response, ii) the lateral distance from the road-line at response, and iii) the magnitude of the steering response. The aim was to use these metrics to determine whether human responses aligned with Accumulator or Threshold framework predictions. Specific hypotheses linked to each metric are discussed within the hypotheses section.

## Method

### Hypotheses

In order to produce hypotheses of human behaviour based on Threshold and Accumulator frameworks, the experimental paradigm was simulated. The radius of the road-line (manipulating the rate at which the perceived control error developed; ) was paired with driver starting position (manipulating initial ) in order to create the range of conditions used within the real experiment. The experimental paradigm settings in the simulations also matched those in the real experiment (car speed: 8 m/s, frame rate: 60 Hz, road-line width: 0.05 m). The driver was represented by a single point and the vehicle body was not simulated. The Accumulator framework accumulated over time with no gain factors, noise, or leakage terms and provided a reaction time and lateral position from the road-line once the integrated quantity surpassed a decision boundary. Conversely, the Threshold framework used the non-accumulated and responded when it surpassed a fixed threshold. A 150 ms motor latency was applied to simulated predictions (Brenner & Smeets, 1997). Decision boundary and fixed threshold values were chosen to give reaction times and lateral position errors similar in magnitude to those observed in previous studies (Markkula et al, 2018) and the pilot investigations. Modifying these parameter values altered the overall predicted values of reaction times and lateral position errors, but the qualitative pattern of differences between framework predictions remained the same. The aim of these simulations was to provide a qualitative description of expected steering behaviour according to Threshold and Accumulator accounts which could then be compared to driver steering responses. Therefore, the Y-axis values of the predictions have been removed as they provide qualitative response patterns rather than quantitative estimates.

### H1 Reaction time

Both Threshold and Accumulator frameworks predict that reaction times will decrease as bend radii reduces because it will take less time for to surpass the fixed threshold or decision boundary. Both frameworks predict that the manipulation of starting position should cause a decrease in reaction time as starting position increases. This is because with a larger initial it will take less time for to build and surpass a fixed threshold or decision boundary. Framework predictions diverge, however, when focusing on between-level differences in starting position and the interaction between radius and starting position (see Figure 4). The Accumulator framework predicts smaller between-level differences in reaction times between 4 m and 8 m compared to 4 m and 0 m. Conversely, the Threshold framework predicts similar between-level differences across starting position levels. The Accumulator framework also predicts a subtle radius-starting position interaction on reaction times, whereby the between-level starting position differences diverge as radii become larger. The Threshold framework predicts that between-level differences in starting position should remain constant regardless of the radius of the road-line curvature.



*Figure 4: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of reaction times that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates.*

### H2 Lateral position error

The Threshold framework predicts that the driver will respond at the same lateral position error regardless of the curve radius. However, in the current set up we might actually expect to see slightly higher lateral position errors for larger radii curves. This is because for larger radii, and as the observer moves through the world, the *visual angle* to a point on the curved road-line grows more slowly than *lateral position error*. Hence the observer would end up travelling a further lateral distance from the road-line until they surpass the fixed visual angle threshold. This results in the Threshold framework predicting larger lateral position errors for larger radii (see Figure 5B). The Accumulator framework has markedly different predictions: responses are expected at increased lateral position error for smaller radii and larger starting positions (see Figure 5A). An interaction is also predicted between radii and starting positions under the Accumulator framework, whereby between-level differences in lateral position error become smaller for larger radii. Conversely, the Threshold framework predicts that drivers will respond at the same lateral position irrespective of starting position and motor latency because a fixed threshold will dictate responses.



*Figure 5: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of lateral position errors that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates.*

### H3 Steering rate

Previous research has suggested steering magnitude should scale according to the being responded to (Durrani et al., 2021; Goodridge et al., 2022; Markkula et al., 2018; Yilmaz & Warren, 1995). Therefore, in the current experiment, predictions for the Accumulator framework are that steering magnitude should increase as radii becomes smaller and the starting position becomes larger, alongside a radii-starting position interaction that matches the predictions for lateral position error (see Figure 6). Conversely, the Threshold framework predicts similar steering magnitudes across all radii and starting positions: although the motor latency influences the measured lateral position error, the lateral position error signal used to initiate the driver’s response should be fixed (hence the magnitude of their steering response should be constant).



*Figure 6: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of steering rates that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates. For the Threshold framework, the starting position levels have been shifted under each other to make them more visible. In practice, we would not expect differences in behaviour between these levels under this framework for this metric.*

### Participants

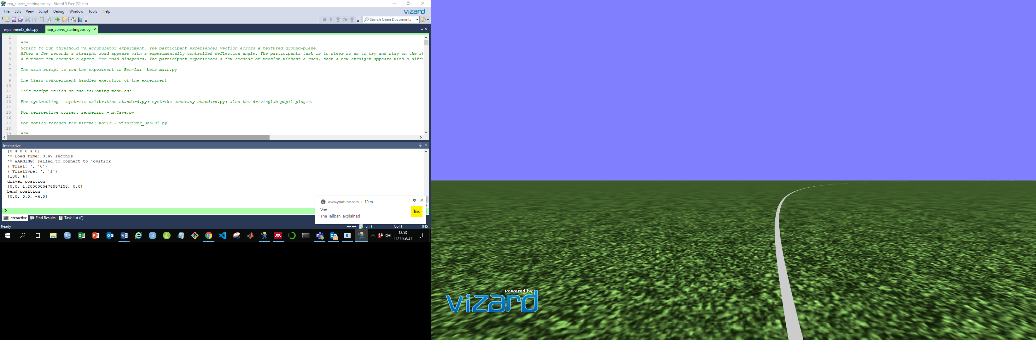
12 participants took part in the experiment, however data for 1 participant had to be removed due to not having a valid UK driving license at the time of testing. This left 11 valid datasets for analysis (5 females, 6 males, mean age = 29.91, range = 22-44) all with normal (or corrected to normal) vision alongside a valid UK driving license. The number of months holding a driving license ranged from 1-312 (*mean* = 73.33 months, *SD* = 100.12).

### Apparatus

The virtual environment was created in WorldViz Vizard 5 and back projected on a screen with dimensions 1.98 m x 1.43 m. Participants sat 1 m away generating a total visual angle of 89.4° x 71.3° with the true horizon being 1.2 m from the ground. Data were acquired using a Logitech G27 force-feedback steering wheel and was synchronised to the refresh rate of the display at 60 Hz. Participants did not operate accelerator/brake pedals and vehicle speed remained constant at 8 m/s.

### Design

In the current experiment, participants responded to appearing curved road-lines, attempting to steer back onto each line as it appeared (see Figure 7). A green ‘gravel’ texture was applied to the ground to ensure participants experienced a compelling sensation of self-motion through the virtual environment. The textured ground plane and the blue sky were the same as those used previously by Goodridge et al (2022).



*Figure 7: Screenshot of the visual display presented to participants.*

*The moment captured is the start of a new trial when the road-line has just been made visible. The driver is travelling linearly, tangential to the curve. The curve shown has a radius of 1500 m with driver being offset at a starting position of 4 m. The ‘Vizard’ label was not visible during experimental trials.*

Curves were chosen from a pool of 6 linearly separated radii (-2000 m, -1500 m, -1000 m, 1000 m, 1500 m, 2000 m) alongside a 0 m condition with no curvature. These radii were chosen based upon extensive piloting: radii below 1000 m produced bends that were sometimes too tight (particularly when paired with an 8 m starting position manipulation) with participants occasionally failing to steer back onto the road-line within the specified timeframe. The 0 m radius condition presented a straight line with no curvature which created a response context where participants did not always have to respond; this was in order to guard against participants adopting a “steer as soon as possible” strategy on the appearance of the road-line. A range of equally spaced starting position levels were also chosen (0 m, 4 m, and 8 m) in order to alter the initial that drivers experienced. Overall, this created a 3 (radius) x 3 (starting position) repeated measures factorial design (see Figure 8). Three dependent variables were measured in this experiment: reaction time of the first steering adjustment (seconds), lateral position error from the road-line when first steering adjustment occurs (metres), and peak steering rate of the first steering adjustment (degrees per second).

C:\Users\pscmgo\OneDrive for Business\PhD\Project\Experiment_Code\experiment_curves\Data cleaning and modelling\Manuscript_Plots\Fig6.tiff

*Figure 8: Bird’s-eye view of the experimental paradigm.*

*The bold curved lines represent the position of the visible road-lines presented within the virtual environment, the vertical dashed line represents the trajectory of the driver, and the black, grey, and white dots highlight the starting position manipulation.*

### Procedure

Informed and written consent was obtained and standardised procedural instructions were delivered. All procedures were approved by the University of Leeds School of Psychology Research Ethics Committee (Reference code: PSYC-183).

Participants were placed into the standardised viewing position within the driving simulator and then completed 10 practice trials to familiarise themselves with the vehicle dynamics and steering wheel. At the beginning of each trial a 0.1 s black mask was presented to indicate the start of the trial. Participants then travelled for 1 s across the textured ground plane. Following this 1 s period, the road-line was presented for 5 s. Participants were instructed to “make a steering adjustment, as fast and as smoothly as possible, that would bring you back onto the road-line if you feel yourself deviate away from it”. After 5 s, the road-line disappeared and the participant travelled for a further 1 s before the next trial began seamlessly. The width of the road-line was 0.05 m and each trial lasted approximately 7 s. Each block was approximately 4 and half minutes long. Radius and starting position conditions were randomised to guard against order effects.

## Analysis

### Pre-processing

In order to identify valid steering responses, the steering wheel angle was recorded and differentiated in order to calculate the steering rate signal. A lower threshold (identifying the start of a correction; 0.02°/s) and an upper threshold (ensuring the ensuing correction was of sufficient magnitude; 0.05°/s) were used on the steering rate signal to identify valid steering responses. Steering responses that did not exceed the upper threshold (thus not being large enough) or exceeded it but quicker than 150 ms (thus being too fast to be valid responses) were excluded. Reaction times were calculated as the time that elapsed between the road-line being presented, to the time when the steering rate surpassed the lower threshold. From valid responses, the lateral position error (LPE) was identified by calculating the lateral distance from the road-line to the closest point to the driver at steering onset.

*Table 1: Data exclusion across radius and starting position conditions for all participants.*

|  |  |  |  |
| --- | --- | --- | --- |
| Radius | Starting position | Total trials | Excluded trials |
| 1000 | 0 | 312 | 35 |
| 1000 | 4 | 312 | 36 |
| 1000 | 8 | 312 | 38 |
| 1500 | 0 | 312 | 34 |
| 1500 | 4 | 312 | 37 |
| 1500 | 8 | 312 | 36 |
| 2000 | 0 | 312 | 41 |
| 2000 | 4 | 312 | 43 |
| 2000 | 8 | 312 | 33 |

### Modelling steering response metrics

Left and right trajectories were mirrored and collapsed into a single data set. Straight line conditions were removed from further analysis as these were only included to provide a response context whereby steering responses were not required in every trial. Analysis was, therefore, carried out on 3 radius conditions (1000 m, 1500 m, and 2000 m) and 3 starting position conditions (0 m, 4 m, and 8 m). Models were fitted using the *lmer()* and *glmer()* functions from *lmerTest* (Luke, 2017) package in R. In order to maintain model convergence, the nAGQ argument within the *glmer()* function was set to 0 (Dorokhova & Imperio, 2020).

The population mean () of each steering metric was modelled using a linear model consisting of an intercept (), a coefficient representing radius (), a coefficient representing starting position (), and a coefficient representing the interaction between radius and starting position (). It should be noted that the radius and starting position predictors were on different numerical scales. Starting position levels ranged from 0-8 m whereas radii ranged from 1000-2000 m. This situation can cause numerical instability during model fitting which can lead to convergence issues. To solve this problem the predictor variable levels were standardised. The *scale()* function calculated the mean and standard deviation of the predictor levels and then subtracted the mean and divided by the standard deviation for each level. By standardising the predictor variables, linear model coefficients were interpreted as the **change in the mean of the response for a 1 standard deviation increase in the predictor**.

For each steering metric, candidate models were fitted with Gamma, Inverse Gaussian, and Gaussian distributions. This is because these distributions provide good statistical approximations of the positively skewed response distributions synonymous with reaction time and steering rate responses (Lo & Andrews, 2015). Therefore, an improved estimation of the mean of the response could be generated. The most parsimonious models for each metric were selected by comparing AIC values. When the maximal random effects structure would not converge or produced singularity estimates, simplification of the random effects structure was conducted. Considering the main hypotheses within this manuscript relate to fixed effects rather than the random effects, Bates et al (2015) suggests it is reasonable to remove random effect components if they are not supported by the data. It is recommended that a maximal model should be fitted first before reducing the complexity to a level where convergence and parameter estimates are stable (Barr et al., 2013; Bates et al., 2015; Singmann & Kellen, 2019). It has been suggested that correlations among the random slopes should be removed first as these contribute the largest number of random effects within the model when specifying two or more factors (Singmann & Kellen, 2019). The distributional model equations and AIC values for each metric are provided in the supplemental material.

## Results

A bird’s-eye view of the average trajectories were inspected to reveal how participants performed across conditions (see Figure 9). The solid points denote the mean position when participants first initiated steering and the thick solid black curved line represents the road-line that was presented during the trial. Overall it appears that drivers responded at a further lateral distance from the road-line as the curvature increased. However, because of the starting position manipulation, it is hard to determine from visual inspection of the trajectories whether there are between-level differences in where drivers responded. In order to examine this further, the parameters from the models were investigated.



*Figure 9: Bird’s-eye view of average participant trajectories for each radius and starting position condition. The bold black curved line represents the road-line presented to the driver. The arrows indicate the starting position of each respective starting position conditions. The thin solid/dashed/dotted lines represent average trajectories for each condition, and the circles denote the average position at which drivers began to steer. The circle fill shade represent the location of the first steering response for 0 m (black), 4 m, (white), and 8 m (grey) conditions.*

### Reaction times

Table 2 summarises the fixed effects and standard errors for each predictor in the reaction time model. Overall, there was a significant main effect of radius, starting position, and a significant interaction. The interaction effect between radius and starting position is demonstrated in Figure 10C. The parameter suggests that for a one standard deviation increase in radius, starting position’s effect on reaction times increases by 0.01 m. The interaction appears to be driven by the 4 m starting position manipulation; reaction times increase by a larger magnitude as radii become larger. This effect is not as prominent for conditions containing the 0 m starting position manipulation (see Figure 10C). Under the Accumulator framework, it was expected that the slope of the dependency on radius would increase with decreasing starting positions. The data demonstrates this relationship strongly between 8 m and 4 m, but not as strongly between 4 m and 0 m. Hence, whilst these patterns are broadly consistent with the Accumulator framework the other metrics may provide more conclusive evidence for which framework best accounts for the behavioural responses.



*Figure 10: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of reaction times that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates. C) Mean reaction times across radii and starting position conditions. Note that the y-axis units have been magnified relative to display the relative pattern of responses across each condition. Error bars represent 95% confidence intervals.*

*Table 2: Fixed effect parameter estimates and standard errors from reaction time model.*

|  |  |
| --- | --- |
| **Fixed effects** | |
|  | |
|  | *Dependent variable:* |
|  |  |
|  | Reaction time |
|  | |
|  | 0.722\*\*\* (0.038) |
|  | 0.062\*\*\* (0.012) |
|  | -0.089\*\*\* (0.013) |
|  | -0.011\*\* (0.005) |
|  | |
| Participants | 11 |
| Observations | 2304 |
|  | |
| *Note:* | \*p<0.1; \*\*p<0.05; \*\*\*p<0.01 |

### Lateral position error

Table 3 summarises the fixed effects and standard errors from each predictor in the lateral position error model. A significant main effect of radius and starting position was found as well as a significant radius-starting position interaction (see Figure 11C). The parameter suggests that for one standard deviation increase in radius, the effect of starting position on lateral position error decreases by 0.004 m. This suggests that when radii were larger, the between level starting position differences in lateral position error were smaller. This interaction provides strong evidence for the Accumulator framework as shown in Figure 11A. Participants did not respond once reaching a fixed absolute error. Rather, the perceived control error they responded to varied according to the rate of error development and initial error that participants were presented with.



*Figure 11: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of lateral position errors that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates. C) Mean lateral position errors across radii and starting position conditions. Error bars represent 95% confidence intervals.*

*Table 3: Fixed effect parameters estimates and standard errors from lateral position error model.*

|  |  |
| --- | --- |
| **Fixed effects** | |
|  | |
|  | *Dependent variable:* |
|  |  |
|  | Lateral position error |
|  | |
|  | 0.035\*\*\* (0.003) |
|  | -0.007\*\*\* (0.001) |
|  | 0.013\*\*\* (0.0004) |
|  | -0.004\*\*\* (0.0005) |
|  | |
| Participants | 11 |
| Observations | 2304 |
|  | |
| *Note:* | \*p<0.1; \*\*p<0.05; \*\*\*p<0.01 |

### Steering rate

Table 4 summarises the fixed effects for the steering rate model. A significant main effect of radius and starting position was found as well as a significant interaction between these variables. A significant radius-starting position interaction is evident with between-level differences of starting position becoming smaller as radii increase, mirroring the effects seen for lateral position error (see Figure 12C). The parameter suggests that for a 1 standard deviation increase in radii, the effect of starting position on steering rate was reduced by around 0.012°/s. This interaction mirrors the one found for lateral position error and provides strong evidence in favour of the Accumulator framework. Participants did not initiate similar steering rates across the conditions, but instead varied them relative to the radius and initial starting position they were presented with.

*Figure 12: Accumulator (A) and Threshold (B) framework predictions of the qualitative patterns of steering rates that might be expected based upon experimental simulations. Y axis values have been removed as these predictions are of qualitative response patterns rather than quantitative estimates. For the Threshold framework, the starting position levels have been shifted under each other to make them more visible. In practice, we would not expect differences in behaviour between these levels under this framework for this metric. C) Mean steering rates across radii and starting position conditions. Error bars represent 95% confidence intervals.*

*Table 4: Fixed effect parameters estimates and standard errors from steering rate model.*

|  |  |
| --- | --- |
| **Fixed effects** | |
|  | |
|  | *Dependent variable:* |
|  |  |
|  | Steering rate |
|  | |
|  | 0.354\*\*\* (0.025) |
|  | -0.033\*\*\* (0.004) |
|  | 0.045\*\*\* (0.008) |
|  | -0.012\*\*\* (0.004) |
|  | |
| Participants | 11 |
| Observations | 2304 |
|  | |
| *Note:* | \*p<0.1; \*\*p<0.05; \*\*\*p<0.01 |

## Discussion

The current experiment is the first targeted investigation into whether the Accumulator framework captures steering behaviours to curved road-lines. Furthermore, this experiment aimed to establish whether the Accumulator framework was still applicable when drivers were provided with optical information consistent with everyday locomotion (i.e. when the direction of motion and the direction of heading were aligned rather than heading being artificially counter-rotated; Goodridge et al, 2022). The rate at which the perceived control error developed () was manipulated by altering the curvature of a road-line (smaller radii were associated with increased ), and initial was also manipulated by altering the starting position of drivers relative to the visible road-line. The results provided strong evidence that drivers accumulated in order to initiate a response, rather than waiting for the perceptual signals to surpass a fixed threshold. Participants altered the timing and magnitude of their steering relative to the and initial experienced. These findings would appear to provide strong evidence that participants were accumulating perceptual information over time rather than utilising time-independent fixed thresholds.

When considering alternative explanations for the patterns of findings it is worth considering whether any of the modelling assumptions could have invalidated the modelled predictions. One potential issue for the lateral position error modelling could be the assumed 150ms motor latency, since longer motor latencies could have led to differences between the conditions, perhaps more akin to observed behavioural response. To investigate this possibility, lateral position errors were modelled for a wider range of latencies (150-600 ms) under a Threshold framework to investigate whether a different latency could generate response patterns more like those that were observed. During the latency period, the observer continues to travel linearly relative to the curved road-lines for each radius-starting position condition. The resultant lateral position errors can be seen in Figure 12 (150 ms is the Threshold framework predictions used in the Results). The starting position conditions do begin to separate but only once motor latencies reach 600ms, and the magnitude of the effect remains very small in comparison to those observed in the human responses, and also those produced by the Accumulator framework predictions. Furthermore, a latency of above 500 ms is unlikely for the sensorimotor actions generated during the current experiment. Brenner & Smeets (1997) identified motor delays ranging from 100-200 ms when asking participants to use the tip of a rod to touch a target location. A potential limitation with using this value within a steering context is that the movement of a steering wheel may exacerbate the magnitude of any motor delay due to the time needed to move the wheel a sufficient amount to register a response. However, research investigating the visual-motor delays in drone steering (when using controller joysticks) have been found to be around 220 ms (Pfeiffer & Scaramuzza, 2021) which is the upper limit to the delays found by Brenner & Smeets (1997). Overall, this analysis suggests that a combination of a motor delay and fixed threshold is unlikely to be an explanation for pattern of lateral position error responses observed in the current experiment.



*Figure 12: Threshold framework predictions for lateral position errors across a range of motor latencies.*

Further evidence that the behavioural data in this manuscript supports the Accumulator framework comes in the form of steering magnitude metrics matching the Accumulator predicted responses for lateral position error. The Accumulator predicted interaction between radii and starting position is consistent with steering magnitude and lateral position error metrics in previous observations of steering toward straight road-lines when manipulating orientation and starting position (Goodridge et al., 2022). This provides good evidence that the magnitude of a steering response scales with the perceived control error that a driver is attempting to reduce (Durrani et al., 2021; Markkula et al., 2018; Yilmaz & Warren, 1995). The current experiment also supports the findings of Mole et al (2020) who found that during silent failures of automation, drivers responded to smaller perceptual errors during more gradual failures. Such a finding is accumulative in nature as the Accumulator framework predicts responses will occur at smaller error signal values when there is more time over which to integrate perceptual signals. Despite this, Mole et al (2020) did not explicitly set out to test Accumulator versus Threshold hypotheses. Rather, the Accumulator framework provided an explanation for the findings of their experiment. Conversely the current experiment was explicitly designed to test the differing framework predictions, with the data and analysis presenting a similar finding: drivers responded at smaller lateral position errors when the perceived control error developed more slowly (i.e. when presented with larger radii curves and nearer starting positions).

A key methodological difference between the current experiment and previous research by Goodridge et al (2022) was the lack of the previously employed camera counter-rotation. The consistent results across both experiments (both with and without the camera counter-rotation) suggest that this manipulation was not the cause for the observed accumulation. Future research could investigate how drivers sample the optical information in order to accumulate evidence, by measuring eye movements. The steering literature has already demonstrated that drivers look where they steer (Wilkie, Kountouriotis, Merat, & Wann, 2010) but they also steer where they look (Kountouriotis et al., 2012; Robertshaw & Wilkie, 2008). These studies show that the direction of gaze is linked to the direction of steering (and vice versa). Because of the wealth of literature detailing the importance of gaze in steering coordination, it may be important to determine whether gaze has influence over the accumulation of information. One way to do this would be to run a similar paradigm to the one presented here with an additional gaze fixation factor (similar to the one used by Wilkie & Wann, 2003). If forced fixations disrupt the orientation/radii-starting position interaction, then that would demonstrate that having free gaze pointed in the direction the driver wants to steer is a prerequisite for the successful accumulation of information. However, if biasing gaze *does not* influence Accumulator framework steering behaviours, then it may be that peripheral vision is adequate to accumulate the perceptual signals necessary to inform a steering response.

Accumulator based predictions of steering behaviours translating to the more general context of steering curved trajectories provides good evidence that the Accumulator framework is not specific to simple straight road-line error-correction contexts. The use of curved paths in the current experiment also opens the door toward another line of investigation; namely, whether the Accumulator framework could be used within a more predictive steering control setting. Throughout this experiment, the Accumulator framework has been viewed through the lens of online steering control, whereby action is mapped directly upon the perceptual input indicating a need for control (Pekkanen, 2019; Zhao & Warren, 2015). However, when presenting a curved road-line, participants may have been able to use a more predictive steering strategy by using a preview of the curved path to guide their steering response. Predictive or “model-based” steering control proposes that action is selected based upon an internal representation of the environment and an estimate of the perceptual variables within it (Loomis & Beall, 1998; Pekkanen, 2019; Warren, 1998; Zhao & Warren, 2015). Whilst the Accumulator framework has been discussed throughout in relation to online steering control, this is not to say it could not be incorporated within a model-based approach. Occlusion studies have demonstrated that drivers can maintain adequate steering control for around 2 seconds along curved paths (Cavallo, Brun-Dei, Laya, & Neboit, 1988; Godthelp, 1986) and during lane changes (Hildreth, Boer, Beusmans, & Royden, 2000) when visual input is occluded. This might indicate that humans have the ability to generate a representation of the environment, spatially update their position within the representation, and produce adequate steering control based upon these predictions. However, whether the proposed model-based updates are accumulative in nature, or whether accumulation only occurs when visual information is directly available, has yet to be investigated. A question for future research will be to see whether drivers can accumulate within their internal model during occlusion, or whether the accumulation stops during occlusion and resumes only once visual input is restored.

Whilst the paradigm presented here was designed to answer theoretical questions as to the nature of human steering control, there are clear parallels with applied situations produced with the advent of vehicle automation, specifically failures of automation. A paradigm implemented by Mole et al (2020) required drivers to steer back towards the centre of curved roads upon the failure of an automated driving system that was guiding the vehicle around a bend. Whilst Mole et al (2020) created a full road context rather than a single road-line, the current experiment is essentially a more controlled version of this automation failure paradigm. One difference between the current experiment and the Mole et al (2020) design is the nature of the failure that produces the error signal. The so-called “silent failures” created by Mole et al (2020) were gradual, whereby the yaw rate of the vehicle was mismatched with respect to the yaw rate of the bend. Consequently, the vehicle would turn around the bend but the rate of steering was insufficient, so the vehicle would slowly drift towards the outside edge of the road. This can be thought of as a lane-keeping system failing without warning the driver (hence the failure is “silent”), causing the driver to slowly drift out of lane. This situation has also been defined as a *curved* failure (Boer, 2016) and it has been suggested that drivers are less accurate at detecting them because even post-failure, the vehicle is (initially at least) still following an acceptable trajectory around the bend from the driver’s perspective (Boer et al, 2016). In contrast, the error signal presented in the current experiment was generated via the driver travelling tangential to the curved road-line. This corresponds more closely to a situation where the automation fails on a straight before the entry into a curve. Our results provide some insight into how drivers might respond in such a failure scenario. Namely, that relying upon drivers to respond appropriately to visual information surpassing fixed values is too much to expect. Rather, drivers need time for visual information to accumulate over a given period to initiate responses that are timely and of sufficient magnitude.

The present paper highlights evidence that drivers accumulate perceived control error information in order to initiate steering action towards curved road-lines targets. This supports previous investigations that drivers accumulate perceived control errors when steering onto straight road-line targets (Goodridge et al., 2022) and adds to growing literature that intermittent online sensorimotor action is facilitated by the accumulation of perceptual information over time rather than perceptual information surpassing time-independent fixed thresholds (Bianchi Piccinini et al., 2019; Durrani et al., 2021; Kovaceva, Bärgman, & Dozza, 2020; Markkula, 2014; Markkula et al., 2021).