Steering bends and changing lanes: The impact of optic flow and road edges on two point steering control

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Successful driving involves steering corrections that respond to immediate positional errors while also anticipating upcoming changes to the road layout ahead. In popular steering models these tasks are often treated as separate functions using two points: the near region for correcting current errors, and the far region for anticipating future steering requirements. Whereas two-point control models can capture many aspects of driver behavior, the nature of perceptual inputs to these two "points" remains unclear. Inspired by experiments that solely focused on road-edge information (Land & Horwood, 1995), two-point models have tended to ignore the role of optic flow during steering control. There is recent evidence demonstrating that optic flow should be considered within two-point control steering models (Mole, Kountouriotis, Billington, & Wilkie, 2016). To examine the impact of optic flow and road edges on two-point steering control we used a driving simulator to selectively and systematically manipulate these components. We removed flow and/or road-edge information from near or far regions of the scene, and examined how behaviors changed when steering along roads where the utility of far-road information varied. While steering behaviors were strongly influenced by the road-edges, there were also clear contributions of optic flow to steering responses. The patterns of steering were not consistent with optic flow simply feeding into two-point control; rather, the global optic flow field appeared to support effective steering responses across the time-course of each trajectory.

Introduction

Humans use multiple sources of visual information to steer when driving down winding roads (Wilkie & Wann, 2002, 2003). However, models of steering control can recreate some aspects of steering behaviors using solely two control points: typically, a far point
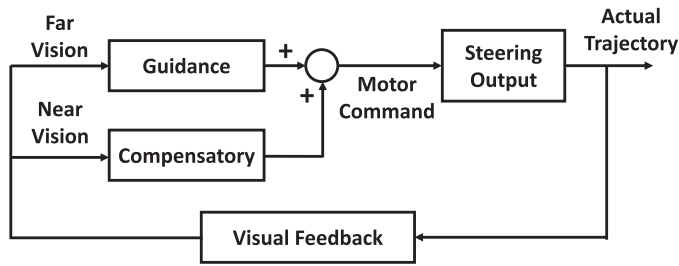
Figure 1. A two-point control model. When steering using the far point the driver is able to match the future road curvature but unable to eliminate positional error, leading to steering which is smooth but inaccurate. Conversely, when relying on just the near point, the driver is able to eliminate positional error but unable to respond in advance to changes in curvature, leading to steering which is jerky but accurate.

(which provides a preview of future changes in direction), and a near point (which indicates current position-in-lane; Donges, 1978; Salvucci & Gray, 2004; Boer, 2016). The key principles of two-point control models have been tested by examining driver behavior when far (preview) or near (position-in-lane) information has been selectively removed. When far road information is removed, steering actions become less smooth because drivers must rely upon near road information to rapidly (and repeatedly) correct errors after they have occurred (Land & Horwood, 1995; Chatziastros, Wallis, & Bülthoff, 1999; Cloete & Wallis, 2011; Frissen & Mars, 2014; Mole et al., 2016). Conversely, when near road information is removed, drivers find it difficult to correct positional errors, leading to larger deviations from the desired path, while managing to maintain smooth steering to match the future road curvature (for in-depth discussions of this evidence the reader is referred to Mole et al., 2016). The behavioral relationship is assumed to be a basic control model which is divided into guidance control using far vision (Figure 1, Guidance) and compensatory control using near vision (Figure 1, Compensatory). Whereas the weightings of the components displayed in Figure 1 will vary depending on the nature of the steering task, the general principles appear to be well supported and act as the basis of many current steering models (e.g., Sentouh, Chevrel, Mars, & Claveau, 2009; Saleh, Chevrel, Mars, Lafay, & Claveau, 2011; Boer, 2016; You & Tsiotras, 2016; Markkula, Benderius, & Wahde, 2014; Mars & Chevrel, 2017).Given the widespread prevalence of such two-point steering models it is worth noting that the precise sources of near and far information are often only weakly specified. Road environments are rich sources of information, containing a large set of features from near and far regions that could contribute to estimates of position in lane and the future steering requirements. The characteristic two-point control behaviours (Figure 1) have been

elicited using displays that only contained "windows" of perspective correct road-edges (Chatziastros et al., 1999; Land & Horwood, 1995; Cleote & Wallis, 2011; Neumann & Deml, 2011) and components are sometimes refined even further to include elements solely containing splay angle information (the angle between the optical projection of the lane edge and a vertical line in the image plane; Beall & Loomis, 1996; Li & Chen, 2010). In theoretical accounts it is often assumed that angular inputs would be obtained from road-edges; however, the precise mechanisms for extracting this information are unclear. Computational driver models during curve following tend to use angular inputs between the direction of travel of the vehicle and points on the road center rather than signals obtained directly from road-edges (Salvucci & Gray, 2004; Boer, 2016; You & Tsiotras, 2016; Markkula et al., 2014; Mars & Chevral, 2017, although in some cases the near point has been implemented as dependent on road-edge information; Kountouriotis, Floyd, Gardner, Merat, & Wilkie, 2012). These accounts do not disentangle use of road-edge information from the other perceptual inputs that are available when looking where you are going (such as gaze direction[1] or retinal flow; cf. Wilkie & Wann, 2003). One issue when determining the role of the visible road edges is that they not only supply useful information about the steering that has been taking place, but they also place hard constraints upon the future steering requirements (e.g., when road edges are visible, it is necessary for the driver to steer within them). Consequently, when removing road edges, it can be difficult to determine whether individuals rely more on remaining perceptual inputs, because removing the road could fundamentally change the nature of the steering task. One way of preserving the steering task (requiring the driver to maintain a position on the road) but weakening the inputs supplied by road-edges is to selectively remove regions of the road (either near or far regions) while leaving road-edges in other regions. The driver's reliance on alternative sources of information (such as optic flow) can then be compared when completing the same lane following task (e.g., Mole et al., 2016).

The two-point control models of steering referred to so far rely solely on a near point and far point to produce trajectories similar in quality (i.e., similar smoothness and variability) to those produced by humans. However, just because the trajectories produced are broadly similar to human data, it cannot be concluded that human drivers are relying on solely two points. Human drivers need to operate in a wide variety of visual environments, including many situations where roads (and critically road edge information) is weak or absent (Kountouriotis et al., 2012). There are many potential informational inputs available to human drivers navigating visually rich environments

(Wilkie & Wann, 2003; Wann & Wilkie, 2004), and evidence across multiple studies suggest that humans exploit the redundancy in perceptual information, using a combination of the available signals to provide reliable and robust steering control (Wilkie & Wann, 2002, 2006; Warren, Kay, Zosh, Duchon, & Sahuc, 2001; Wood, Harvey, Young, Beedie, & Wilson, 2000). In particular, humans are highly sensitive to optic flow (Warren, Mestre, Blackwell, & Morris, 1991), and there is evidence that optic flow information provides information distinct from that supplied by the road-edges (Kountouriotis, Mole, Merat, & Wilkie, 2016; Mole et al., 2016).

Using Land and Horwood's (1995) method of adjusting 1° vertical viewing "windows" (a small segment where both road edges were visible, and outside of which road edges were invisible), Chatziastros et al. (1999) found that adding road texture (i.e., optic flow information) reduced lateral deviation uniformly across all viewing segment conditions. Indeed, humans appear to use optic flow as a control source even when current and future steering requirements are specified by visible road-edges (Kountouriotis et al., 2013; Kountouriotis et al., 2016; Mole et al., 2016). Kountouriotis et al. (2013) demonstrated that placing different textures either side of the road caused predictable biases to steering trajectories. Most strikingly if one region was left untextured or kept static (and so created a region that produced no optic flow), participants were biased toward the "no-flow" region despite the presence of visible road-edges. Kountouriotis et al. (2016) and Mole et al. (2016) manipulated flow speed independent of the locomotor speed (by rotating the ground plane independent of the road-edges) and were also able to bias steering trajectories despite veridical road-edge information. Furthermore Mole et al. (2016) demonstrated that the extent of steering bias (caused by fast or slow flow speed) varied according to whether near or far road components were visible. It seems, therefore, that specific components of flow interact with near and far road-edge information in different ways (Mole et al., 2016), prompting Mole and colleagues to call for two-point models to be developed that incorporate flow information.

In contrast with models identifying the importance of road edge information, there are also steering control solutions that predominantly rely upon optic flow (Gibson, 1958) or retinal flow (the flow pattern available to an animal that looks where it wants to go; Kim & Turvey, 1999; Wann & Swapp, 2000). While these solutions support steering toward the point of fixation, they also generalize to steering down a demarcated road if the fixations are guided by the road edges, e.g., gaze is directed to the midpoint between the road edges, or even toward the inside road-edge when cutting the corner (Wilkie et al., 2010). It may be,

therefore, that the flow signal available when fixating where you want to go is the primary informational variable, with road edges merely guiding the placement of gaze. It seems, then, that accurate models of human steering control will somehow need to combine the signals derived from optic flow and road edges perhaps in a two-point control model that allows for additional perceptual inputs. An issue when trying to develop such a two-point control model is that the contribution of flow and road edge information to near and far points remains unclear. While Chatziastros et al. (1999) found that the presence of a flow signal made the same contribution across varying road-edge conditions (i.e., there was no interaction), they only added texture to the road surface (not the entire scene) which may have limited the availability of flow information from the visual periphery. It has been shown that optic flow and road-edge information can interact (Mole et al., 2016), but this evidence has only been collected under specific conditions where the flow signals are biased with respect to the road edges. The extent to which the presence of optic flow within near and far zones is used to support accurate steering control remains to be tested.

The current experiment examines whether flow and road edge information can be simply modelled with a two-level steering control model.[2] In particular, the aim is to examine whether the use of optic flow varies depending whether the signal comes from near or far regions and whether the impact of optic flow interacts with the presence of road edge information. When researchers were using a driving simulator, near or far portions of optic flow and/or road-edge information were selectively masked. In line with studies that selectively removed road-edge information (Land & Horwood, 1995; Chatziastros et al., 1999; Cloete & Wallis, 2011; Frissen & Mars, 2014; Mole et al., 2016), it was expected that removing far road edges would produce steering that is lagged with respect to upcoming changes in the road (reduced anticipation), whereas removing near road edges would reduce steering accuracy (increased distance from the invisible center of the road). Crucially, selective removal of optic flow information (by masking ground texture) from near and far regions, alongside road edge information, tested whether there were interactions between these sources of information. In order to control for the potential differential patterns of eye-movements elicited by the various visual conditions, gaze was directed to a fixation point placed at the center of the road ahead (see method for more details).

Whereas removing near or far road edge information provides a pure test of whether each source is being used, this form of manipulation does effectively force the driver to rely on alternative sources to control steering. Another way of examining reliance on

(A) Clothoid - Steady Circle - Clothoid (CSC) course

(B) Curvature of the CSC course

(C) Double Lane Change (DLC) course
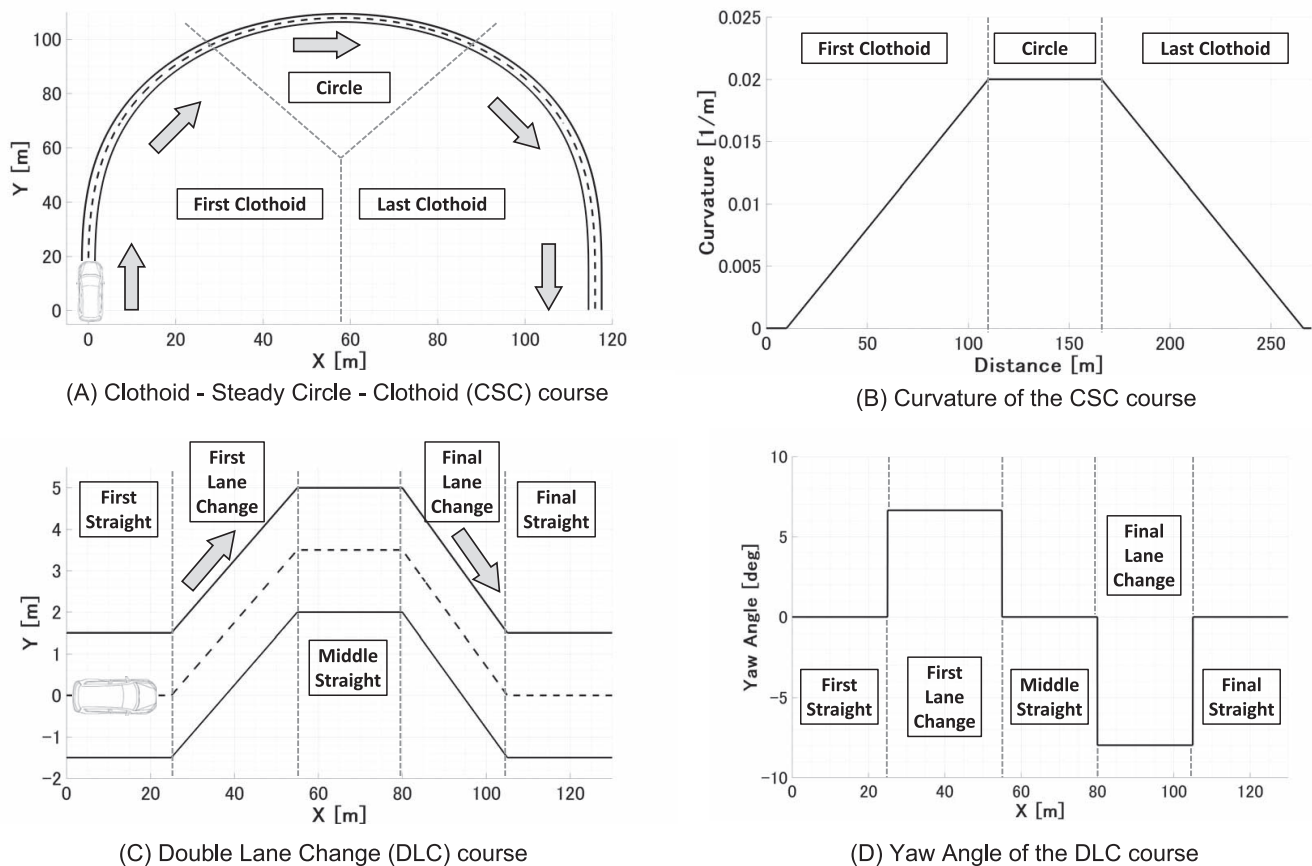

(D) Yaw Angle of the DLC course

Figure 2. Course design.

perceptual information is keeping the availability constant but changing the utility across conditions. Therefore, we also wished to examine whether there were more subtle interactions between optic flow and road edges depending on whether near and far information was more or less useful for the steering task. Even when driving along simple sections of road (such as a straight leading into a bend) the extent to which far road information will be a useful input to steering control can vary (e.g., far road information is less important when maintaining steering on a straight road section than on a bend of varying curvature). To examine this issue we used two steering situations that frequently occur during routine driving (described further in the method section: Course design), and which varied the task requirements: (a) a clothoid bend with changing and constant curvature sections (Figure 2A and B) and (b) a double lane-change maneuver (ISO 3881-1; Figure 2C and D). Trajectories during both tasks were subdivided to examine phases based on the particular steering requirements. The road sections that could lead the driver to stabilize the wheel angle at a set value (straight road for the lane change task; or constant curvature bend for the clothoid task) might be predicted to cause drivers to predominantly rely on

information from near regions (to stabilize steering). These sections were contrasted with phases that require the driver to respond to future changes in road (the point when the lane change occurs or the change in bend curvature for the clothoid) where the driver may rely more on information from far regions (anticipating future steering requirements). Our aim was to determine whether both optic flow and road edges contributed to steering during these particular phases of control, and whether there were interactions between the sources.

We considered two main hypotheses: whether the region of the scene (near or far) supplying optic flow information altered steering (H1), and whether there were interactions between the regions supplying optic flow and the road-edge information (H2).

Hypothesis one (H1): Optic flow affects steering control

Optic flow from the near region contains flow vectors that are larger and more informative about observer translation than far regions (Van den Berg, 1992), so masking flow from the peripheral near region (Figure 3;
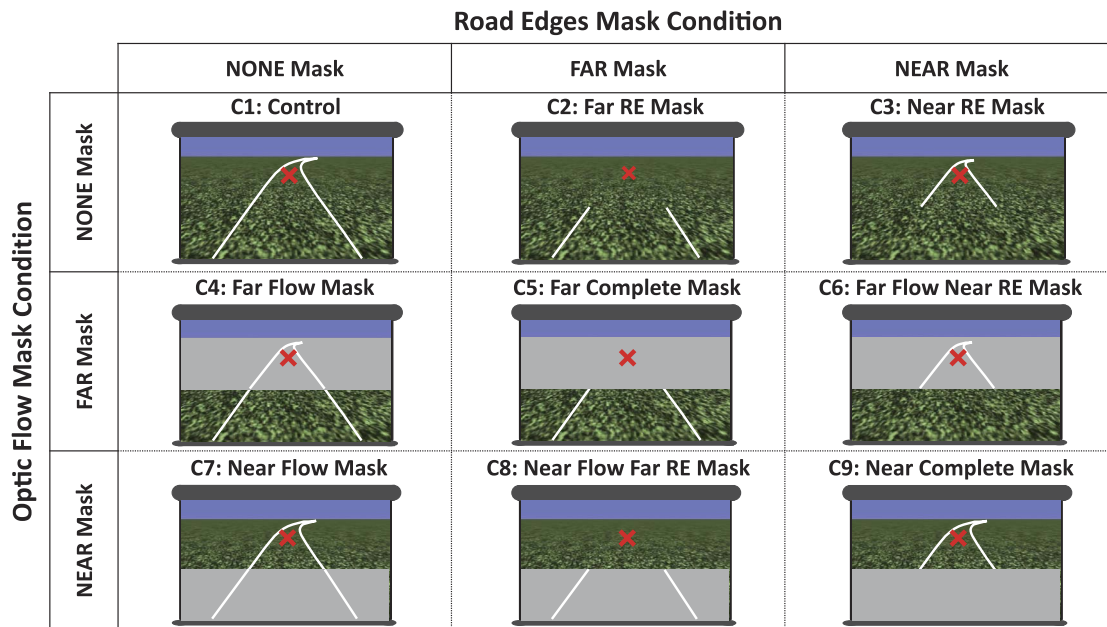
Road Edges Mask Condition

Figure 3. A schematic representation of the nine experimental conditions showing the various combinations of Optic Flow Mask (None, Far, or Near) and Road Edge Mask (None, Far, or Near). The "X" symbol indicates the presence of a fixation cross positioned over the road center that drivers were required to look at throughout trials (note that the cross has been artificially enlarged in this figure, the actual fixation cross was optically much smaller relative to the display).

C7 through C9 Near Flow Mask) may have the biggest effect upon steering (H1A). In contrast, it has been suggested that central vision is specialized for the detection of heading (Warren & Kurtz, 1992), so it might instead be predicted that flow from around the point of fixation (in the far region) would be most useful for controlling steering in which case masking far regions (Figure 3; C4 through C6) will have the greatest influence over steering (H1B). Finally, masking either region of the ground might impair steering because this will reduce the overall quality and extent of optic flow (H1C). There is evidence that direction discrimination from flow is relatively constant across the visual field, with no preference for central/peripheral regions (Crowell & Banks, 1993; Habak, Casanova, & Faubert, 2002); however, far regions predominantly contain rotation components that could be used to help decompose flow present elsewhere in the scene (where there is a mixture of translation and rotation components; Van den Berg, 1992). It may be that it is primarily the quality and quantity of optic flow that is the main predictor of steering performance (Kountouriotis et al., 2016; Crowell & Banks, 1993; Habak et al., 2002) rather than flow from a specific region (as outlined in H1A and H1B). If this is the case, we would expect steering accuracy to deteriorate whenever there is a flow mask present irrespective of where the mask falls (Figure 3; C4 through C9).

The first set of hypotheses is mutually exclusive, and is concerned with which regions of flow influence steering (independent of road edges). However, an interaction between flow and road-edges could take many different forms depending on which hypothesis within H1 is most supported. The second set of hypotheses considers the two most extreme cases provided under the two-point control framework.

Hypothesis two (H2): The effect of optic flow on steering control depends on road-edges

If optic flow is incorporated into the estimate of near and far points, we might expect that the utility of flow depends on the proximity with these points, in which case optic flow from a region should be most useful when the corresponding road-edge in the same region is also visible. If this is the case, we would expect steering to be more accurate when the visible flow and road regions are aligned (Figure 3, C5 and C9) compared to when the flow and road regions are not overlapping (Figure 3, C8 and C6), even though there should be a similar quantity of road and flow information across the whole visual scene (H2A). Alternatively, optic flow may provide useful information for two-point control independent of road edge information (i.e., provide redundancy). If this is the case, we might expect similar steering patterns in conditions where the flow and road masks were aligned (Figure 3, C5 and C9) compared to when the masks were not overlapping (Figure 3, C8 and C6) because of similar quantity of road and flow information (H2B).

Methods

Participants

A sample of 20 University students and staff (two males and 18 females, 21–33 years, mean = 27.4 years) took part in this study. All participants had normal vision (participants did not need glasses) or corrected-to-normal vision (participants wore glasses). All held a full driving license (mean time since test = 7.85 years). Participants received £10 for taking part in the study. All participants gave written informed consent, and the study was approved by the University of Leeds, School Psychology Research Ethics Committee (Reference number: 17-0216), and complied with all guidelines as set out in the declaration of Helsinki.

Apparatus

Virtual environments were generated using World-Viz Vizard 3.0 (WorldViz, Santa Barbara, CA) on a PC with Intel i7 3770 (3.40 GHz), and projected (EPSON EH-TW5210) with matte-black surroundings. The projections subtended 1.96 m × 1.12 m and were perspective correct from a viewing distance of 1 m and an eye-height of 1.2 m (field of view 88.84° × 55.5°). The display refresh rate was synchronized with data recording at 60 Hz. Steering was controlled using a force-feedback wheel (Logitech G27, Logitech, Fremont, CA), which was linearly mapped onto rate of change of heading through a minimum step size of 0.36°/s. The wheel applied a center-return spring force to ensure that the wheel was recentered at the end of trials (when participants released the wheel). This meant the wheel was centered and ready for the next trial. The force was not tied to vehicle dynamics; therefore, participants did not require extensive training to learn how forces changed according to the vehicle state. The steering dynamics used a point mass model that was not matched to a particular vehicle. All participants were given practice before the actual experiments and rapidly became familiar with the simple simulator model and the mapping of movements of the wheel onto the directional changes that occurred.

Stimuli

Course design

Driving in the real world typically consists of negotiating straight sections of road connected by a series of bends. The nature of the bends will change the balance between stabilization of lane position and anticipation of upcoming changes in steering. Two different courses were created to examine steering when the balance between stabilization and anticipation components was altered. Both courses had an initial 10 m straight section, with the driver starting in the road center. Path direction (left or right bend) was randomized from trial to trial to ensure that trials were not so repetitive that participants learned the motor action required to steer each bend.

The first course was a "U-shaped" bend (Figure 2A) consisting of alternating Clothoid-Steady Circle-Clothoid (CSC; also used in Okafuji, Fukao, Yokokohji, & Inou, 2016, to assess performance of automated driving control models). During data analysis steering trajectories along CSC were separated into the "first clothoid" (increasing curvature), "steady circle" (constant curvature), and the "last clothoid" (decreasing curvature), to isolate the segments where greater anticipation should have been required (compared to the steady circle phase). In this task, we expect that far information will be most useful during the first clothoid and the last clothoid (because the far information indicates that there is an upcoming change in steering wheel angle required), rather than the middle constant curvature (steady circle) period (because the far information in this phase does not differ from the curvature specified by nearer road edges; Figure 2B).

The second course consisted of a Double Lane Change (DLC), which is consistent with the ISO Double Lane Change Test (ISO 3881-1; Figure 2C). This type of course has been successfully used to discriminate between different driver steering behaviors (e.g., Prokop, 2001). Since DLC has discrete changes in heading angle there are sections where anticipation should be more useful (i.e., immediately before the lane change) than when holding course on the straight sections where compensatory control may be predominant (Figure 2D). This course differs from CSC in a number of ways. Not only does it place greater emphasis on anticipation prior to the lane change, but because of steering dynamics there is no way for drivers to generate trajectories that exactly match the center of the road at all points in time (effectively trying to fit a sinusoidal path to square-wave-like signal). As such, the driver will be attempting to gauge when they should initiate steering to generate a trajectory that leads to a road position that is closest to the center of the lane.

Gaze fixation requirements

During an experiment that used similar displays with constant curvature bends, Mole et al. (2016) found that removing far road edges (see next section: Optic flow and Road edges mask) affected driver's

gaze patterns, with participants reorienting their gaze lower in the scene toward the remaining visible portion of the near road. Eye-movements will alter retinal flow information, so it is possible that participants are less able to use flow information if they are not looking proximal to where they wish to travel (Wann & Swapp, 2000). In order to avoid systematic differences in gaze behavior between conditions (while also minimizing between-participant differences that would be caused by varied eye-movement strategies), we controlled for eye-movements by asking participants to look, throughout each trial, at a red cross displayed in the road center approximately 16.1 m (1.2 s) ahead of the participant. In previous research we have found that participants usually look on the region 1–2 s ahead, and we have used this method to control gaze patterns when investigating the other visual factors influencing steering behaviors (Wilkie & Wann, 2003; Kountouriotis et al., 2012; Wilkie et al., 2010).

It could be argued that constraining gaze in this way prevents the visual system from optimally sampling the information available in the optic array, while also imposing cognitive load costs on the driver. The problem of course with free gaze is that the loss of control potentially confounds exploration of the data depending on the behaviors adopted by the participants. The decision to require gaze fixation of a point on the road ahead was determined by the nature of the two-point model that we were investigating since it explicitly uses such a point as an input. Whereas freely fixating a point on the road ahead is likely to be somewhat different from being forced to fixate a fixation cross drawn in the world, the loss of ecological validity was felt to be more than outweighed by the improved experimental control provided.

Optic flow and road edges mask

The simulated virtual environment consisted of a green tinted texture, with a 3 m wide road demarcated with white road-edges (see Figure 3). Our virtual environments were designed so that two primary sources of information were made available to control steering: optic flow and road-edges. In order to assess the importance of each source to two-point control, we selectively applied a flow or road-edge mask to near or far portions of the scene (see Figure 3). Two masked areas were determined based on the half distance (8.0 m) of the fixation point distance. This distance was chosen so that the far mask would remove crucial information (such as direction of the upcoming bend). Previous studies have applied masks which simultaneously cover road and flow information (e.g., Frissen & Mars, 2014), but no study has

applied road or flow masks independently or applied masks while controlling for changes in gaze. A 3 ($FlowMask_{No}$; $FlowMask_{Fr}$; $FlowMask_{Nr}$) $\times$ 3 ($REMask_{No}$; $REMask_{Fr}$; $REMask_{Nr}$) design leads to eight conditions that include one or two mask combinations, and one mask-free condition (i.e., $FlowMask_{No}$ and $REMask_{No}$, the control condition). Whereas it would have been possible to also introduce complete masks to both information sources, masking both near and far road edge regions then made it impossible to perform the steering task. For ease of analysis (to keep factors balanced), we did not include a condition where both far and near flow regions were masked.

Task instructions

Participants were instructed to fixate the red cross displayed on the screen and "attempt to steer a central trajectory, keeping to the middle of the road," to steer "as smoothly and as accurately as you can." We were aware that instructing the participants to keep to the road center may have reduced natural "cutting the corner" behavior; however, we wanted to use this instruction since it then allows precise measurement of steering bias relative to this center point, and is especially useful for examining systematic steering biases with reference to the same ideal trajectory (zero bias) for all participants. As per previous studies (Mole et al., 2016; Kountouriotis et al., 2013; Kountouriotis et al., 2016) simulated locomotor speed was kept constant at 13.41 m/s (30 mph) throughout all trials to avoid any differences between trials, conditions, and/or participants. This meant that participants were not required to use the foot pedals for longitudinal control.

Procedure

Participants were given 10 practice trials on each of the two courses (20 trials in total) in order to become familiar with the driving simulator dynamics, steering tasks, and visual mask conditions, and to minimize changes in performance throughout the experiment caused by learning effects. During practice trials participants were exposed to each condition for a single trial (only the control condition was repeated twice) in the order C1, C5, C9, C7, C4, C3, C2, C8, C6, C1 (see Figure 3 for condition labels). In the experiment proper, trials were randomly interleaved, and participants experienced six trials per condition (as per Kountouriotis et al., 2012; Kountouriotis et al., 2016; Mole et al., 2016), resulting in 54 trials per course. The trial durations were 10 s for DLC and 19 s for CSC, resulting in a block running

time of 9 min and 17.1 min respectively. Participants first performed the CSC task and then the DLC task. Participants took a 5-min break between tasks.

Analysis

The hypotheses outlined in the introduction require steering metrics, which predominantly capture anticipatory and compensatory steering behaviors. Steering wheel angle, and position, and orientation in the world were recorded per frame, allowing driver performance to be examined with respect to the ideal trajectory (road center, as per instructions), or with respect to key environmental events (such as approaching a large change in road direction). The first 0.84 s (50 frames) of each trial were stationary to allow the participant to prepare for the next trial and recenter the wheel.

Three main measures of steering performance were calculated:

a. Steering bias (SB) provides a signed measure of accuracy and was calculated using the average deviation of position away from the road center for each frame of each trial in meters. (For analysis purposes, data from left hand bends were "mirrored" onto right hand bends, and performance was then be averaged across CSC bends irrespective of bend direction.) It is a signed measure of error and for the clothoid bends, positive values indicate steering biased toward the inside road edge (a behavior referred to as "oversteering") whereas negative values indicate steering biased toward the outside of the bend ("understeering"). Note that the labels understeering and oversteering should not be confused with the terms "oversteer" and "understeer" commonly used to describe the steering properties of real vehicles on roads (and the associated requirements for the driver to compensate for these properties). The DLC task did not have a single direction of bend so rather than indicating over/understeering the sign indicates systematic bias toward the left (negative) or right (positive) road edges during these trials.

$$SB = \frac{1}{N}\sum_{i=1}^{N}(Vehicle\ Position - Centre\ Line);$$

b. Root-Mean-Squared Error (RMSE) provides a measure of precision of each trajectory relative to the road center in order to capture the extent of lateral deviation across each trial (in meters). Larger values of this unsigned measure indicate

trials where the driver spent longer periods deviating further from the road center.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\begin{array}{c}Vehicle\ Position\\ -Centre\ Line\end{array}\right)^2}; \text{and}$$

c. Initiation Point provides a measure of lag/anticipation (in seconds) on the DLC roads. Steering performance leading up to the first lane change was isolated (the later bends are potentially contaminated by prior steering making it is difficult to obtain a "pure" measure of the timing responses) and the time at which drivers made their first large steering turn was calculated. The time at which a 1° change in steering occurred since this approximates to a 10% change in heading angle. For CSC there was not a single point that the Initiation Point could be measured from (because the change in heading was incremental) so it was not considered as a useful metric to calculate.

SB and RMSE are calculated per each phase to analyze the steering performance depending on the tracking path. For both CSC and DLC tasks a 3 ($REMask_{No}$, $REMask_{Fr}$, $REMask_{Nr}$) $\times$ 3 ($FlowMask_{No}$, $FlowMask_{Fr}$, $FlowMask_{Nr}$) repeated measures ANOVA were conducted on each of the steering metrics. Bonferroni corrections were made for any posthoc comparisons. For ease of understanding, main effects and interactions are reported in Tables 1 and 2, and key contrasts that explain interactions are depicted in figures. When sphericity assumptions were violated, Huynh-Feldt corrections (when $\varepsilon > 0.75$) or Greenhouse-Geisser corrections (when $\varepsilon < 0.75$) were used (Girden, 1992).

Results

The two steering tasks (CSC and DLC) were designed to put different demands on the drivers, while also varying the potential utility of prospective information sources for steering control. Each task was analyzed separately to see whether similar patterns of steering were apparent independent of particular task characteristics.

CSC Steering task

To determine the influence of road edges and optic flow when steering curved roads we divided each trial into three phases: (a) First Clothoid (0.84–9.50 s), (b) Steady Circle (9.50–14.17 s), and (c) Last Clothoid

| | SB | | | | |
Variable	All phases	First clothoid	Steady circle	Last clothoid	RMSE
Flow	($\varepsilon = 0.73$†)	($\varepsilon = 0.67$†)		($\varepsilon = 0.68$†)	
F	14.00	1.73	25.16	21.25	6.98
df	1.45, 27.55	1.35, 25.61	2, 38	1.36, 25.80	2, 38
p	< 0.001*	0.20	< 0.001*	< 0.001*	0.003*
η_p^2	0.42	0.083	0.57	0.53	0.27
RE	($\varepsilon = 0.60$†)	($\varepsilon = 0.65$†)	($\varepsilon = 0.68$†)	($\varepsilon = 0.65$†)	($\varepsilon = 0.65$†)
F	10.43	9.54	4.56	16.60	2.18
df	1.21, 22.89	1.30, 24.68	1.37, 26.00	1.30, 24.73	1.30, 24.72
p	0.002*	0.003*	0.032*	0.001*	0.15
η_p^2	0.35	0.33	0.19	0.47	0.10
Flow $\times$ RE	($\varepsilon = 0.74$†)	($\varepsilon = 0.72$†)	($\varepsilon = 0.74$†)	($\varepsilon = 0.74$†)	($\varepsilon = 0.68$†)
F	1.86	2.29	0.98	4.99	2.31
df	2.95, 56.10	2.89, 54.88	2.95, 56.04	3, 56.94	2.73, 51.95
p	0.15	0.091	0.41	0.004*	0.10
η_p^2	0.089	0.11	0.049	0.21	0.11

Table 1. ANOVA main effects and interactions for SB (Figure 5B–E) and RMSE (Figure 6). *Notes*: *$p < 0.05$; † $\varepsilon < 0.75$ (Greenhouse-Geisser corrections are applied). RE = road edges.

(14.17–19.00 s). The first clothoid was a tightening bend, the middle phase was a bend of constant curvature, and the last clothoid was a straightening bend (Figure 2A). A 3 (*REMask*) $\times$ 3 (*FlowMask*) ANOVA was run on steering bias measures from across the whole trial, and also for each phase (main effects and interactions are reported in Table 1).
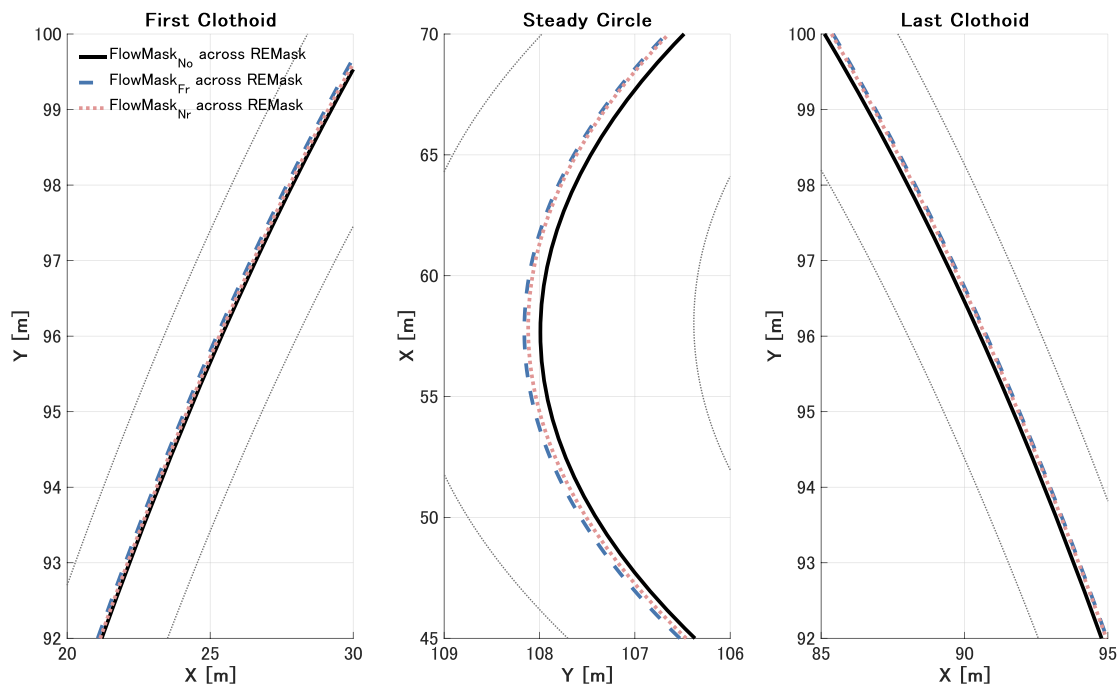
Steering bias

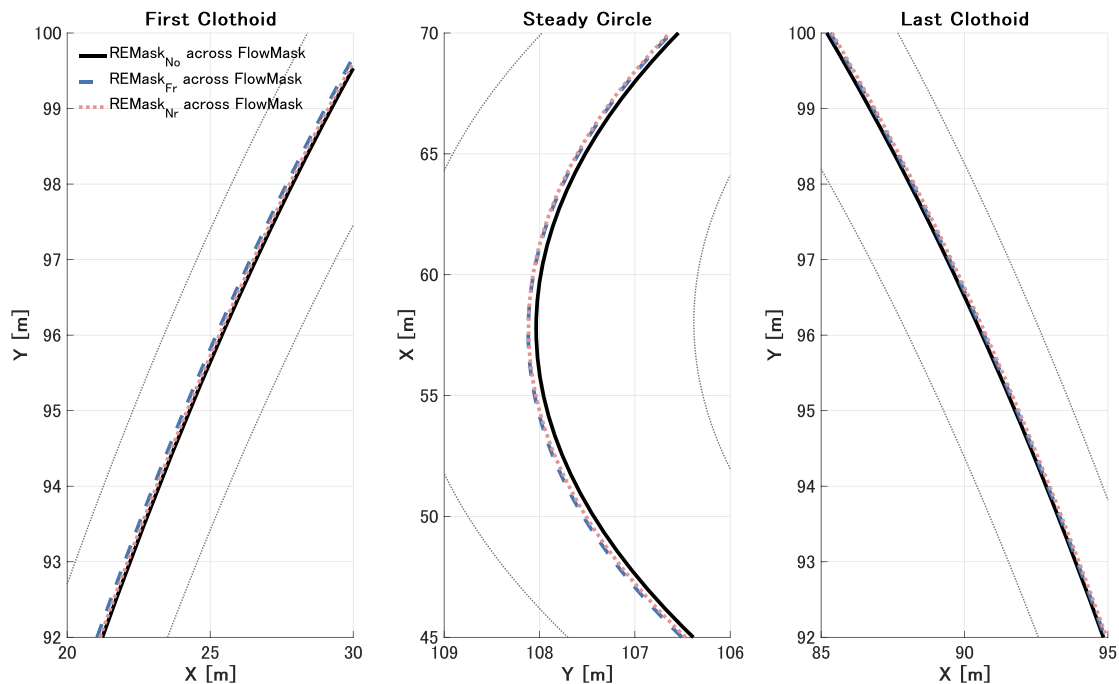Average trajectory plots across *REMask* and *FlowMask* conditions for three phases of CSC path are shown in Figure 4. These results are related to main effects that are reported in Table 1. When no masks were in place (all optic flow and road-edge information was present), steering was relatively unbiased during the first two phases of the trial, but then oversteering (corner cutting) occurred during the final phase as the road straightened (Figure 5). This is consistent with a number of other studies showing a propensity for human drivers to cut corners (Robertshaw & Wilkie, 2008; Raw et al., 2012). From Figures 5A and B it can be observed that removing either flow or road-edge information altered trajectories, leading to an increased propensity for understeering (Figure

| | | SB | | | | | |
Variable	Initiation Point	First St	First LC	Mid St	Final LC	Final St	RMSE
Flow							
F	3.73	1.11	4.38	14.45	2.04	11.42	1.48
df	2, 38	2, 38	2, 38	2, 38	2, 38	2, 38	2, 38
p	0.033*	0.34	0.019*	< 0.001*	0.14	< 0.001*	0.24
η_p^2	0.16	0.055	0.19	0.43	0.097	0.38	0.072
RE	($\varepsilon = 0.67$†)	($\varepsilon = 0.74$†)	($\varepsilon = 0.56$†)	($\varepsilon = 0.55$†)	($\varepsilon = 0.63$†)	($\varepsilon = 0.54$†)	($\varepsilon = 0.53$†)
F	50.80	22.97	44.54	25.78	31.91	48.90	2.30
df	1.34, 25.49	1.48, 28.20	1.12, 21.22	1.11, 21.05	1.26, 23.85	1.09, 20.6	1.06, 20.12
p	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	0.14
η_p^2	0.73	0.55	0.70	0.57	0.63	0.72	0.11
Flow $\times$ RE		($\varepsilon = 0.68$†)			($\varepsilon = 0.61$†)		($\varepsilon = 0.69$†)
F	0.69	0.75	1.96	0.736	5.27	1.91	4.13
df	4, 76	2.71, 51.48	4, 76	4, 76	2.44, 46.30	4, 76	2.74, 52.02
p	0.57	0.52	0.11	0.57	0.006*	0.12	0.013*
η_p^2	0.035	0.038	0.093	0.037	0.22	0.091	0.18

Table 2. ANOVA main effects and interaction for Initiation Point (Figure 8B), SB (Figure 9B–F), and RMSE (Figure 9B–F) for DLC. *Notes*: *$p < 0.05$; † $\varepsilon < 0.75$ (Greenhouse-Geisser corrections are applied).

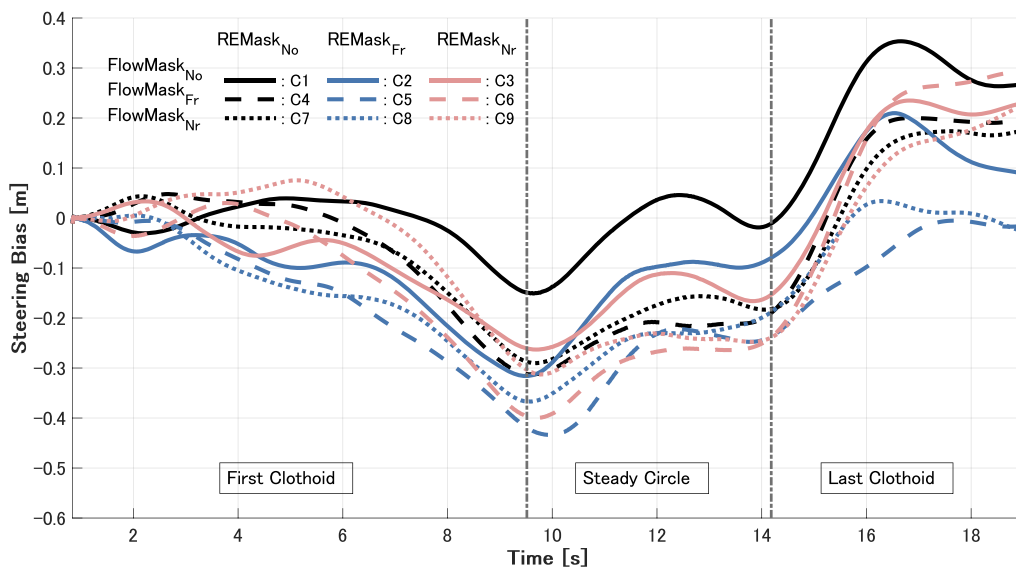(A) Average FlowMask trajectory plots across REMask

(B) Average REMask trajectory plots across FlowMask

Figure 4. Average trajectory plots for the three phases of CSC trials (first clothoid, circle, and last clothoid; see Figure 2B) across *REMask* and *FlowMask*. Note: The middle panel uses different vertical and horizontal scales to highlight the performance differences across conditions.
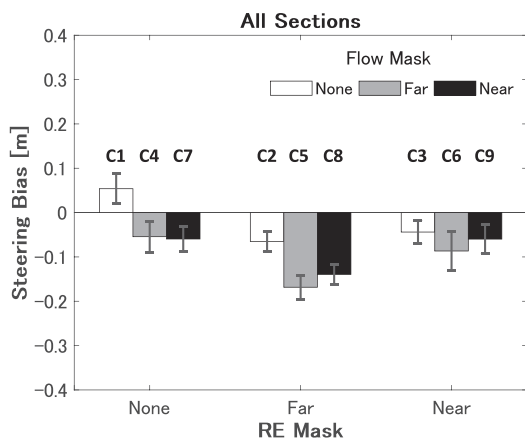
4). Across the whole course (Figure 5B) this resulted in significant main effects for manipulations of optic flow and road edges, but not a significant interaction (see Table 1). Removing either region led to increased understeering compared to when there were no masks

($FlowMask_{No \ vs \ Fr}$: $p < 0.001$; $FlowMask_{No \ vs \ Nr}$: $p < 0.001$; $REMask_{No \ vs \ Fr}$: $p = 0.003$; $REMask_{No \ vs \ Nr}$: $p = 0.001$).

On closer inspection of the individual phases of steering, it seems that masking road or flow informa-

Figure 5. Average steering bias relative to the road center for the three phases of CSC trials (first clothoid, circle, and last clothoid,; see Figure 2B). Negative values indicate understeering (outside position relative to the centerline in Figure 2A) and positive values indicate oversteering (inside positions relative to the centerline). Stars represent key comparisons where interactions are present. Error bars represent standard error of the mean.
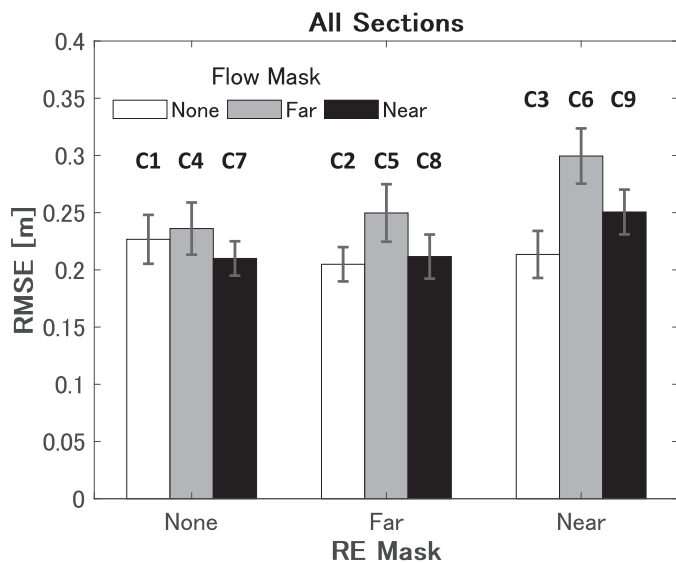
Figure 6. Average Root-Mean-Squared-Error relative to the road center for CSC. Error bars represent standard error of the mean.

tion had differential effects on steering depending on the task requirements. During the First Clothoid phase, $REMask_{Fr}$ caused the greatest bias ($REMask_{No\ vs\ Fr}$: $p = 0.003$; $REMask_{No\ vs\ Nr}$: $p = 0.132$; Figure 5C), presumably because without this information it is not possible to predict whether the future path curved to the left or right (path direction was randomized from trial to trial). During the Steady Circle phase (Figure 5D) both flow masks and only $REMask_{Nr}$ caused significantly greater understeering (compared to the no mask condition; see Table 1; $FlowMask_{No\ vs\ Nr}$: $p < 0.001$; $FlowMask_{No\ vs\ Fr}$: $p < 0.001$; $REMask_{No\ vs\ Nr}$: $p = 0.001$; $REMask_{No\ vs\ Fr}$: $p = 0.091$). During the Last Clothoid phase (Figure 5E), masking either flow or road edges reduced oversteering compared to when there was no mask (Table 1). Interestingly, during the Last Clothoid phase there is also an interaction (Table 1), caused by $FlowMask_{Fr}$ and $FlowMask_{Nr}$ reducing oversteering relative to $FlowMask_{No}$ during $REMask_{No}$ ($FlowMask_{No\ vs\ Nr}$: $p < 0.001$; $FlowMask_{No\ vs\ Fr}$: $p = 0.001$) and $REMask_{Fr}$ ($FlowMask_{No\ vs\ Nr}$: $p = 0.002$; $FlowMask_{No\ vs\ Fr}$: $p < 0.001$), but not $REMask_{Nr}$ ($FlowMask_{No\ vs\ Nr}$: $p = 1$; $FlowMask_{No\ vs\ Fr}$: $p = 0.097$).

Root-Mean-Squared Error

The steering bias metric usefully distinguished between performance accuracy across the display conditions, identifying systematic shifts in position relative to the road center. It is possible, however, that nonsystematic directional changes in position would not be captured by steering bias (since positive and negative errors could effectively cancel one another out). An alternative metric of lateral deviation (relative to the road center) is Root-Mean-Squared Error
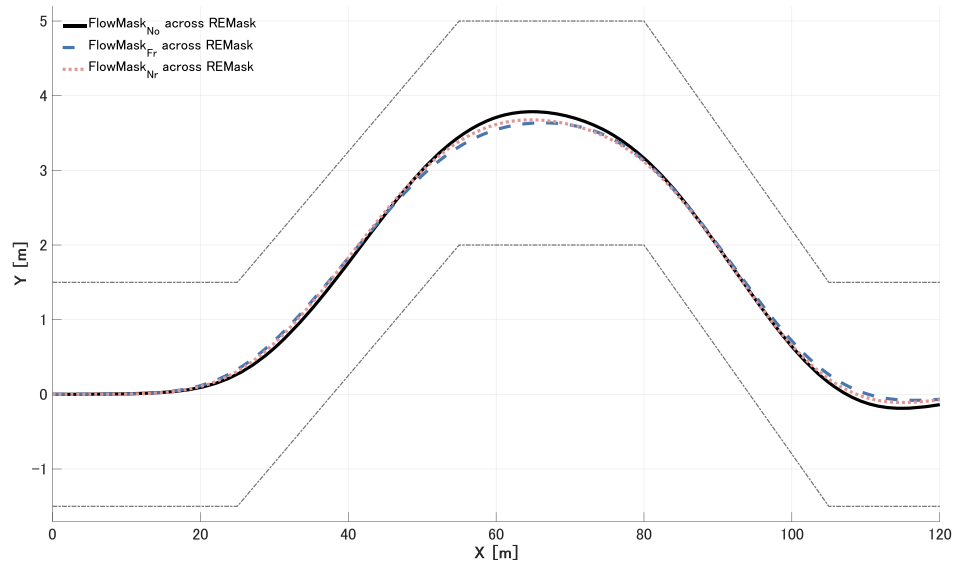
(RMSE; Figure 6). *RMSE* was calculated for the whole course to act as a metric of variability, whereby larger values reflect a trajectory that was further from the road center. As can be seen in Table 1, the ANOVA revealed a main effect of *FlowMask*, but no main effect of *RoadMask*, and no interaction. The main effect of *FlowMask* was caused by $FlowMask_{Fr}$ increasing RMSE relative to the other two flow conditions ($FlowMask_{No\ vs\ Fr}$: $p = 0.019$; $FlowMask_{Fr\ vs\ Nr}$: $p = 0.026$).
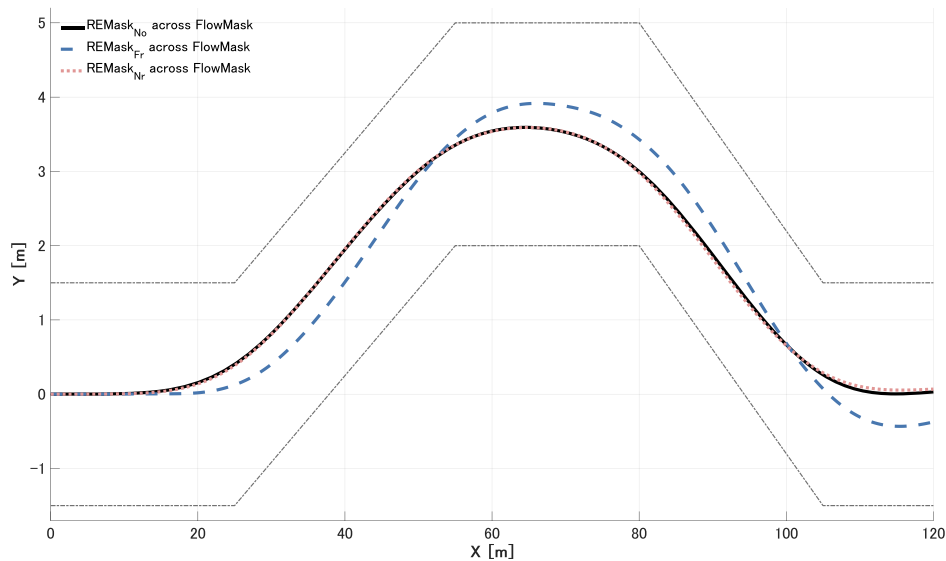
DLC steering task

The DLC task consisted of a series of straight sections of road connected by large, sudden changes in road direction (Figure 7). During analysis the whole trajectory was divided into five phases aligned with each change in direction (see Figure 2D): (a) First Straight (0.84–2.69 s), (b) First Lane Change (2.69–4.96 s), c) Middle Straight (4.96–6.83 s), d) Final Lane Change (6.83–8.72 s), e) Final Straight (8.72–10.00 s). Whereas the straight sections themselves required little/no steering (if the trajectory was aligned with the road), the sudden changes in direction introduce a need to make large corrections. These characteristics should create conditions where greater emphasis is placed upon far road information in the moments preceding the direction change than during the CSC steering task.

Initiation point

The Initiation Point indicates the time at which the first major steering response was produced on the *DLC* road. The results of the ANOVA (Table 2) show that there were reliable differences in Initiation Point across Flow and Road Edge conditions. The average trajectories across *REMask* and *FlowMask* condition are displayed in Figure 7, and the most obvious pattern is the lagged trajectories that occur when far road-edge information is removed ($REMask_{Fr}$, blue), compared to conditions where far road-edge information was available (e.g., Control, $REMask_{Nr}$). Figure 8A shows the heading angle of the vehicle across the trajectory, which is used to identify the region that marks out the initiation point. Figure 8B shows the average timing of steering initiation for each condition. $REMask_{Fr}$ was lagged compared to the other *REMask* conditions ($REMask_{No\ vs\ Fr}$, $p < 0.001$; $REMask_{Fr\ vs\ Nr}$, $p < 0.001$). In contrast $REMask_{Nr}$ did not cause reliable differences in initiation point lag compared to $REMask_{No}$ ($REMask_{No\ vs\ Nr}$, $p = 1.0$). The flow mask also caused changes in the Initiation Point, though these effects were more subtle. Removal of far flow ($FlowMask_{Fr}$)

(A) Average FlowMask trajectory plots across REMask

(B) Average REMask trajectory plots across FlowMask

Figure 7. Average steering trajectories for the DLC task across *REMask* and *FlowMask* conditions. Note: Vertical and horizontal axes (in meters) are not to scale to make trajectory differences easier to view.
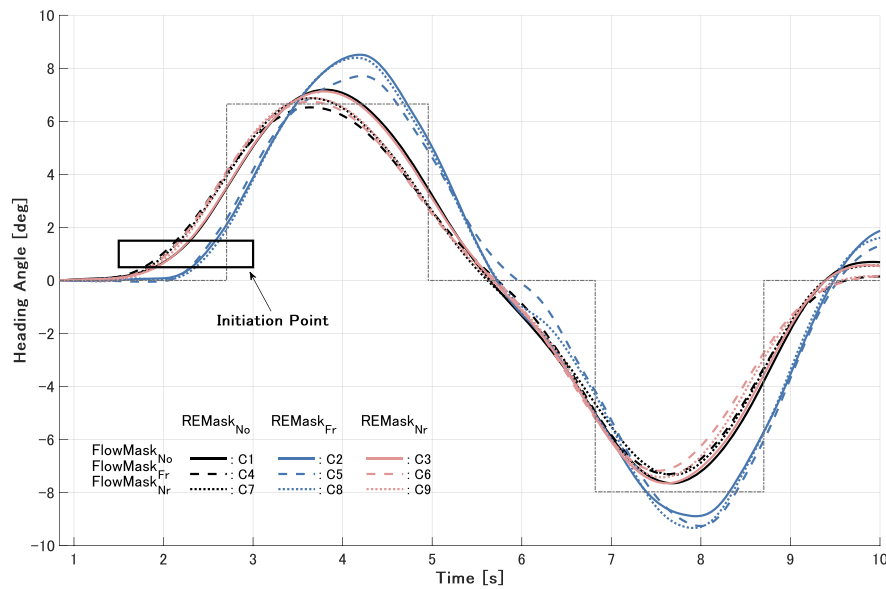
actually caused earlier steering (less lag) compared to when flow was unmasked ($FlowMask_{No\ vs\ Fr}$, $p = 0.031$). There seemed to be no systematic differences between initiation point when the near region was masked ($FlowMask_{No\ vs\ Nr}$, $p = 0.33$).
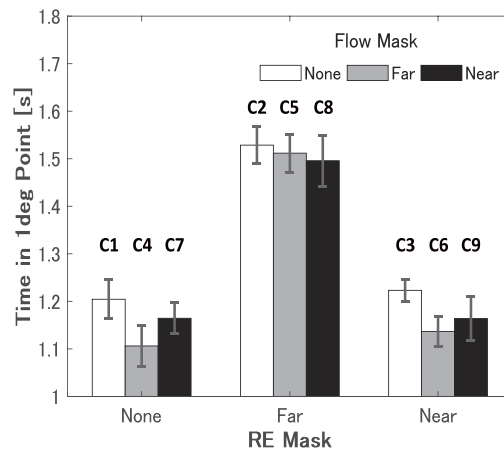
Steering bias

The lag in steering initiation due to $REMask_{Fr}$ (Figure 8) manifests in biased steering during the initial straight (Figure 9B). Drivers without far road-edges stay close to the midline, whereas drivers with far road-edge information anticipate and begin to steer early in the direction of the bend (see Table 2). These

differences cause relative understeering around the initial bend during the $REMask_{Fr}$ conditions (Figure 9C), and lagged steering through the remainder of the course (Figures 9D through F).

The change in steering associated with the absence of far road-edge information is entirely predictable. Perhaps more interesting is the gradual emergence (after the First Straight) of differences in steering depending on whether flow information was masked or not. The steering bias differences are clearest for Middle Straight and Final Straight phases (Figures 9D and F), where a road position is adopted consistent with greater corner cutting when either Near or Far

(A) The average heading change plots, with the initiation point marked.

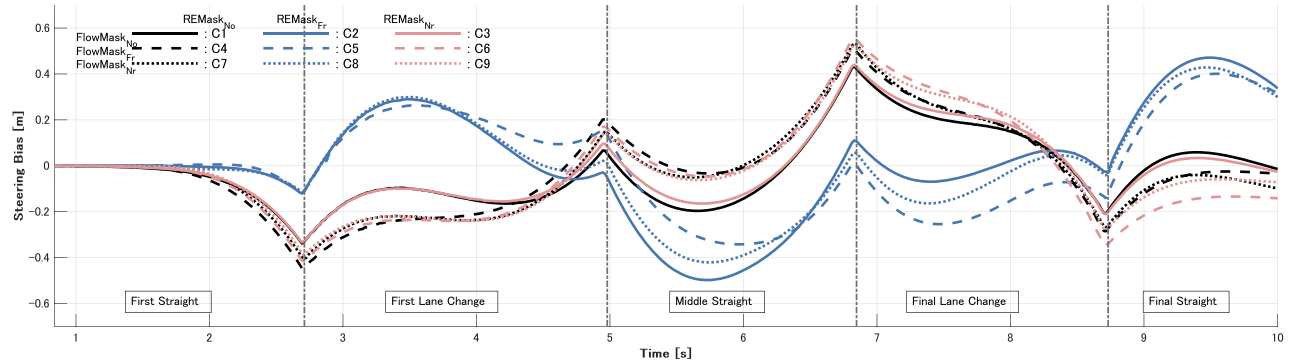(B) Average Initiation Point. Error Bars represent atandard error of the mean.

Figure 8. The results of Initiation Point for DLC.

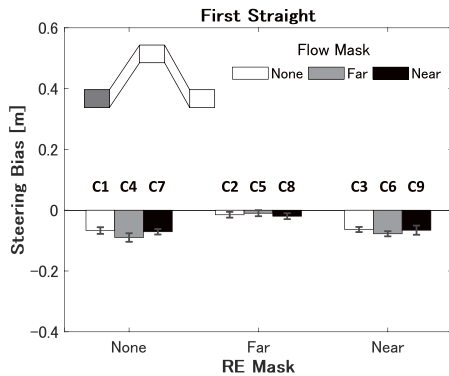flow masks are applied (see significant main effects for Middle Straight and Final Straight in Table 2).

For the most part, these effects (lagged steering due to lack of far road information; corner cutting when either flow section is masked) appear to be largely independent of each other. For the final lane change, however, an interaction emerges (Table 2; Figure 9E), due to a large isolated shift in understeering for $FlowMask_{Fr}$, but only when the $REMask_{Fr}$ is applied (Figure 9E). It is worth noting that the interaction is only present for the final lane change (not the first lane change) and also disappears during the final straight, so it is difficult to conclusively determine whether this specific combination of $FlowMask_{Fr}$ and $REMask_{Fr}$ conditions as being processed in a qualitatively different way to the other $REMask_{Fr}$ conditions.
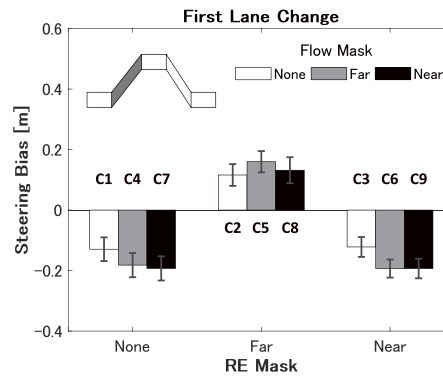
Root-Mean-Squared Error

Since the *DLC* contains sections where bias was observed in opposite directions (i.e., there are an equal number of left and right turns), it might be expected that directional errors from one phase to the next effectively cancel out—especially the phases where the driver is coming up to a bend in the opposite direction to the one they have just exited. To examine deviation of lateral position the unsigned RMSE scores were calculated (Figure 10). While there were no main effects of *REMask* or *FlowMask*, there was an interaction between these factors (see Table 2). The interaction is driven by there being no reliable differences across levels of *FlowMask* during $REMask_{Fr}$, but during both $REMask_{No}$ and $REMask_{Nr}$ there was an effect of $FlowMask_{Nr}$ ($p = 0.041$) and $FlowMask_{Fr}$ ($p = 0.007$), causing greater steering errors than $FlowMask_{No}$.
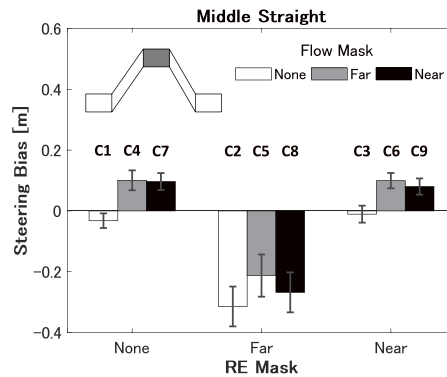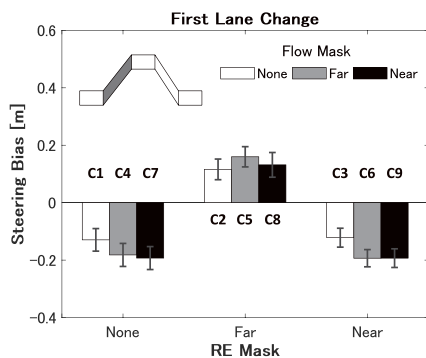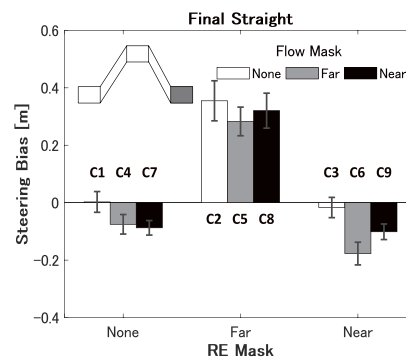
Figure 9. (A) Steering bias averaged across all participants. (B–F) Average steering bias relative to the road center for the five phases of the DLC trials (first straight, first lane change, middle straight, final lane change, and final straight; see Figure 2D). Note that in this task, negative values indicate a leftward position relative to the centerline (see Figure 7) and positive values indicate rightward positions relative to the centerline (not oversteering and understeering as in the CSC task). Where there is an interaction present, the stars denote significant contrasts. Error bars represent standard error of the mean.
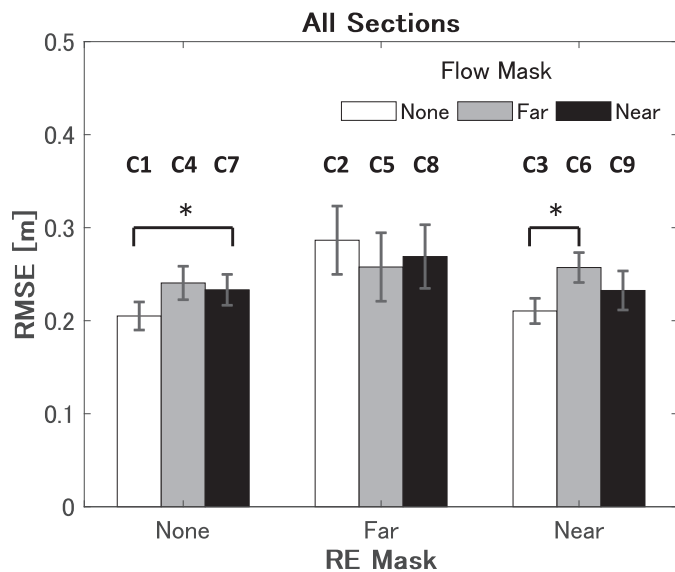
Figure 10. Average Root-Mean-Squared-Error relative to the road center for DLC. Error bars represent standard error of the mean.

Discussion

The main purpose of the present study was to test whether optic flow influenced steering control when the availability of road edge information changed. If optic flow information did influence steering, then the secondary aim was to determine whether it interacted specifically with the signals provided by the road-edges for two-point steering control. To examine these issues, steering tasks were used that altered the utility of far-road information, while also specifically manipulating visual conditions in order to vary the presence of optic flow and road-edge information from near and far regions. Two main steering tasks were used, a clothoid bend (CSC) and a road with a double-lane change (DLC), since these courses could be separated into subcomponents that allowed the examination of distinct steering phases where prospective signals would be more or less useful. Maintaining constant paths (straight line or constant curvature bends) should have been less affected by the absence of far road-edge information than phases where there was an upcoming curvature change or lane change. Indeed, for the CSC steering task this pattern was broadly observed: steering bias was affected most when a mask was applied to far road information during the First and Last Clothoid phase, but there was little difference between near and far road masks for the constant curvature section. The *DLC* task was designed to place a greater emphasis on prospective control from the far road, and the results demonstrated that this was indeed the case: Masking the far road caused large changes to steering across all phases of the *DLC* steering task; this

was also reflected in poorer overall precision (RMSE scores) for the far road mask.

Having established road-edge mask conditions that caused systematic changes to steering, the next step was to determine whether the presence or absence of optic flow in near or far regions altered steering responses. Masking regions of optic flow did alter steering responses across conditions but this was true for both near and far flow masks and also for most phases of both CSC and DLC steering tasks. For the most part the nature of the changes induced by the near or far flow mask appeared to be similar: masking either flow region caused understeering during CSC and increased corner cutting during *DLC*. At first glance this pattern may seem contradictory; however, the types of steering response required are qualitatively different for the two tasks. The CSC trials require gradual steering adjustments to ensure that a midroad position is maintained, and these sorts of corrections seem to be supported by global optic flow quality. In contrast, the *DLC* requires a sudden large realignment of the locomotor axis from one straight road section to another straight road section. In many ways this response is similar to conditions that require the observer to become aligned with an eccentric target (Wilkie & Wann, 2002, 2003). In this previous work degrading global optic flow caused more direct trajectories to be taken due to participants executing rapid realignment of trajectories rather than making gradual steering adjustments (Wilkie & Wann, 2003; Figure 10). It seems, therefore, that it is the quality of the global flow pattern that is the primary contributor to steering responses across the range of situations examined here (consistent with H1C; Kountouriotis et al., 2016) rather than there being a specific region of flow supporting use of near or far road edges for two-point control. There has been some circumstantial evidence that flow from far regions may be more important for steering control than flow from near regions (Okafuji, Fukao, & Inou, 2015; Authié & Mestre, 2012). In the present study this was not a pattern that was universally observed, but there were instances consistent with far flow sometimes having a greater role: we observed that masking far flow led to increased steering errors accrued across the whole time-course of CSC bends (though there were no reliable differences in steering bias), and also observed earlier turning during the first phase of the DLC task when far flow was absent.

As outlined in Hypothesis 2, differential effects of near and far optic flow depending on near and far road edges could be considered as evidence for optic flow having an input into two-point steering control. However, we would urge caution in interpreting our findings in this way. Firstly, the majority of the effects of optic flow on steering appear to be largely independent of the presence or absence of near/far

road-edge components. The DLC steering task was designed to increase the utility of far information, so if the use of flow information was dependent on far road edge signals (as seems to be the case for flow speed; Mole et al., 2016), then we would expect to see clear interactions with the presence or absence of far road information in this task. Instead, for the majority of the course there was no interaction between road-edges and optic flow, suggesting that there is limited use of optic flow for anticipatory control in these conditions. Secondly, whereas interactions were found for some steering phases/metrics (e.g., steering bias during the final lane change of DLC and total course RMSE for DLC), the pattern was not a consistent one. The far flow/far road interaction supports H2A; however, the near flow/far road interaction is more consistent with H2B. It seems, therefore, that the relationship between the use of optic flow and road edges is not straightforward. The CSC task was designed to place greater emphasis on steering stabilization, and in that task interactions between optic flow and road-edges emerged across the time-course of the bend (during the final phase of steering). It seems then that when performing a complex visual-motor steering response there will be complex interactions between the use of optic flow and road edge information, but not in a fashion that can be captured simply using a two-point control model.

One aspect of steering control that was not examined in the present study was the impact of differential gaze strategies on the use of optic flow and road edge information. Previous work (Mole et al., 2016; Kountouriotis et al., 2012) highlighted that gaze patterns change depending on the road edge components visible in the scene. The present study controlled this factor by enforcing gaze fixation on a far point, in a region where gaze usually falls when steering along a road with no masked information (Wilkie & Wann, 2003). Placing gaze at this point may have unintentionally led to additional emphasis on the information available from around the point of fixation (the far region), and gaze fixation of this point may also have provided a further source of information to aid steering (as per Wilkie & Wann, 2005). One issue worth mentioning is that gaze behaviors were not directly measured; rather, we relied on participants complying with the fixation instructions. Our previous work demonstrates that participants are quite reliable at following these instructions (Wilkie & Wann, 2003) especially when they are looking where they want to steer; however, it is possible that intrusive saccades took the eye away from the point of fixation for brief periods during some trials. It seems unlikely that the reliable patterns of behavior observed in this study can be explained by the odd failure to fixate since the only likely outcome would be more variable steering responses for those conditions depending on the extent to which intrusive saccades were employed. Future studies could examine similar combinations of near/far flow and road masks with no fixation requirements to determine the way in which gaze patterns adapt to removal of information sources, and the degree to which they can effectively compensate for the loss of information. Conditions C6 ($REMask_{Fr} + FlowMask_{Nr}$) and C8 ($REMask_{Nr} + FlowMask_{Fr}$) would be particularly interesting test cases for the gaze fixation system since in these conditions useful information needs to be retrieved from two separate parts of the scene at the same time, leading to potentially conflicting gaze demands.

The present work controlled locomotor speed, keeping this variable constant. It might be expected that flow information would have more influence over steering as the signal quality increases, and this may naturally occur when travelling at higher speeds. Whereas changes to flow speed have been studied independent of the road edges (Mole et al., 2016) further experiments are needed to systematically vary locomotor speed in the presence of near and/or far components to test whether drivers rely more on flow at higher speeds.

Overall our findings suggests that global optic flow does reliably contribute to steering bends and changing lanes, but that the optic flow signal does not seem to be a primary input to the estimation and control of the near or far components as described by the two-point control model.

Keywords: two point model, optic flow, road edges, driving simulation, steering

Footnotes

[1] The angle of gaze (relative to the body midline) can specify the steering requirement when looking where you want to go, i.e., looking straight ahead (eye and

head aligned with body midline) indicates no steering is required, whereas looking to the side provides signals for both the direction and magnitude of steering required. Gradually steering toward that point will cause the angle of gaze to gradually reduce (and the rate of change on gaze angle can also be controlled).

[2] The terms two-point control and two-level control are often conflated in the literature. The term "two-levels" (anticipatory; compensatory) stems from Donges (1978; see also McRuer et al., 1977). In Donges (1978) the two-levels refer to modes of control (in the original conception anticipatory was 'feedforward' and compensatory was 'feedback'), rather than referring to the information obtained from specific points in the scene. The two levels have since been linked to specific near and far portions of the scene (Land & Horwood, 1995) and further explicitly implemented as two points (Salvucci & Gray, 2004; see also Boer, 2016). Therefore, for most discussions two-levels and two-points can be considered synonymous, but there is a distinction to be drawn whereby the two point model remains only one possible implementation of the two-level concepts. For further consideration of the full historical background to the development of these concepts the reader is referred to Lappi & Mole (2018).

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