# Anticipatory look-ahead fixations in real curve driving

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# Contents

# Abstract

In the visual control of locomotion, gaze is used to sample information in an anticipatory manner. In car driving, this anticipation functions at both a short and long time distance. At the short time distance, gaze leads the locomotion with a small (1–3 s) time headway. Many steering models have explained this behavior by interpreting that drivers track a steering point on the road to obtain visual information which is directly translated to steering actions. This gaze behaviour can be called guiding fixations, because the gaze is providing information for the online control of the steering. At the long time distance, gaze serves trajectory planning by picking up information from the road further ahead. In curves, a part of the road can be visible in highly eccentric positions relative to the typical guiding fixations' direction. In these situations, the information needs of the trajectory planning can result in eccentric look-ahead fixations toward the curve. The role of these fixations in the visual control of locomotion is not well understood.

In this thesis, I have developed algorithmical methods for the identification of look-ahead fixations from eye movement data collected with an instrumented vehicle on real roads. In a series of three experiments, gaze behavior in curves was studied. The effects of driving experience and cognitive load were also investigated.

In general, fixation distributions do not suggest a clear division between guiding and look-ahead fixations. However, a clear tail of eccentric fixations is present in the distributions, which can be operationally defined as look-ahead fixations in curves. Look-ahead fixations target the whole visible road, but locations with a smaller eccentricity relative to the guiding fixations were more commonly fixated than those with a high eccentricity. Experienced drivers allocated more time to look-ahead fixations compared to novices. Cognitive load may negatively affect trajectory planning by interfering with look-ahead fixations. Based on the results, the role of trajectory planning in the control of steering is discussed. The results are consistent with a hierarchical model of driving behaviour, where trajectory planning supplies the intended path for the level of the online control of steering.

# Tiivistelmä

Liikkeen visuaalisessa ohjauksessa katse poimii informaatiota ennakoivasti. Autolla ajettaessa tämä ennakointi tapahtuu lyhyellä ja pitkällä aikaetäisyydellä. Lyhyellä etäisyydellä katseen suunta ennakoi liikkeen suuntaa 1–3 sekunnilla. Useat ohjausmallit ovat selittäneet tämän johtuvan siitä, että ajajat seuraavat jotakin ohjauspistettä tiessä. Ohjauspisteestä saatava informaatio muunnetaan suoraan ohjausliikkeiksi. Tätä katsekäyttäytymistä voi nimittää ohjaaviksi fiksaatioiksi, koska se palvelee online-ohjauksen tasoa. Pitkällä etäisyydellä katse poimii informaatiota kauempaa tieltä ajolinjan suunnittelua varten. Mutkissa osa tiestä voi olla näkyvissä hyvinkin eksentrisesti suhteessa ohjaavien fiksaatioiden suuntaan. Tällaisessa tilanteessa saatetaan tehdä eksentrisiä, etenemistä ennakoivia fiksaatioita mutkan suuntaisesti, jotta ajolinjan suunnittelu saa tarvitsemansa informaation. Tällaisten fiksaatioiden roolia ajamisen visuaalisessa ohjauksessa ei tunneta hyvin.

Tässä väitöskirjassa olen kehittänyt laskennallisia menetelmiä etenemistä ennakoivien katseiden tunnistamiseen instrumentoidulla autolla tiellä kerätystä silmänliikeaineistosta. Katsekäyttäytymistä mutkissa tarkasteltiin kolmessa osatutkimuksessa, joissa selvitettiin myös ajokokemuksen sekä kognitiivisen kuormituksen vaikutusta etenemistä ennakoiviin fiksaatioihin.

Yleisesti ottaen fiksaatioiden jakautumien tarkastelu ei osoita selkeää eroa ohjaavien ja etenemistä ennakoivien fiksaatioiden välillä. Jakautumissa on kuitenkin havaittavissa selkeä häntä, joka voidaan operationalisoida etenemistä ennakoivina fiksaatioina. Etenemistä ennakoivat fiksaatiot kohdistuvat koko näkyvälle tielle, mutta kohteen eksentrisyyden kasvaessa fiksaatiot harvenevat. Kokeneiden ajajien katse teki suuremman osan ajasta etenemistä ennakoivia fiksaatioita kuin kokemattomien. Kognitiivinen kuormitus voi haitata etenemistä ennakoivien silmänliikkeiden suorittamista. Tarkastelen ajolinjan suunnittelun osuutta ohjauksessa tulosten pohjalta. Tulokset ovat yhteensopivia hierarkisen mallin kanssa, jossa ylempi ajolinjan suunnittelutaso tuottaa tavoiteltavan reitin online-ohjauksen tasolle.

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October 2014, Helsinki

Esko Lehtonen

## List of original publications

This thesis is based on the following original articles, which are referred to by their Roman numerals in the text:

**Study I** : Lehtonen, E., Lappi, O., & Summala, H. (2012) Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation Research Part F: Traffic Psychology and Behaviour 15*, 369–377, doi: 10.1016/j.trf.2011.08.007.

**Study II:** Lehtonen, E., Lappi, O., Kotkanen, H., & Summala, H. (2013). Look-ahead fixations in curve driving. *Ergonomics 56*, 34–44, doi: 10.1080/00140139.2012.739205.

**Study III**: Lehtonen, E., Lappi, O., Koirikivi, I., & Summala, H. (2014). Effect of driving experience on anticipatory look-ahead fixations in real curve driving. *Accident Analysis and Prevention 70*, 195–208, doi: 10.1016/j.aap.2014.04.002.

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# 1 Introduction

Among the senses, vision is very suitable for human locomotory control because it provides spatially precise information from a distance. Consequently, using vision it is possible to anticipatorily adapt the steering actions and speed so that the right trajectory can be followed and collisions to any obstacles are avoided. This is especially important when moving at high speeds — for example when driving a car — as consequences of collisions are potentially fatal.

When performing a visuomotor task, gaze is mostly directed to objects or locations relevant for the task (Yarbus, 1967; Land et al., 1999; Tatler et al., 2011). Directing the fovea to the targets helps to extract high resolution information of them, which is not available via the peripheral vision (Previc, 1998). Therefore, the study of eye movement can be used to infer what visual information is especially important for the task execution (Tatler et al., 2011).

In the visuomotor task of car driving, gaze is mostly in the direction of travel, leading the direction changes with an anticipatory preview of 1–3 s (Shinar et al., 1977; Land & Lee, 1994; Wilkie et al., 2010). This pattern of gaze has inspired many steering models which suggest that the visual information from the fixated location is used in the control of steering actions (Land & Lee, 1994; Wann & Land, 2000; for review see Lappi et al., 2013a; Steen et al., 2011). Such steering models are typically *online* models (Frissen & Mars, 2014), where the visual information is directly translated to steering actions and this translation can be described with a control law (e.g. Salvucci & Gray, 2004; Fajen & Warren, 2003). Online models are anticipatory in a sense that the visual information is obtained with some time preview.

In this thesis, I demonstrate that drivers frequently make fixations over the curves with open views with considerably longer visual preview times than useful for online control. Instead, a more likely explanation is that they are related to anticipatory planning of the future trajectory. I will apply the concepts of *guiding* and *look-ahead fixations* to make a distinction between the fixations guiding the online control of steering and those providing information for the trajectory planning (Land et al., 1999; Pelz & Canosa, 2001; Mennie et al., 2007).

I will describe how to identify algorithmically look-ahead and guiding fixations in car driving from eye movement data collected with an instrumented vehicle on a real road. The empirical studies will give an insight into when the look-ahead fixations are performed and what parts of the driver's future trajectory they target. Moreover, the studies investigate the effects of driving experience and cognitive load on the allocation of gaze between the guiding and look-ahead fixations. Finally, the empirical results are discussed respective to a hierarchical model of car driving, where the trajectory planning is understood as a level superior to the online control of steering. Practical implications of the findings for the human factors of car driving are discussed.

First, I will give a short review on how gaze direction and task execution are linked in visuomotor manipulation tasks in general. This will also introduce the background theory for the concepts of guiding and look-ahead fixations. Then, eye movements in the visual control of locomotion with an emphasis on car driving will be reviewed, as well as the role of peripheral vision. Finally, I will present how the concepts of guiding and look-ahead fixations are related to widely used Donges' (1978) two level steering model.

## 1.1 Guiding and look-ahead fixations in the visual control of actions

Execution of skilled actions can be understood to be guided by hierarchical schemata, which are memory representations of the task and its execution (Cooper & Shallice, 2000; Grafton & Hamilton, 2007; Land, 2009). The highest levels of the hierarchical schemata represent the goals and purposes of an action, and the lowest level represents the concrete actions. The middle levels are involved in the organization of the concrete actions to orchestrated task performance. Often, such a hierarchical representation results in a sequential task structure, as some actions must be performed before other parts.

Schemata also guide the gaze while performing a task (Yarbus, 1967; Land & Furneaux, 1997; Land, 2009). The gaze does not follow reactively the execution of the task sequence, but anticipates it. Gaze leads initiation of an action typically with a small lead time (< 2 s) (Land et al., 1999; Hayhoe et al., 2003). For example, when writing a post-it note with a pen, the gaze would fixate the pen on the desk before the hand would move toward the pen in order to pick it. The gaze would remain fixated on the pen in order to provide visual guidance for the picking action, but it would be shifted from the pen toward the post-it note slightly before completion of the picking movement in order to prepare the placement of the pen on the post-it note. That is, in skilled actions fixations do not typically stay on an object to be manipulated until the manipulation is over, but they leave the object slightly before the completion of the current task, when it does not require visual guidance anymore. Then the gaze can be anticipatorily shifted toward the objects or locations relevant for the immediately following task phase (Mennie et al., 2007). These fixations serving the current task phase in the aforementioned fashion are called called *guiding fixations* (Hayhoe et al., 2003; Mennie et al., 2007).

Guiding fixations give information supporting the action execution in just-in-time fashion, minimizing the information which must be kept in the working memory (Ballard et al., 1995). The visual information obtained with guiding fixations is processed and stored in some intermediate form to a visual buffer (Land & Furneaux, 1997). This buffer makes it possible for the action execution to continue without interruption even thought the gaze were shortly diverted away from the current task. Gaze is often diverted from guiding fixations to *look-ahead fixations* toward future phases of the current task (Land et al., 1999; Pelz & Canosa, 2001; Hayhoe et al., 2003; Mennie et al., 2007). Look-ahead fixations are quickly returned back to the guidance of the current phase of an action, which distinguish them from the guiding fixations which may shift anticipatorily toward the next phase when the completion of the current phase does not need visual guidance anymore (Mennie et al., 2007). For example, when writing on a post-it note, the gaze would be predominantly guiding the writing, but it could make look-ahead fixations towards location where the post-it note will be attached.

It has been proposed that look-ahead fixations have a role in planning or organization of the task execution (Pelz & Canosa, 2001; Mennie et al., 2007). This is plausible, as eye movements are typically motivated by the information needs of the task (Yarbus, 1967; Tatler et al., 2011) and look-ahead fixations are oriented toward the objects and locations relevant for the future task execution.

In a controlled laboratory task, Mennie et al. (2007) investigated look-ahead fixations in a task that required reaching and grasping of items in a sequential manner. Look-ahead fixations increased the spatial accuracy of the following shift of guiding fixations to the next target. After a look-ahead fixation, a larger proportion of gaze shifts went directly to the next target compared to shifts without a preceding look-ahead fixation. Look-ahead fixations were also linked to earlier shifts of the gaze to the next target. Overall, this suggests that look-ahead fixations could facilitate the shifts of attention by providing spatial information of the future targets. In this regard, the name of locating fixations given by Land et al. (1999) is very appropriate.

However, Mennie et al. (2007) were not able to show that a preceding look-ahead fixation would have had an effect on the execution of reaching and grasping movements (or planning of the task sequences). The frequency of look-ahead fixations appeared to be linked to the visual demands of the current task phase: when the completing of the current task (screwing two pieces together) did not require much visual guidance, gaze could be allocated to look-ahead fixations.

In this thesis, I will apply the concepts of guiding and look-ahead fixations to context of locomotion. In sequential manipulation tasks, it is easy to identify when gaze is directed toward the objects or locations relevant for the present or future actions. In a locomotor task, the environment is not as clearly divided discretely to current and future locations. In locomotion, guiding fixations could be identified as those fixations which serve the visual control of the steering actions. Look-ahead fixations, on their part, could be those fixations which serve the planning of the trajectory which the steering actions attemps to accomplish.

## 1.2 Guiding fixations in locomotion

In locomotion, gaze is typically towards the direction of locomotion, leading direction changes with a small time headway of at most 1–3 s. This pattern is seen in car driving (Shinar et al., 1977; Land & Lee, 1994; Wilkie et al., 2010) as well as in walking (Grasso et al., 1998; Jahn et al., 2006; Bernardin et al., 2012). When approaching an obstacle, gaze is often directed toward the obstacle, but disengaged from the obstacle and directed toward the location where the foot will be placed (Patla & Vickers, 1997; but see Franchak & Adolph, 2010). When the track is uneven and foot placement needs constant effort the gaze leads with two steps ahead (Patla & Vickers, 1997; Marigold & Patla, 2007). Similarly, when negotiating through gates in a steering simulator, the participants tend to fixate the approaching gate, shifting towards the following gate a bit before passing the gate (Wilkie et al., 2008).

Small anticipatory time headway between fixation locations and locomotory actions appears to be linked to optimal programming of motor actions. In walking, the programming of locomotory actions needs a preview of 1–2 s for normal performance, smaller preview leading to disruption of gait (Matthis & Fajen, 2014). Similarly, in car driving restricting the visual information to a very small preview leads to less stable steering (Land & Horwood, 1995; Salvucci & Gray, 2004; Frissen & Mars, 2014).

Many steering models have been proposed to explain how this gaze behavior is linked to online control of steering in curve driving. Typically the models postulate that drivers use one or more steering points. The seminal paper by Land and Lee (1994) proposed that drivers use the tangent point in curves. From the tangent point it is possible to straightforwardly calculate the radius of the curve and thus the required steering wheel rotation, given that the distance from the road edge can be estimated and the curve can be approximated as being of constant curvature.

However, more recent research has challenged this tangent point steering model (e.g., Lappi et al., 2013a,b). The tangent point steering model does not generalize to situations where the tangent point is not available, for example when there is no visible road-edge and or during the unwinding of a curve. Also, more elaborated analyses of the eye movement data suggest that drivers are not predominantly fixating the tangent point as Land & Lee (1994) suggested, but some point on the future path, in the vicinity of the tangent point (Mars, 2008; Wilkie et al., 2010; Lappi et al., 2013a,b).

Future path steering models (Wann & Swapp, 2000; Wann & Land, 2000; Salvucci & Gray, 2004) suggest that drivers choose a steering point along the future path. According to these models, steering is adjusted so that by keeping the chosen curvature radius, the vehicle will pass over the steering point. Of course, this means that the location of the steering point on the future path must be frequently updated as the vehicle moves forward (Wann & Swapp, 2000; Wann & Land, 2000).

Different steering models propose different roles for the steering point. In some models, the direction of the steering point is used as the steering signal (e.g. Land & Lee, 1994; Boer, 1996; Salvucci & Gray, 2004). Other models suggest that the optic flow is used in the steering and looking at the steering point is a way to align the optic flow in useful fashion (Wann & Swapp, 2000).

The steering models reviewed above are all online models (Frissen & Mars, 2014), which describe how the visual information is directly translated to steering actions and this translation can be described with a control law (e.g. Salvucci & Gray, 2004; Fajen & Warren, 2003). In other words, even though the visual information is obtained with a small time preview, the steering actions are not planned before their execution is due to start. Especially, there is no reason to choose the steering point too far along the future path because the online nature of the models impose the constant curvature assumption (cf. Wann & Land, 2000). That is, the steering point must be selected so that the constantly curved trajectory will stay within the boundaries of the lane or road. In real roads, where curves are not perfectly circular and may form a complex sequences of curves, selecting a steering point too far along a winding road renders the information useless for the online models. This leads to an important conclusion regarding the present work: in winding roads, fixations very far towards the future trajectory unlikely serve the online control of steering. Instead, they are more likely look-ahead fixations, which provide information for planning or organization of the future actions.

## 1.3 Peripheral vision in locomotion

It is important to keep in mind that in addition to the foveal vision — the gaze — also peripheral vision is effectively used in visual control of locomotion (Previc, 1998). The accuracy of peripheral vision is not as high as foveal vision's, but during locomotion humans are able to perceive the spatial dimensions of the space in relatively accurate manner without foveal vision. For example, Franchak and Adolph (2010) showed that frequent fixations to obstacles reported in earlier studies (e.g. Patla & Vickers, 1997) can be partially an artifact of research settings. They set up an obstacle course to a room, and asked participants to find items scattered in the room. As the participants had a visual search task to perform, they very seldom fixated the obstacles they were approaching or stepping over, in contrast to studies without a visual search task. In their study, this did not result in any falls for participating adults. This suggests that adult humans are able to rely on peripheral vision for obstacle negotiation in many everyday settings. However, if there is nothing else to look at, they probably look at the obstacles.

Another example of the role of peripheral vision in locomotory control is that persons with impaired foveal vision but intact peripheral vision due to retinoschisis are still able to drive a car in normal traffic (Lamble et al., 2002). Further, when accurate foveal vision is impaired with artificial blurring, object and road sign detection deteriorates, but keeping the road position and steering through cones is relatively unaffected (Higgins et al., 1998). In contrast, restricting the peripheral field of view leads to lower speeds and increases reaction times (Wood & Troutbeck, 1994).

This is in line with results from the forced peripheral driving (Summala et al., 1996; Summala, 1998). Experienced drivers (lifetime driving experience > 30 000 km) are able to maintain the lateral position of the car on a straight road even when their gaze is directed to a visual secondary task located inside the car 20 ° downwards from the horizon. Also, in a simulator study while performing a visual in-vehicle-task, drivers did not need to increase the rate of fixations to the road to compensate for simulated wind turbulence, indicating that the peripheral vision is enough for lane-keeping because the increasing task demands do not affect the gaze behavior (Horrey et al., 2006).

However, the drivers apparently prefer to look where they are going Land & Lee (e.g., 1994); Wilkie et al. (e.g., 2010); Lappi et al. (e.g., 2013a); Lehtonen et al. (e.g., 2014). This suggests that foveal vision has advantages over peripheral vision also in the visual control of steering. It has been even suggested that gaze direction is strongly linked to the steering (Wilson et al., 2007; Readinger et al., 2002). Also other needs than steering control may motivate looking where you are going. For example, foveal vision supports earlier hazard perception than peripheral vision (Summala et al., 1998; Lamble et al., 1999b).

## 1.4 Two-level steering model

Two-level steering models (Donges, 1978; McRuer et al., 1977) provide a framework which helps to understand the complementary roles of peripheral and foveal vision in the online control of steering. In Donges' (1978) two-level model, the steering control has both *guidance* and *stabilizing* levels. Stabilizing level minimizes the current deviation from the intended path, as the guidance level anticipatorily adjusts steering relative to the points on the future path, so that the current deviation is not minimized at the expense of the future path deviation. Consequently, for the stabilizing level the most relevant visual information would be near the vehicle, as the guidance level would need visual information further ahead (Donges, 1978; Land & Horwood, 1995; Salvucci & Gray, 2004)

The main support for the two-level model is based on behavioral studies. In a simulator, where the time distance of available information can be restricted with occlusions (Land & Horwood, 1995; Salvucci & Gray, 2004; Frissen & Mars, 2014), the steering patterns change as a function of visual occlusion. Steering relying on near information is less smooth, resulting in jerkier ”bang bang” movements (Land & Horwood, 1995), as steering based on more anticipatory information further ahead is smoother but less accurate relative to the lane position. When both near and far information is available, steering is both smooth and accurate. Salvucci & Gray (2004) replicated the behavioural results using a cognitive model based on two point steering points. Their model included a *near point* and a *far point*, the first corresponding to the stabilizing and the latter to the guidance level control. In their computational model, the far point in curves was the tangent point.

Originally Donges (1978) did not attempt to specify how the drivers' eye movements relate to the two-level steering model, but he cited results by Shinar et al. (1977) that drivers tend to start making fixations toward the curve 1–3 s before entering it. He interpreted this to support the existence of the guidance level. Later, Salvucci & Gray (2004) suggested that the near point providing the stabilizing information is monitored peripherally while the far point providing the guiding infromation is monitored with foveal vision.Their suggestion is in line with the eye tracking studies, which have demonstrated that all but perhaps very learner drivers fixate the area just in front of the vehicle (Mourant & Rockwell, 1972; Falkmer & Gregersen, 2005). In general, the tangent point (Land & Lee, 1994) and future path (Wilkie et al., 2010) steering models can be integrated with the two level model by postulating that the steering point (either the tangent point or the point on the future path) is used for the guidance level of steering, and the peripheral vision is used for the stabilizing level.

## 1.5 Trajectory planning

In Donges' (1978) two level steering models, the trajectory is seen as the forcing function for the guidance and stabilizing levels. Consequently, trajectory planning can be seen as a level superior to the online control of steering in the hierarchical control of driving. Trajectory of the car typically follows closely the geometry of the road. However, perception and selection of the trajectory are drivers' cognitive processes, which consume, manipulate and produce information. I will call these processes *trajectory planning*.

The roadway and other road users place both static and dynamic possibilities and constraints for locomotion (Gibson & Crooks, 1938; Fajen & Warren, 2003; Summala, 2007). Trajectory planning uses this information to produce a trajectory plan, which can be understood as a solution which can satisfy these constraints. Especially, a trajectory plan is not only about the path. The paths which can be safely and comfortably taken depend on the speed. For example, cutting a corner allows higher speed. Driver may also have other motives, like maintenance of some level of comfort or seeking of excitement, for choosing a trajectory over others (Näätänen & Summala, 1976; Summala, 2007). Trajectory plan is of course also affected by the performance of the vehicle and skills of the driver.

As the situation unfolds, the trajectory plan may be updated – for example when an oncoming car emerges – if sufficient cognitive capacity and time is available. In other words, trajectory planning can be thought also as a process for anticipatory maintenance of safety margins or a safety zone (Gibson & Crooks, 1938; Summala, 2007). For example, by choosing a trajectory with a low enough speed drivers increase the time-to-line crossing, i.e. the time available before the car runs off the lane (Godthelp et al., 1984), increasing the safety margin. It is also possible to think that more abstract level processes, like knowledge of the traffic rules and culture, as well as skilled hazard perception (ability to predict what happens next) can affect trajectory planning (Underwood, 2007; Jackson et al., 2009).

The role of trajectory planning for driving is most striking in rally driving. For example, when negotiating curves over crests (Fig. 1), the driver must turn the vehicle into the right direction already before the curve, because due to the crest and high speed, the car jumps to the air losing steerability during the curve. If the driver would not have anticipated the trajectory, the car could have ended up in the forest.

However, trajectory planning appears to be present also in more ordinary driving. In a controlled experiment, Cavallo et al. (1988) demonstrated that drivers are able to time the steering wheel rotation correctly even when the visual field was occluded 2 s before entering a curve. Furthermore, experienced drivers (> 100 000 km) were able to match the amplitude of the steering wheel rotation correctly under occlusion, while novices underestimated the required rotation. Without occlusion, there was no difference between learner and experienced drivers, because visual feedback was available for online control of steering to complete the trajectory plan. This experiment demonstrates that even without any online visual information, accurate steering is possible, even only at limited extent.

The result can be interpreted to show that the steering actions can be based on some kind of representation of the future trajectory instead of continuous visual information, but that this representation is limited in the accuracy over longer periods. It can be that, in this case, the visual buffer (Land & Furneaux, 1997) is used to support the online control of steering. It is even possible to interpret that the trajectory plan is the visual buffer in locomotion, but that the buffer's accuracy is satisfactory for steering actions only over

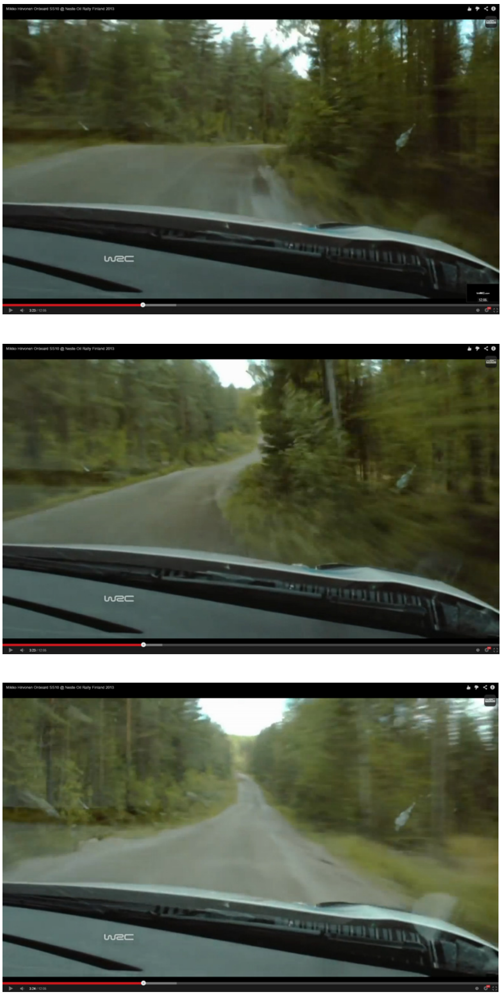


Figure 1. A rally driver needs to understand the possibilities and contraints of the road environment in order to plan the future trajectory effectively. When approaching a bend with a crest, the car heading must be aligned in line with the road beyond the curve already before entering the curve (top), because within the curve, the car jumps due to a crest, losing steerability (middle). Due to anticipatory adjustment of the heading, the car lands pointing to the right direction (bottom). Screenshots form “Mikko Hirvonen Onboards SS10 @ Neste Oil Rally Finland 2013” https://www.youtube.com/watch?v=hhJEqlzRxdU, at positions 3.23–3.24.

small time periods. Therefore it is frequently updated (Summala et al., 1996; Tsimhoni & Green, 2001).

A more mundane manifestation of trajectory planning is how drivers anticipatory adjust their speed before entering a curve (Hassan & Sarhan, 2012; Cruzado & Donnell, 2010; Shinar et al., 1980). Spacek (2005) also showed that drivers use very different paths while driving through curves, which can reflect different trajectory planning rather than random steering fluctuations.

In the context of sequential manipulation tasks, it has been suggested that look-ahead fixations would be serving planning or organization of actions (Pelz & Canosa, 2001; Mennie et al., 2007). In steering along a curved road, similar kind of anticipatory look-ahead fixations serving the trajectory planning would be expected, because trajectory planning needs visual information on the roadway and on the other road users. Anticipatory look-ahead fixations toward the direction of the curve has been been reported earlier (Cohen & Studach, 1977; Shinar et al., 1977; Land & Horwood, 1996; Mars & Navarro, 2012; Muttart et al., 2013 cf. Marigold & Patla, 2007 for trajectory planning in walking). However, when the look-ahead fixations are done and what part of the road they target, have not yet been investigated. Also their role in the steering models is not yet well understood.

# 2 Aims of the current thesis

This thesis has the following four aims:

*1) Identify anticipatory look-ahead fixations in curve driving, and examine how they are different from the guiding fixations.* The distinction of guiding and look-ahead fixations is based on the functional role of the fixations. Guiding fixations serve the execution of the current actions, and the look-ahead fixations provide anticipatory information for the future action execution (Pelz & Canosa, 2001; Hayhoe et al., 2003; Mennie et al., 2007). In car driving, the concepts of guiding and look-ahead fixations can be linked to online control of steering and trajectory planning respectively. However, along a straight road, both of these tasks could be presumably well served by fixating approximately straight ahead. Therefore, it is necessary to investigate curves, where part of the future road is in highly eccentric position. Online control models of steering suggest that drivers need to fixate only with a time preview of a couple of seconds. Consequently, eccentric eye movements toward the road over a curve with an open visibility are most likely look-ahead fixations, because they are not serving the online control of steering (Fig. 2). For contrasting the look-ahead and guiding fixations, I will investigate the origin and landing location of the look-ahead fixations over curves, and whether the look-ahead fixations target some specific part of the future trajectory.

*2) Investigate how driving experience and cognitive load affect the allocation of gaze between guiding and look-ahead fixations.* It would be expected that cognitive load and inexperience could negatively affect trajectory planning. Cognitive load may hinder the shift of attention between the road ahead and eccentric future road (Victor et al., 2005; Wickens et al., 2009), decreasing the proportion of look-ahead fixations. Inexperienced drivers need more foveal vision for steering (Summala et al., 1996), which leaves them less time for look-ahead fixations. Also, their trajectory planning can be less elaborated, meaning that utility of anticipatory information from far of the road is lower for them than for experienced drivers. Understanding these factors helps both to develope theoretical models as well as to assess the practical implications of the present results for driving safety.

*3) Development of computational methods to identify anticipatory look-ahead fixations in real curve driving.* From the eye movement data collected on-road, it is difficult to say where people look at. The standard way has been to manually annotate the fixations

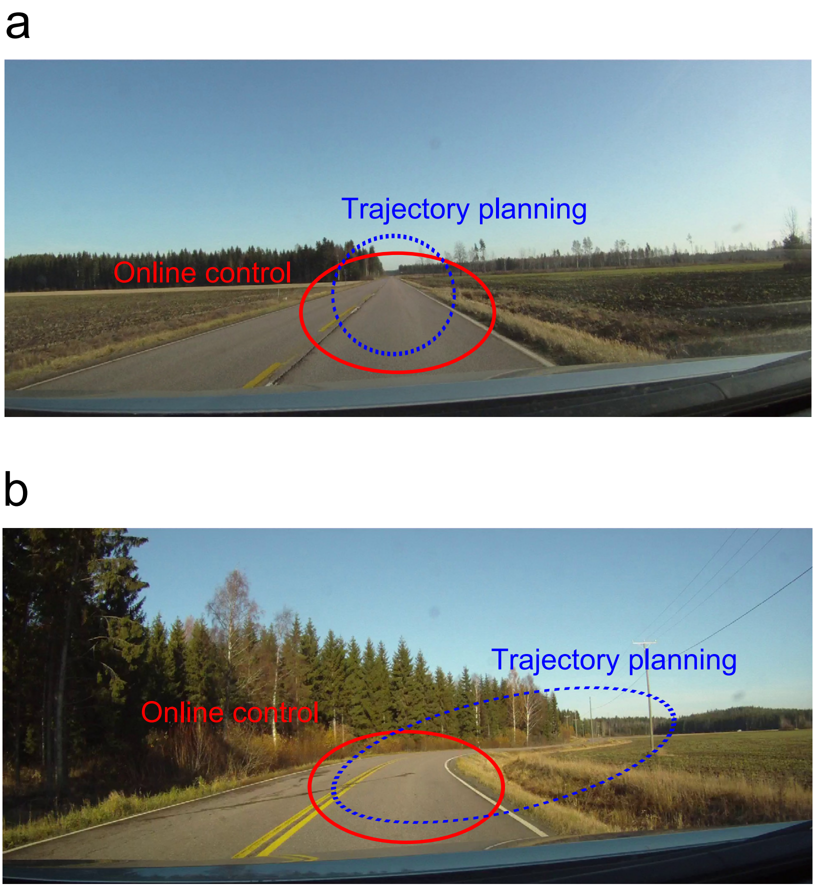


Figure 2. Online control of steering and trajectory planning may use visual information from partially overlapping spatial areas. Online control of steering requires information relative near the vehicle, as the trajectory planning can utilize information further along the road also. On a straight road (a) the relevant areas for online control and trajectory planning are largely overlapping, but in curves with an open visibility (b) the relevant area for the trajectory planning extends to eccentric locations. Consequently, only eccentric look-ahead fixations in curves are clearly distinguishable from guiding fixations.

using visualization of the eye movement data over video footage. In this thesis I have developed methods to estimate the direction of the guiding fixations in curve driving using only the movement and positioning data of the vehicle. Estimates for the guiding fixation direction can then be used to identify look-ahead fixations. I have also developed methods for estimating what part of the road the look-ahead fixations target at.

*4) Present a conceptual model illustrating the role of trajectory planning in control of steering*, and discuss the model from the perspective of visual sampling.

# 3 Methods

All three studies of this thesis were on-road studies with an instrumented vehicle. During the experiments, the participants drove the vehicle along a predefined route on rural roads while their eye movements and vehicle data were recorded.

## 3.1 Equipment

The instrumented car was a Toyota Corolla compact sedan with a manual transmission (model year 2007). The car was equipped with a two-camera Smart Eye Pro remote eye tracker (Smart Eye AB, Gothenburg, Sweden, www.smarteye.se), fixed to the dashboard and operating at 60 Hz. Version 5.1 was used in study I and II, and version 5.5 in study III. The vehicle also had a forward looking video camera and a GPS receiver. Yaw rate was recorded from CAN bus. The data were timestamped and stored in the car. Based on the GPS signal, the studied segments were extracted and the road location based representation was formed.

The passenger side of the car was equipped with a brake pedal, extra mirrors and a speedometer. Safety supervisor on the passenger side was thus able to intervene by braking in case of hazardous situation. However, during the experiments intervention was never needed.

## 3.2 Participants

In all studies, relatively experienced drivers were recruited as participants (lifetime driving experience more than 20 000 km). In Study III, the experienced drivers were also compared to a group of novice drivers (lifetime driving experience less than 5 000 km). The number of participants, their age, sex and driving experience is summarized in Table 1.

Summala et al. (1996) suggested that drivers with more than 30 000 km of lifetime driving experience can use their peripheral vision more effectively for lane-keeping than the drivers with less than 5 000 km. The limit of 20 000 km was deemed sufficient enough to guarantee that the drivers would not be fixating the near zone of the road constantly (Mourant & Rockwell, 1972), which could have strongly affected the eye movement parameters calculated. The limit was lowered from 30 000 to 20 000 km because it was

Table 1. Summary of the participants in the Studies I–III.

| Study | Group | N | male/female | Age | Lifetime driving experience |
|---|---|---|---|---|---|
| I |  | 10 | 6/4 | 25–52, M=30, SD=8 | > 20 000 km |
| II |  | 12 | 7/5 | 23–46, M=30, SD=6 | > 20 000 km |
| III | Novices | 9 | 3/6 | 18–33, M=24, SD=5 | < 5 000 km |
| III | Experienced | 9 | 7/2 | 23–30, M=26, SD=2 | > 20 000 km, > 5 years |

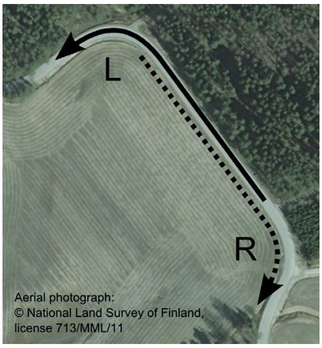
difficult to recruit enough participants who could report confidently having more than 30 000 km of driving experience.

Because drivers with less than 5 000 km need their foveal vision for their lane keeping compared to drivers with more than 30 000 km (Summala et al., 1996), it was expected that this would be reflected also in fewer look-ahead fixations among the novice group compared to the experienced group in Study III.

Participants were recruited through email lists of the university and via personal contacts of the experimenters. All participants were required to have a valid driver's license and normal or corrected to normal vision with contact lenses. Participants gave an informed consent to take part in the study.

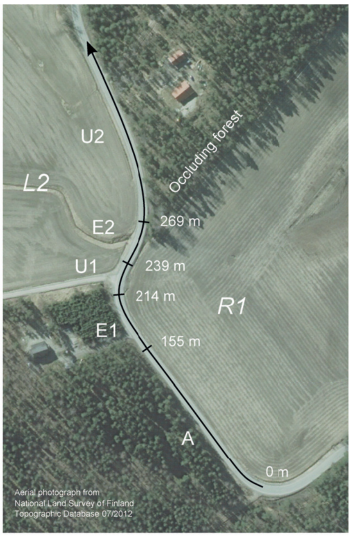
## 3.3 Roads and curves

Studies were conducted on two-lane rural roads. The roads had a low to moderate traffic and they were surrounded by open fields and patches of forest. In Study I, a straight approach segment for two open curves were selected for detailed analysis (Fig. 3). The two curves were located in the opposite ends of the same straight segment of 100 m. The straight segment of the road and the curves were adjacent to an open field. In Study II, three open curves sequences were selected (Figs. 4, 5, 6). One of the curves (R1) was the same as the right curve of Study I. In Study III, six open curves driven in both directions were studied (Fig. 7). In Study I, the studied segments were manually identified. In Study II and III vehicle yaw rate based curve segmentation with manual identification of the approach phase was used.



Aerial photograph:
© National Land Survey of Finland,
license 713/MML/11

Figure 3. Study I: Aerial photograph with annotations: the left curve (L, solid) and the right curve (R, dotted) used in the study.



Aerial photograph from
National Land Survey of Finland
Topographic Database 07/2012

Figure 4. Study II: Aerial photograph with curve phases and their boundary locations from the beginning of the segment. Segment symbols are the following: A = approach, E = Entry, U = unwinding. Phases E1 and U1 belong to curve R1 and phases E2 and U2 to L2. When approaching the right curve R1 along phase A, the forest occludes visibility along the road creating an occlusion point.

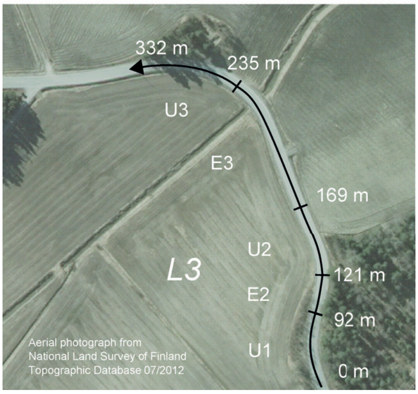


Figure 5. Study II: Aerial photograph with curve phases and their boundary locations from the beginning of the segment. Segment symbols are the following: E = Entry, U = unwinding. Phases E2 and U2 belong to the left curve L3.

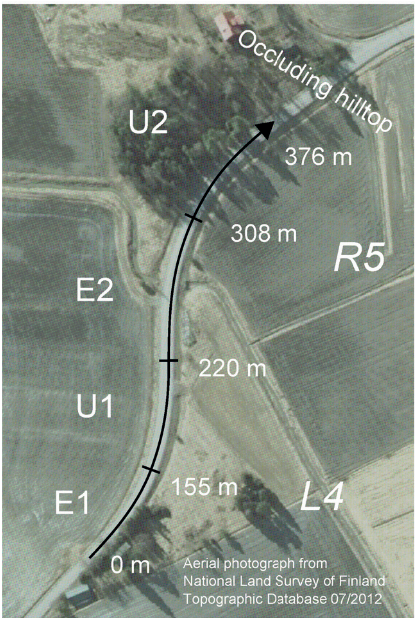


Figure 6. Study II: Aerial photograph with curve phases and their boundary locations from the beginning of the segment. Segment symbols are the following: A = approach, E = Entry, U = unwinding. Phases E1 and U1 belong to left curve L4, phase E2 and U2 to right curve R5. A hilltop occludes visibility, creating an occlusion point when driving on curves.

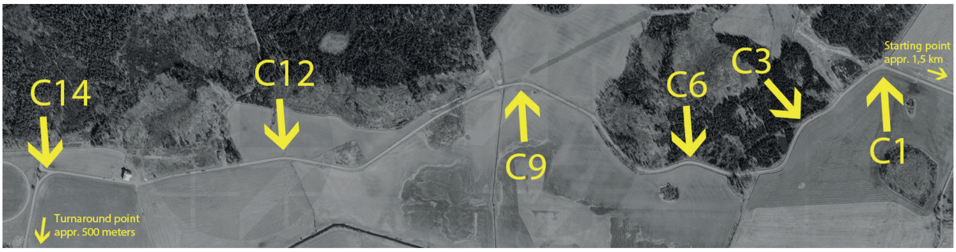


Figure 7. Study III: The curves analyzed from the road Kytäjäntie, Hyvinkää, Finland (N 60°36.81 E 24°42.96).

## 3.4 Procedures

Participants were always accompanied by two researchers. One of the researchers was seated on the passenger side as the safety supervisor, monitoring the driving. He or she had a brake pedal for intervention in case of hazardous situation, but it was never needed. Another of the researchers was seated on the backseat, administrating the secondary task (Study I & II) and monitoring the data collection. In Studies I and II the secondary task was practiced before start of driving and when participants were driving from the campus to the experimentation site. A predefined route including the studied curves was repeated multiple times in all the studies. Between the repeats a small pause was taken in a bus stop or a parking place. Car-following situations were avoided by waiting until there were no other vehicles visible before entering the road. The safety supervisor gave route directions, but other interaction was avoided during the runs.

In Studies I and II the instrument panel was occluded in order to minimize distraction and to render the free and cognitively loading runs more comparable. Participants did not express discomfort at having to drive without a speedometer. The safety supervisor had a brake pedal and access to the vehicle speed through a separate display, in case the driver would not have been able to maintain a safe and legal level of speed. The safety supervisor did not have to intervene in driving at any point.

## 3.5 Cognitive secondary task SPASAT

As a cognitive secondary task we used a self-paced variant of the PASAT task (Sampson, 1956; Gronwall, 1977), referred to below as SPASAT (Self Paced Serial Addition Task;

Lamble et al., 1999a). In SPASAT, the experimenter reads out two numbers between 1 and 9. The driver's task is to mentally add the two latest numbers together and to report the result verbally. Immediately after the driver has answered, the experimenter will give a single new number. Thus, the task requires the driver to keep the last number in working memory during reporting the answer, and then encode the new number, add this to the number in working memory, and commit the new number to working memory while reporting the sum. If the driver was unable to provide an answer, she or he would say "pass", and the instructor would give two new numbers to add. Two numbers were always given in the beginning of each recording segment. Wrong answers were recorded, but the driver was never corrected.

## 3.6 Algorithms for identification of guiding and look-ahead fixations

For eye movement data collected on-road, it is difficult to determine what targets drivers look at. The most straightforward method is to manually annotate the targets using a visualization of the eye movements overlaid on video footage. However, this method is very time consuming. Fixation targets could be of course computed geometrically, if the location of the car in the world and a model of the environment would be available. With modern GPS technology, the location of vehicle is easily obtained, but good models of the environment are still typically not available. In the following, I will describe the developed methods which were used to identify guiding and look-ahead fixations from eye movement data collected on-road.

### Study I: Vehicle heading as an estimate for the direction of the guiding fixations

When a remote eye tracker fixed to the dashboard is used, the gaze direction can be always referenced to the vehicle center line. When driving on a straight road, the direction of the vehicle center line will coincide with the directon of guiding fixations. Therefore, it is possible to identify the look-ahead fixations using a simple eccentricity threshold relative to the vehicle center line (Fig. 8). This method was used in Study I, where threshold of 10 ° was used. It was still necessary to manually inspect the targets of fixations, in order to establish that the eccentric glances were really targeting the future road.

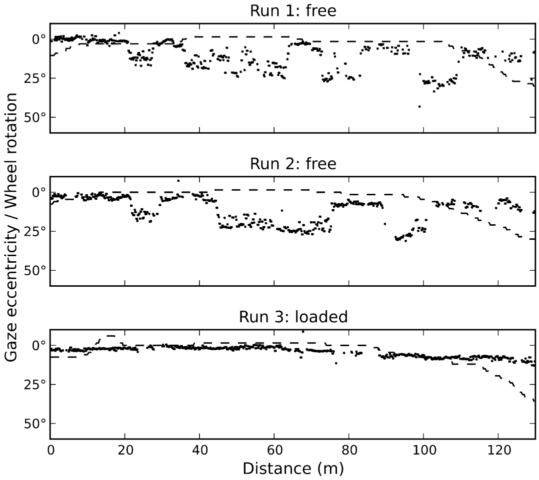


Figure 8. Study I: Raw gaze eccentricity (black dots) relative to the vehicle center line from one participant when approaching a right curve under three different runs. During the free runs the gaze makes look-ahead fixations over the following curve, but under the cognitive loaded run, the look-ahead fixations are not present. Wheel rotation marked with dashes.

### Study II: Median gaze direction as an estimate for the direction of the guiding fixations

However, the simple eccentricity threshold method cannot be applied to curves, because the guiding fixations anticipate the road, and therefore they become eccentric relative to the vehicle centre line. This renders a threshold relative to the vehicle centre line useless for identification. In order to extend the identification of look-ahead fixations to curved sections, it is necessary to estimate the direction of the future road. In Study II, this estimation was done by calculating the direction of median gaze (Fig. 9) and using a threshold relative to the median gaze as a criteria for look-ahead fixations. Based on the visual inspection of the gaze data, it was deemed that the threshold of 6 ° was reasonable for distinguishing between the guiding and look-ahead fixations. Furthermore, in order to filter out such fixations which were not targeting the future road, the future road was modeled in 2D so that the potential intersection of gaze and the road could be calculated (Fig. 10).

A 2D model makes it also possible to estimate the landing location of look-ahead fixations. A look-ahead fixation can be located along the modeled trajectory because all

(a)

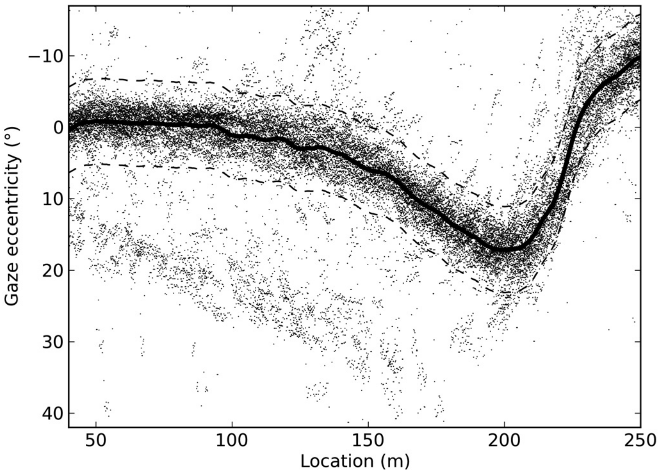


Figure 9. Study II: Scatter of raw gaze eccentricities with the guiding fixations reference (solid line with 6° dashed boundaries) on curve R1 of Study II.

the data are timestamped. Because the eye tracker reports the eccentricity of a fixation relative to the vehicle center line, it is possible to calculate the vector marking the direction of the look-ahead fixation in 2D. Consequently, it is possible to estimate the point where the future trajectory and the vector will cross. This crossing point can be taken as the landing point of a look-ahead fixations, when it is assumed that the look-ahead fixations target the future road. This model was further extended by modeling also occluding forest around the future trajectory, which filters out such fixations which cannot be targeting the future road because it is not visible.

### Study III: Eccentricity threshold relative to the individual trajectory

In Study III, the road-ahead direction was calculated independently for each trajectory so that the variation between trajectories could be better accounted. A trajectory representation was calculated independently for each run, and then the eccentricity of 1, 2, 3 and 4 s time-headway points were calculated. In other words, the 2 s time-headway point is the point on the trajectory where the vehicle will be after 2 s (Fig. 12). The eccentricity of fixations was then calculated relative to these time-headway points. It was found that the 2 s

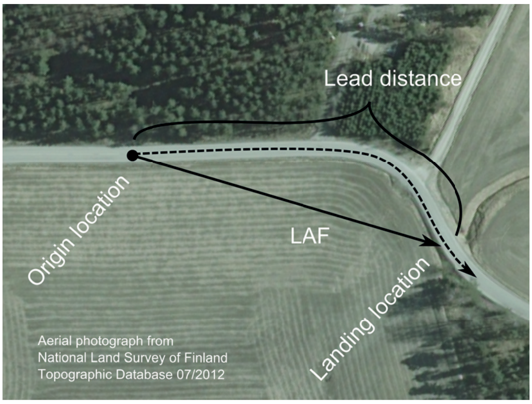


Figure 10. Study II: A look-ahead fixation visualized over the terrain. Look-ahead fixation (LAF) is done at the origin location, and it is directed to the landing location on the road ahead.

time-headway point was a good estimate for the guiding fixations, both when approaching and driving in curves (Fig. 11).

In Study II, it was proposed that the look-ahead fixations could be directed according to the different phases of the future trajectory. However, the landing point analysis used was feasible only for eccentric look-ahead fixations. For guiding fixations along a straight road, estimating a landing point is very difficult, because visual angle between the near and far of the road ahead is relatively small. This restricted the analysis of fixation targets to eccentric look-ahead fixations, and made comparison to guiding fixations difficult.

In Study III, instead of the distribution of the landing points, the fixations were categorized relative to various reference directions calculated from the trajectory representation (Fig. 12). The fixations where categorized to those targeting the road ahead or the future trajectory in terms entry, exit and beyond sectors. If a fixation was within 6 ° of 2 s time-headway direction, it was categorized as road-ahead fixation. More eccentric fixations towards the road were assigned to the entry sector, if the eccentricity was smaller than the eccentricity of the maximum yaw rate point. In other words, if a vector origination from the fixation origin location would cross the cross the entry sector of the future trajectory. The exit and beyond sectors were categorized similarly (Fig. 13). In Study III, fixations belongind to the entry, exit and beyonds sectors were operationalized as look-ahead fixations.

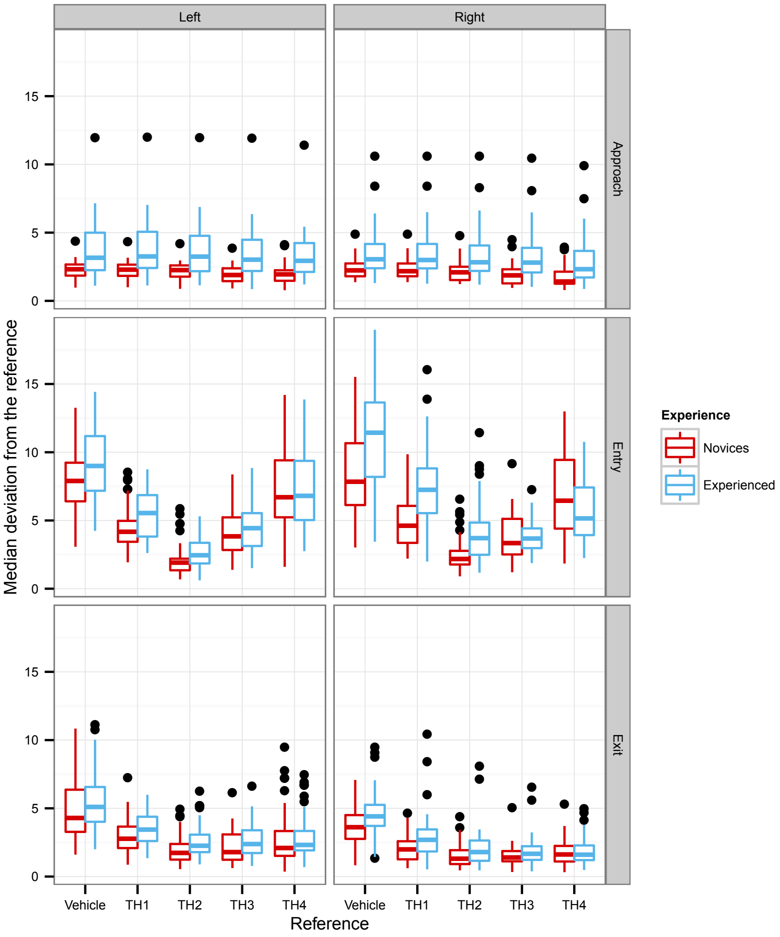


Figure 11. Study III: Median absolute deviations (i.e. half of the fixations are within the eccentricity) relative to the vehicle center line and to different time-headway reference directions with 1, 2, 3 and 4 s lead times (TH1—TH4). Median absolute deviation is calculated separately for each participant, curve, direction (left, right) and phase (approach, entry, exit). In the boxplots the hinges represent the first and third quartile, whiskers extend 1.5 * IQR of the hinge, and outliers are marked with dots.

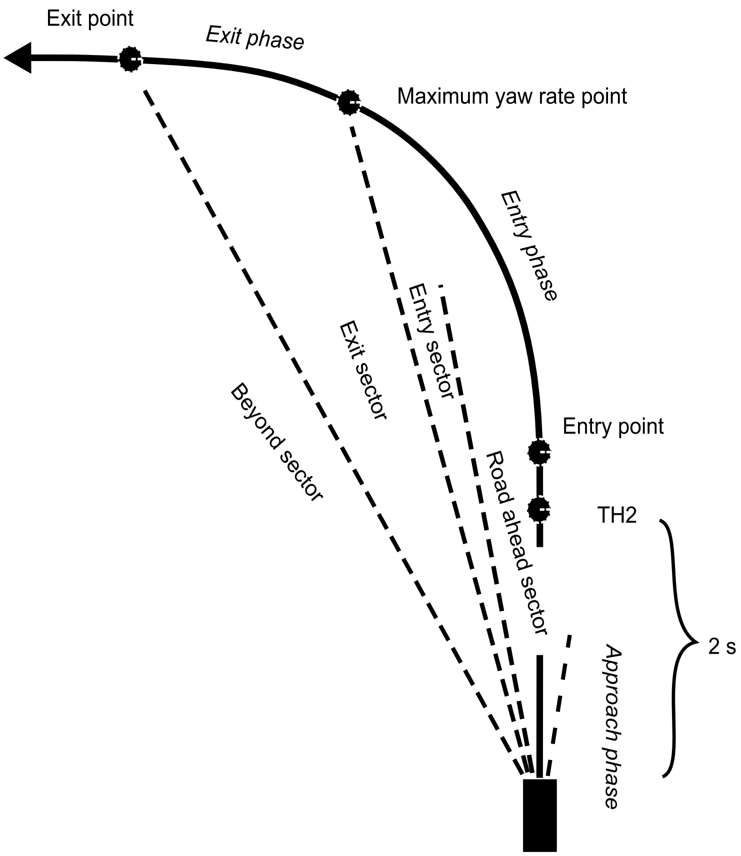


Figure 12. Study III: The figure shows the trajectory (line with arrow) of the vehicle (black box). Along the trajectory, there are the entry, maximum yaw rate and exit points of the curve. These points segment the trajectory to approach, entry and exit phases. The time-headway point with 2 s lead time (TH2) is also marked. From the driver's point of view, the direction of these points define sectors used for categorizarisation of fixations to road ahead, entry, exit, beyond sectors.

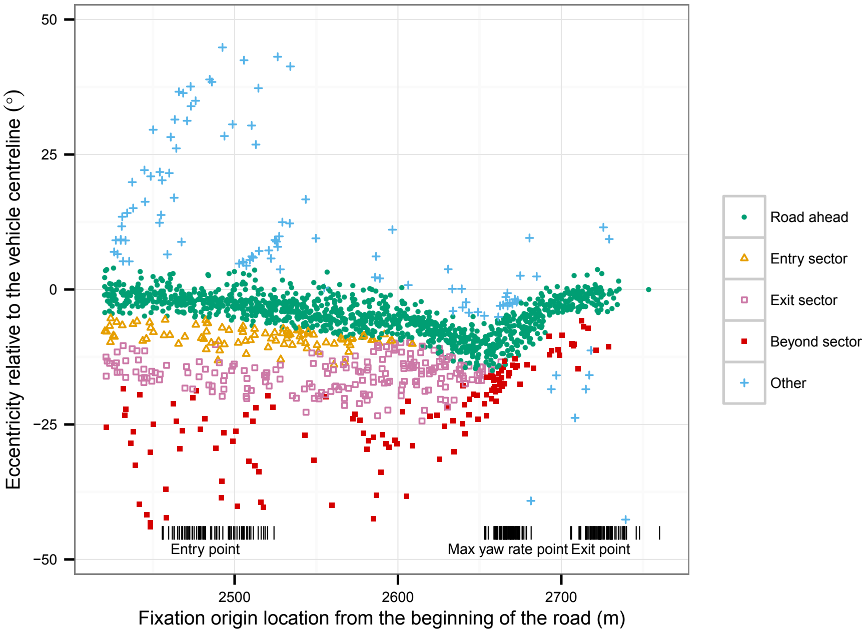


Figure 13. Study III: All the fixations from all participants identified in the right curve C9. The x-axis represent the origin location of a fixations. Locations of individual entry, maximum yaw rate and exit points are marked in the bottom of the figure with vertical lines. The y-axis shows the eccentricity (up: to the left) of fixations relative to the vehicle center line. Based on the eccentricity, each fixation was assigned to dynamically defined areas of interests (color and shape). Fixations toward the road ahead are denoted with green points, fixations toward the entry phase of the drivers' trajectory with yellow triangles, fixations toward the exit phase with purple rectangles, fixations target the road beyond the curve with red rectangles, and other fixations with blue crosses. Fixations with different areas sectors may mix due to differences in individual driving lines, which affect sector boundaries.

# 4 Results

## 4.1 Look-ahead fixation origin locations

The look-ahead fixations are performed both during the straight approach before a curve and within the curves. Within curves, look-ahead fixations were typically identifiable in the entry phase (between the entry point and the maximum yaw rate point of the curve where the turning movement speeds up). In exit phases (after the maximum yaw rate point until the exit of the curve) there were very few look-ahead fixations which could be detected using the threshold method. This is because in the exit phase, the eccentricity of the end of the curve, the exit point, approaches the road-ahead direction, rendering the rest of the current curve visible in the same direction as the road ahead.

Look-ahead fixations appear to be most frequent near the entry point of the curve (Fig. 14). Increase of the look-ahead fixations when approaching the curve can be related to information needs of the trajectory planning. The closer the curve is, the more important it is to keep the trajectory plan up-to-date. The decrease of the look-ahead fixations after the entry point can be partially due to road geometry: as the curve unwinds, there is less and less future road in eccentric position.

Overall, Study III suggests that dwell time on look-ahead fixations would be larger in the approach phases than in entry phases. However, the reduction of look-ahead fixation dwell time is present only in left curves. Here, the visibility over the curve can be the main factor. The vehicle A-pillar blocks the part of the curve especially in the entry phases, hindering look-ahead fixations. It might be that drivers compensate this by making look-ahead fixations more during the approach. On the other hand, it is possible that the difference is due to selection of the curves. The right and left curves were not exactly identical, because they they were the same curves driven in opposite directions.

## 4.2 Look-ahead fixation landing locations

In Study I there was no trajectory model available, and the interpretation of the landing locations was done only qualitatively based on visual inspection of gaze visualization. In Study I, the look-ahead fixations appeared to focus toward the occlusion point of the road when approach a curve along a straight road. The occlusion point can be defined as the nearest point on the road where view of the road is blocked by some obstacle (for

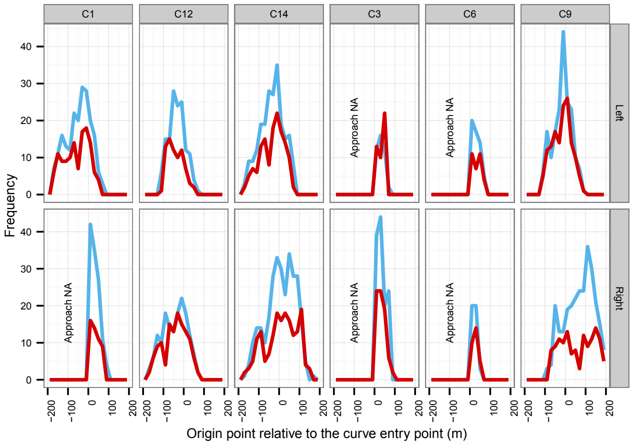


Figure 14. Study III: Look-ahead fixation origin locations relative to the curve entry point, separately for different curves (C1–C14), curve directions (left, right) and experience groups (red novices, blue experienced). The curves which had no straight approach phase have been marked Approach NA, and no fixations from the approach are included.

example vegetation or a crest). Therefore, the location of the occlusion point on the road changes continuously as the car (the observer) travels along the road. The oncoming cars and obstacles on the road become first visible at the occlusion point of the road. For both anticipation of oncoming cars and geometry of the road, it would be therefore reasonable to monitor the occlusion point.

In Study II, the landing locations of look-ahead fixations were determined using a 2D model of the future trajectory. Study II suggested that look-ahead fixations do not always target an occlusion point, even though such a point would be available. Rather, the look-ahead fixations appeared to predominantly go over the next maximum yaw rate point (the point where the magnitude of the yaw rate starts to decrease), but not over two maximum yaw rate points. This suggested that the look-ahead fixations could be linked to some kind of sequential structure in the curve driving sequence.

However, some problems were identified in the landing points analysis used in Study II. First, the analysis of landing points did not show concentration of look-ahead fixations to any specific location along the future trajectory. As the hypothesis was that the look-ahead fixations could be related to the curve phases, perhaps targeting certain point on

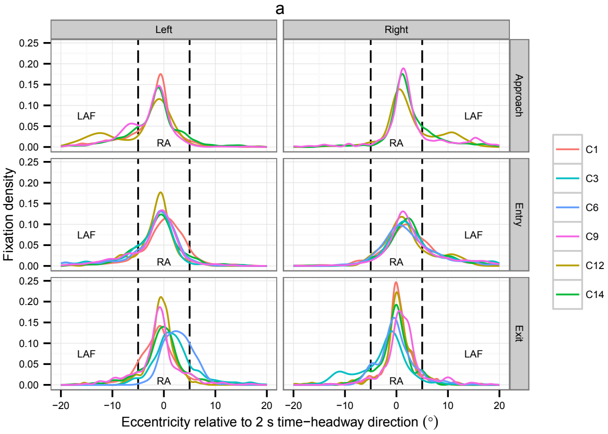


Figure 14. Study III: Density estimates of horizontal fixation eccentricity relative to the 2 s time headway point (TH2) separately for different curves (C1–C14), curve directions (left, right) and phases (approach, entry, exit). Note how referencing the fixations to TH2 direction center the distributions. Areas for road-ahead (RA) and look-ahead fixations (LAF) marked.

the trajectory sequence like the maximum yaw rate point or the exit point (see Fig. 12), it was deemed necessary to investigate individual curve phases instead of the averaged ones used in Study II. Furthermore, just focusing on the landing points of the look-ahead fixations it is possible to miss the greater picture of the gaze behavior. The threshold which determines what is a look-ahead fixations and what is not, is only an operational definition after all.

Therefore, in Study III, the look-ahead fixations eccentricities relative to the 2 s time headway point was analyzed (Fig. 15). First, the analysis showed that guiding and look-ahead fixation targets are not clearly spatially separable, that is, the distribution is unimodal. The look-ahead fixations formed a tail toward the direction of the curve. Second, the analysis showed that the curve phases did not strongly determine the direction of the look-ahead fixations. Rather, the density of the look-ahead fixations is better explained by the eccentricity required to make those fixations. The more eccentric a location, the less it is fixated.

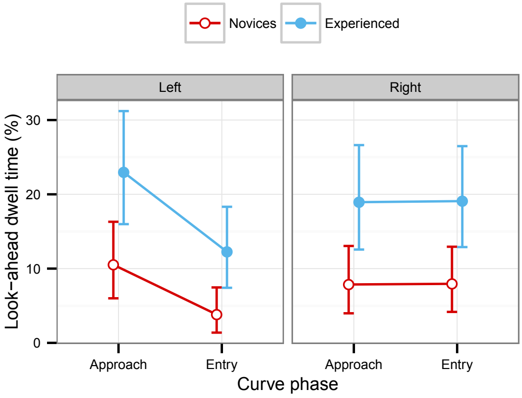


Figure 16. Study III: Model predicted percentage of look-ahead dwell time in approach and entry phases, separately for left and right curves and novice and experienced drivers. 95% confidence intervals are marked. 95% confidence intervals are marked.

## 4.3 Effect of driving experience

In Study III, the effect of driving experience on allocation of gaze between guiding and look-ahead fixations was studied. Experienced drivers had a significantly larger dwell time on look-ahead fixations compared to novice drivers (Fig. 16). This difference was due to their greater number of look-ahead fixations, as the duration of the look-ahead fixations was not significantly different between the experienced and novice drivers.

## 4.4 Effect of cognitive load

In Studies I and II free driving was compared to driving while performing a cognitively loading secondary task. In Study I, the cognitive load decreased significantly the dwell time on fixations toward the occlusion point while approaching a curve on a straight segment of road (Fig. 17). However, the effect was not replicated in Study II (Table 2). Instead, it was found that look-ahead fixation landing locations did shift closer along the trajectory under cognitive load. Interestingly, it would be expected that this produced decrease on the look-ahead dwell times too, when the look-ahead fixations are identified using an eccentricity threshold.

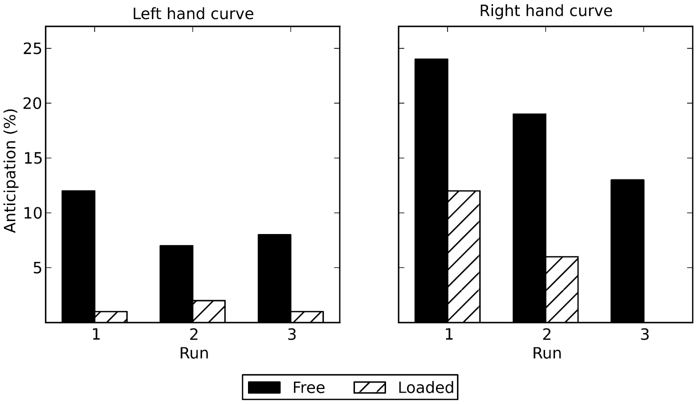


Figure 17. Study I: Visual anticipation over the runs in different task conditions. Percentage of time spent on looking towards the occlusion point (y-axis) over runs 1-3 (x-axis) in the left hand curve (left) and the right hand curve (right). Solid bars represent the mean value of anticipation in the free condition and hatched bars represent the mean value of anticipation in the load condition.

Between Studies I and II, there were differences in the quantification of anticipatory look-ahead fixations. In Study I, only highly eccentric fixations were taken into account and analysis was restricted to straight segment before a curve. In Study II, fixations with smaller eccentricity threshold relative to the median gaze direction were recorded and both fixations during the approach of the curve and within the curve was investigated. Together, the results of Studies I and II suggest that cognitive load may affect negatively to trajectory planning by interfering with look-ahead fixations.

## 4.5 Effect of familiarity

In all of the studies, the drivers drove the same road repeatedly. In Study I, the same road was repeated three times, in Studies II and III four times. The data from the Study III showed a clear and significant effect of familiarity on the look-ahead fixations. The dwell time on the look-ahead fixations decreased as a function of repetitions. This can indicate memorization of the road environment, so that drivers need smaller amount of visual input to anticipate because part of the required information comes from a memorized representation of the road. On the other hand, it can be that the effect is due to increasing fatigue or boredom induced by the driving.

Table 2. Study II: Average percentage of gaze within 6 ° of guiding fixation reference, percentage in look-ahead fixations, in free and cognitively loaded conditions. Standard deviation in parenthesis.

| | Guiding fixations (%) | | Look-ahead fixations (%) | | LAF rate (N/s) | |
|---|---|---|---|---|---|---|
| Curve | Free | Loaded | Free | Loaded | Free | Loaded |
| R1 | 83 (5) | 87 (7) | 11 (6) | 11 (8) | 0.21 (0.12) | 0.20 (0.14) |
| L2 | 83 (9) | 77 (15) | 8 (10) | 10 (11) | 0.21 (0.21) | 0.30 (0.26) |
| L3 | 77 (12) | 83 (10) | 18 (13) | 13 (13) | 0.46 (0.34) | 0.37 (0.37) |
| L4 | 68 (16) | 65 (20) | 25 (16) | 33 (24) | 0.65 (0.47) | 0.78 (0.53) |
| R5 | 86 (8) | 87 (12) | 12 (8) | 10 (12) | 0.32 (0.21) | 0.21 (0.21) |

It is important to note that such a clear and significant decrease was not found in Studies I and II. However, in these studies the part of the runs were always run under cognitive load and number of curves was smaller. In such a design, the runwise effect contains probably much more noise than in Study III. Also, the cognitive load may itself disturb learning, damping the learning effect.

# 5 Discussion

With vision, it is possible to guide locomotion in an anticipatory manner. This is very important in high speed locomotion, where consequences of collisions are potentially fatal. In car driving, gaze is used to sample visual information at anticipatory manner in two ways. These two ways can be conceptualized as guiding and look-ahead fixations. Guiding fixations give information supporting the action execution in just-in-time fashion, minimizing the information which must be kept in the working memory (Ballard et al., 1995). In look-ahead fixations, gaze is disengaged from the guidance of the current task phase, and directed toward the objects of location relevant for the future task execution, but quickly returned back to the guidance of the current phase of an action (Land et al., 1999; Pelz & Canosa, 2001; Hayhoe et al., 2003; Mennie et al., 2007).

In car driving, guiding fixations are understood to serve the online control of steering (Frissen & Mars, 2014). They are anticipatory in a sense that the visual information with a couple of seconds preview is used for the control of steering (Land & Lee, 1994; Mars, 2008; Wilkie et al., 2010; Lehtonen et al., 2014). This time preview gives enough time for motor programming and execution, and provides a visual buffer allowing short glances away from from the guidance of the steering (Land & Furneaux, 1997; Matthis & Fajen, 2014). When approaching and driving in curves with an open view over the curve, gaze often disengages from guiding fixations to look-ahead fixations toward the future road (Mars & Navarro, 2012; Lehtonen et al., 2012, 2013, 2014). Guiding fixations can be linked to the online control of steering as the look-ahead fixations are linked to the trajectory planning.

## 5.1 Main empirical results

When the fixation eccentricity distribution relative to the road ahead is analysed, the look-ahead fixations can be seen as a long tail toward the curve in the distribution. In other words, the guiding and look-ahead fixations in the visual control of steering cannot be easily separated based on the direction of the gaze. However, operational definition of the look-ahead fixations using a threshold relative to some road ahead reference direction, can be useful for characterising the cognitive processing underlying the gaze behaviour.

Anticipatory look-ahead fixations were frequently made both when approaching and driving within a curve. Results of Study III suggest that look-ahead fixations were most common near the entry point of the curve. In some curves, look-ahead fixations appeared to concentrate on certain locations, but in general the look-ahead fixations were distributed along the visible road so that the density of the look-ahead fixations decreased as the eccentricity increased. This pattern is consistent with the proposal that the look-ahead fixations server the trajectory planning. When approaching a curve along a straight road, there is plenty of time to pick up the relevant information. However, the closer the curve entry is, the more important it is to update this information, which explains the concentration of the look-ahead fixations near the curve entry. The current results cannot tell much about the nature of the trajectory representations. Apparently the entry, exit and beyond phases analyzed here are not clearly linked to the eye movements.

The effect of driving experience was investigated in a between-subjects experiment in Study III. Novice drivers had smaller dwell times on look-ahead fixations, and the effect was relatively large. Analysis of look-ahead fixations durations and frequencies indicated that the difference was mainly due to novice drivers' fewer number of look-ahead fixations rather than difference in duration of look-ahead fixations.

The effect of cognitive load was investigated with within-subject experiments in Studies I and II. In Study I, cognitive load was found to significantly decrease the percent dwell time on look-ahead fixations. In Study II, cognitive load had no significant effect on the dwell times. These mixed results can be due to different operationalization of the look-ahead fixations used in the studies, as well as in differences between the curve segments studied. In Study I, only highly eccentric fixations were classified as look-ahead fixations and only a straight segment before a curve was studied. The decrease in anticipatory look-ahead fixations under cognitive load would be in line with other studies, which have found that cognitively loading secondary tasks during driving lead to concentration of the gaze toward the road ahead (Victor et al., 2005; Recarte & Nunes, 2000). However, Study II found that look-ahead fixation landing locations shifted closer under cognitive load. Together these results suggest that cognitive load may affect the look-ahead fixations in curve driving, but it is not possible to say whether the effect predominantly decrease the total dwell time on look-ahead fixations or shift the look-ahead fixations closer along the trajectory. In both cases, the trajectory planning may get less information from the road far ahead, which can indicate less elaborated anticipation under cognitive load.

Additionally, route familiarity was found to decrease the dwell times on look-ahead fixations in Study III. This can be due to memorization of trajectory related information, making the look-ahead fixations less necessary.

## 5.2 Trajectory planning as part of the hierarchical control of driving

I have suggested that the anticipatory look-ahead fixations could be serving the trajectory planning. The trajectory planning constructs and updates the future trajectory, which the online control of steering attempts to accomplish. In Donges' (1978) framework, the trajectory planner would be the forcing function dictating the trajectory which the online control of steering — the guiding and stabilizing levels of steering — would follow.

A conceptual model illustrating the role of trajectory planning in control of steering is presented in Fig. 18. The model shows that trajectory planning is on a higher hierarchical level relative to the online control of steering, feeding it the trajectory to follow. The online control of steering produces the motor actions which actually control the vehicle, most importantly the steering wheel rotation and use of gas and brake pedals. Trajectory planner may monitor the tracking performance of the online control of steering, which provides feedback of steerability of the trajectory plan. Both the trajectory planner and the online control of steering uses both foveal and peripheral vision as sources of information. Peripheral vision can provide low resolution representation of the spatial environment and especially about the drivers' locomotion relative to the environment (Previc, 1998). On the other hand, foveal vision can supply high resolution information on restricted area, and supports better identification of objects and hazards (Muttart et al., 2013; Lamble et al., 1999b). The trajectory plan is also affected by higher level situation awareness, which includes the ability to detect and predict occurrence of hazards (Underwood, 2007). Additionally, memory of the route may supplement information to the trajectory planner.

In simple environments, the trajectory planning may function effortlessly. For example, on rural roads the trajectory can be perceived in affordance like fashion (Gibson, 1958), as the open road surface and the surrounding vegetation are in distinct contrast even at the level of visual stimuli. On the other hand, for example in city traffic, the trajectory planning must take into account complex information, including the predictions of the other road users actions and traffic rules.

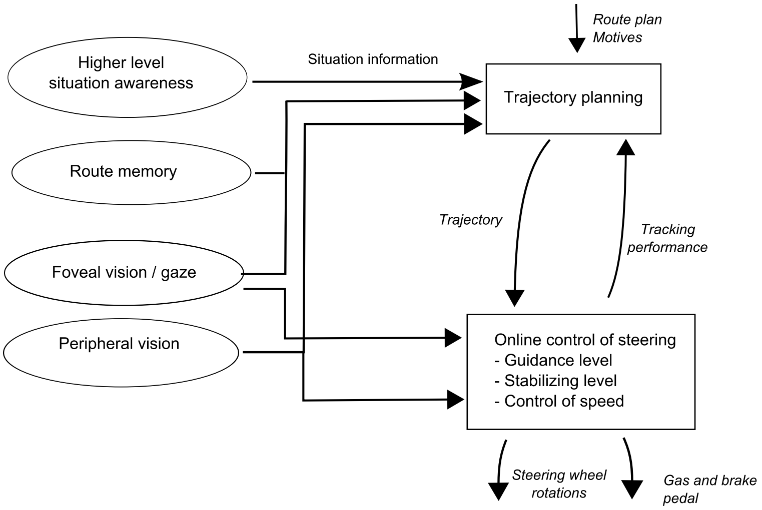


Figure 18. Conceptual model of hierarchical control of driving, which demonstrates the role of trajectory planning relative to the online control of steering and flow of information.

## 5.3 Allocation of gaze between online control and trajectory planning

In this thesis, I have investigated the guiding and look-ahead fixations in curve driving. The fixations can be interpreted as visual sampling of information. In human factors research, the multiple factors affecting the visual sampling of information has been identified (Senders, 1964; Horrey et al., 2006; Wickens et al., 2009). The sampling rate, i.e. the number of fixations per time, is determined by *expectancy* of the *bandwidth* of the information source. Bandwidth refers to the rate at which the information changes at the source, and expectancy is observer's representation of it. Visual sampling models can be elaborated by increasing the number of explaining factors. Visual salience may increase the number of fixations to a target. Value of some information can be higher than of some other, for example monitoring the road position is of higher value than monitoring the fuel consumption. In other words, value can be understood to reflect the priority of the information. Higher effort required to make a fixation can inhibit fixations to a target, for example effort can be high if a fixation requires a large saccade to eccentric location (Wickens et al., 2009).

Adaptive sampling behavior is needed in many tasks, because foveal vision can be thought as a single-server queue, which can provide information only for one component of the task at once if the their information is not spatially co-located (Horrey et al., 2006). In other words, the simultaneous information needs of different task components are in structural interference with each other, and this needs to be resolved through scheduling the access to the foveal information. Regardless the mechanism used in the scheduling, the sampling behavior can consequently interpreted to reflect the processing demands and priorities of the underlying task components.

The present results can be interpreted from the perspective of the visual sampling models, by interpreting that the online control of steering and the trajectory planning have different, even though most of the time spatially overlapping, information sources. In allocation of gaze, not only the number of fixations but also the durations of fixations matter. Fixations durations can be interpreted to depend on the amount of information processing needed, increasing when there is more information to process or the processing is slower. A shortcoming of such a visual sample model is that it does not account the influence of more complex time-sharing strategies. For example, for the best in-vehicle task performance and driving safety, drivers' should learn to optimize the length of the fixations to in-vehicle tasks (Wikman et al., 1998).

From the perspective of visual sampling models, experienced drivers' more frequent anticipatory look-ahead fixations compared to novices can be interpreted to indicate that 1) they have expectancy of higher rate of information regarding the future trajectory, 2) the value of the trajectory information is higher to them, or 3) the effort required to make eccentric fixations is lower to them.

All of these can be related to driving experience. Experienced drivers are generally considered to anticipate more, and be better able to predict what happens next (Underwood, 2007; Jackson et al., 2009). This can increase the expectancy of the rate of information at which the trajectory related information may change, and it may also lead to increasing value of such information. With experience, drivers may also learn better time-sharing strategies (Wikman et al., 1998) which makes the coordination of visual attention between multiple sources less effortful.

Furthermore, experienced drivers' greater automaticity in the online control of steering can decrease their need for foveal information in steering control. With experience the steering task can become more automatized, meaning that it requires either less visual monitoring (Fitts & Posner, 1967; Horrey et al., 2006; Sailer et al., 2005) or that it can increasingly rely on peripheral vision (Summala et al., 1996; Horrey et al., 2006). Interestingly, Mars & Navarro (2012) found a related effect when investigating the effect of steering automation in curve driving. When the need for online control of steering is removed, the look-ahead fixations over curves increased.

Studies I and II investigated the effect of cognitive load on anticipatory look-ahead fixations. The potential decreasing effect of cognitive load on look-ahead fixations could be understood as an increase in effort to make eccentric fixations linked to increased executive load (Anderson et al., 2008).

In the future, it would interesting to investigate the effect of road environment to the guiding and look-ahead fixation behaviour. It is known that in steepness of curves increase the visual demands of the steering task (Tsimhoni & Green, 2001). It would be expected that complexity of the trajectory would increase the need for more anticipatory information. For this purpose, simulator experiments with more control over the environment could be useful.

## 5.4 Practical implications

From practical point of view, road accidents pose the greatest challenge for traffic psychology. This thesis suggests that one cause of the young drivers higher rate of single vehicle curve accidents (Clarke et al., 2006; Abdel-Aty & Radwan, 2000) could be their less developed trajectory planning skills. As their skills are not yet fully developed, they probably underestimate the risks involved and are therefore more willing to satisfy other motives, like enjoyment of excessively high speed driving.

Investigation of trajectory planning is also in interesting relationship with the steering automation and automated vehicles. For example, will the lane-assistant system free the drivers to anticipate better their trajectory, or does it allow them to attend more to in-vehicle-tasks, resulting in decrease of trajectory planning and situation awareness in general? Also regarding the development of driver assistance systems which attempt to monitor the state of the driver using the eye movement data, it is important to recognize that some eccentric fixations are indeed part of the normal safe driving, and should not be interpreted to indicate distraction.

# 6 Conclusion

In this thesis, I have applied the conceptual distinction of guiding and look-ahead fixations to analyze the gaze behavior while driving a car through curves. I have shown that anticipatory look-ahead fixations are common in curve driving. However, the existing models of curve driving has almost exclusively focused on the processes which describe how the information relatively near the vehicle is transformed to steering actions. While limiting the scope of the models helps in developing and testing them, it may also restrict the perspective which is used to understand driving.

I have interpreted that the anticipatory look-ahead fixations over curves serve trajectory planning. Trajectory planning creates a desired path and speed, which the online control of steering attempts to follow. The trajectory can be understood to use both visual information regarding the road environment, but also on predictions of other road users, present or potential, future actions. Thus trajectory planning provides a way to understand the higher level anticipation, especially hazard perception, within the same framework with the online control of steering.

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