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Visual attention while driving: sequences of eye fixations made by experienced and novice drivers

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Eye fixations were recorded while novice and experienced drivers drove along three types of roads (rural, suburban and dual-carriageway). An analysis of the content of those fixations was performed in order to identify differences in the scanpaths that can be associated with skill acquisition and that can indicate a sensitivity to road type. This analysis itemized the part of the visual scene that was inspected with each fixation, and identified what the driver looked at as a function of what they had looked at previously. Single-fixation, two-fixation, and three-fixation patterns of eye-movements were identified. Differences in sequences of fixations were found between novice and experienced drivers on the three types of roads, with experienced drivers showing greater sensitivity overall, and with some stereotypical transitions in the visual attention of the novices. A number of individual sequences were identified, including a roadway preview pattern (alternating fixations between near and far views of the road ahead), and patterns involving mirror inspections that varied according to the road type.

1. Introduction

Young drivers have a high accident liability relative to those with just a few years of driving experience. Whereas 20% of 17–20-year-old drivers have an 'own fault' accident each year, the figure for 31–40-year-old drivers is 4.5% (Rolls and Ingham 1992). This suggests that as driving experience is acquired there is learning of something that helps drivers to avoid collisions, and so the concern is to identify the factor that is associated with learning to drive safely. This concern has prompted investigations of differences in the attitudes and actual roadway behaviour of those recently qualified and those who have been driving for a number of years (Underwood *et al*. 1997). The eventual aim of these investigations is to identify differences in the behaviour of novice and experienced drivers and then introduce a component of the driver training schedule that will help to accelerate the learning of skills associated with the behaviour of experienced drivers. One focus in this study of the roadway behaviour of novice and experienced drivers has been to record their eye fixations while they encounter different types of roads (Crundall and Underwood,

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1998) and while they perform lane-changing manoeuvres on multi-lane highways with different demands (Underwood *et al*. 2002a). Differences were found that are consistent with Lestina and Miller's (1994) study of road traffic accidents in California, in which the most frequently found contributory factor for young drivers was inattention. The allocation of visual attention was described as a major factor in the police reports analysed by Lestina and Miller (1994), with failing to search ahead, and failing to avoid distraction being characteristic problems for novice drivers. The driver training schedule developed by Chapman *et al*. (2002) takes account of this change in the allocation of visual attention as driving experience is acquired, and emphasizes visual scanning and the search for potential hazards.

Drivers may fail to allocate their attention optimally for a number of possible reasons that fall into two main categories which can be considered as endogenous and exogenous. An endogenous shift of attention would be prompted by the driver's knowledge of the current road and traffic conditions, including awareness of sources of important information such as hazards, and may anticipate problems that are about to arise. Reduced cognitive resources at times of high workload would adversely influence drivers' anticipations of emergent problems and their use of knowledge to avoid hazards. These hypothetical causes of an attentional problem in driving would be exacerbated by lack of experience. An exogenous shift of attention would be prompted by sudden changes in the visual field, such as another road user moving into the field of view, or an existing road user changing direction to an intersecting trajectory. The present paper focuses upon endogenous changes that are related to driving experience, although previous work has addressed the driver's recognition of sudden changes away from the part of the field currently inspected (Crundall *et al*. 1999, 2002). To investigate differences in endogenous shifts of attention, the approach taken in the present authors' studies has been to look at the fine-grained behaviour of novice and experienced drivers and to identify the specific components of visual attention that change as drivers acquire experience. In the study reported here, eye fixations were monitored to answer the question of where do drivers look next, given that it is known where they looked last. This provides a description of what it is that young drivers look at while driving as well as identifying the regularly occurring scanpaths that they make. This study looks for differences in the scanpaths used by novice and experienced drivers, and relates them to the task as is apparent on roads that make different demands of the driver.

In an exploratory study of the eye movements of groups of novices (observed within a few weeks of passing their driving test) and experienced drivers (averaging eight years since their successful test), Crundall and Underwood (1998) found a number of indicative differences during on-road driving. A fixed test route included three sections of main interest: a simple rural road with no intersections or sharp bends, with good distant visibility, and with light traffic; secondly, a congested suburban road that included a number of different types of junctions, pedestrian crossings, and other obstacles such as parking bays and bus stops; and finally, a section of dual-carriageway with slip roads entering and leaving both to the left and to the right. A number of differences were found in the eye movements of the two sets of drivers, with the most striking of these being the variance of fixations along the horizontal axis. On the dual-carriageway only, horizontal variance was greater for experienced drivers, and this indicated that these drivers varied the direction of their gaze more than the novice drivers on these roads. Unlike the novices, they were searching the roadway, possibly in response to the need to establish the presence of traffic in the other lanes in preparation for a lane-change, and in order to identify any developing hazards associated with merging traffic from the slip-roads. The analysis of fixation durations was also of interest, with experienced drivers showing long fixations on the rural road, where there were few hazards, and with novice drivers having long fixations on the dual-carriageway, where there were multiple hazards. On dual-carriageways the novices tended to look longer at a restricted area directly ahead of them with long gazes either on the road itself or on the leading vehicle.

This result prompted two studies designed to test the hypothesis that the novices were not looking around them under difficult driving conditions because they were unaware of the hazards that exist on dual-carriageways. Alternatively, they might have been cognitively overloaded and so unable to search for potential difficulties such as interweaving vehicles. In the first study the necessity of controlling a vehicle was removed (Underwood *et al.* 2002b), and novice and experienced drivers were shown video recordings taken from the driver's position in a car travelling along the same roads as were used in the Crundall and Underwood's (1998) study. If novices are aware of the dangers on a dual-carriageway, then their eye fixations should resemble those of experienced drivers when sat in a laboratory performing a hazard monitoring task while watching video recordings of drives. More fixations and greater variance of fixations were found when watching recordings of dual-carriageways than of other road types, but there were few differences between novice and experienced drivers in this experiment. On very demanding sections of dual-carriageway the novices scanned less than the experienced drivers. This suggests that when the cognitive load of vehicle control is removed, novice drivers look around them as much as experienced drivers, except when the driving scene is particularly complex. This supports the suggestion that novices inspect the roadway to a lesser extent than experienced drivers because they have an incomplete mental model, particularly of the dynamics of events on demanding roadways.

The driver's mental model may be likened to the idea of 'situation awareness' (Adams *et al.* 1995, Endsley, 1995), by which the driver keeps a dynamic record of the location, speed and heading of their own vehicle as well as others in the vicinity. This model of the current situation serves to inform decision-making processes concerning changes in direction prompted by navigational constraints and by the need to manoeuvre relative to other vehicles. Gugerty (1997) has further investigated the situation awareness of drivers, finding that their knowledge of other vehicles is largely explicit, with little contribution from implicit knowledge. Implicit processes would be expected to be involved in the control of the task when attention is focused on one car that is causing a change in our own direction, for example, and when a second car is present but not under close scrutiny. Our awareness of the second car may be said to be implicit if our manoeuvring takes account of its path while the focus of our attention remains on the car causing that manoeuvring. A second example of the use of implicit knowledge while driving comes during 'time-gaps' (Chapman *et al.* 1999), when the driver has no clear conscious recollection of the events of the last few minutes and appears to driving without full awareness of the driving environment. Gugerty's (1997) study of drivers' knowledge of spatial information used direct recall and indirect performance measures to demonstrate that implicit knowledge has little influence upon behaviour. The driver's mental model or situation awareness is constructed of knowledge that is largely accessible to verbal report.

The second test of the situation awareness hypothesis was performed on three sections of dual-carriageway not previously studied, with novices and experienced drivers given the task of making a lane-change (Underwood *et al.* 2002a). The three sections of road required the driver to move into an empty filter lane on the near-side, or to an empty lane on the offside, or into a lane of existing traffic on their offside. The extent to which the two groups of drivers consulted their internal and external mirrors while negotiating the lane-changes was recorded. The most appropriate source of information about existing traffic in the offside lane with competing traffic is the external door mirror, and so it was expected that drivers who are unaware of the complexities of dual-carriageways would have reduced inspection relative to more experienced drivers. Indeed, novice drivers did look into the external mirror less often than experienced drivers during all three sections, but on the dual-carriageway, as with the experienced drivers, they did increase the extent to which they used the external mirror. This result pointed to low-level differences in skill between the two groups of drivers, rather than differences in situation awareness. The reliance upon use of the internal mirror, by novice drivers, was possibly a consequence of the training practices that they had recently completed, whereby an exaggerated inspection of the internal mirror is often seen as being necessary to convince the driving examiner that the mirror has been consulted.

When the demands of controlling the vehicle were eliminated, the results indicated that novices generally looked around the roadway in a similar manner to experienced drivers, and their mirror inspections also showed some awareness of the task demands. Although an initial analysis of the areas of the world to which eye movements are directed can be of considerable value, it is not sensitive to the order in which different objects are fixated. It has been proposed that certain patterns of fixations are related to particular cognitive processes. Noton and Stark (1971a,b) for example have proposed that particular sequences of fixations at the time of initial object viewing are characteristic of the coding and later recognition of patterns. The idea that cognitive models of the world actively control specific scanpaths (e.g. Stark and Ellis, 1981) has been extended by Liu (1998) to the domain of driving. The present study uses Liu's methodology to further examine differences between novice and experienced drivers in their visual search. The study adopted the procedure described by Liu (1998, 1999, Liu *et al.* 1998), by which eye fixation sequences were determined for specific situations. Liu attempted to identify the sequences of fixations that were associated with specific intentions of the driver, such as overtaking and turning right. Two scanpaths were identified in these studies, one involving a preview of the road ahead, with fixations then returning to the roadway directly ahead of the vehicle, and one involving lateral transitions that were probably associated with vehicle positioning within the simulated roadway. In the present study the concern was to identify the scanpaths used by drivers of different experience and on roads that imposed different demands. Another principal difference between the present study and Liu's studies is that this study used natural driving on real roads that had unpredictable traffic conditions, whereas Liu used the simpler and controlled environment of a driving simulator. The results from the simulator may have reflected the artificial nature of the display and traffic behaviour, and so one of the purposes of the study was to attempt to confirm Liu's identification of scanpaths in natural conditions. The present study exploits the benefit of averaging across a sample of recordings taken from a sample of drivers who are observed on real roads, to identify general patterns of search in natural situations. Visual search in driving is susceptible to the resolution of the display in video, and therefore presumably, in simulator studies (Hughes and Cole 1986; Staplin 1995). Carter and Laya (1998) have reported some differences between the fixation patterns of drivers on a simulator and the same drivers on a test track, and the question arises of whether simulator studies can be used to provide reliable estimates of the behaviour of drivers when they use a natural road with all of the inherent variations in the design and incidental occurrence of fixed road features and in the behaviour of other road users. The primary purpose of the study was to identify the fixation sequences made by drivers of different experience, to answer the question of whether their different accident liability can be associated not only with their distribution of attention, but also with the subject of their attention.

2. Method

2.1. *Participants*

This study used the same 32 drivers described by Crundall and Underwood (1998). The sample consisted of 16 novice drivers (mean age 19:9 years, mean experience 0:2 years) and 16 experienced drivers (mean age 27:7 years, mean experience 9:0 years). The novice drivers were recruited with the help of the Driving Standards Agency, their contact information being collected at the time of their successful driving test, and the experienced drivers were recruited through an advertisement in a local newspaper. The local Ethics Committee gave approval for the project, and comprehensive motor and personal accident insurance was provided for all drivers. The participants were therefore not liable for any vehicle damage or for third party liability, but they were obliged to drive with legal constraints, and the task did not require them to violate any traffic regulations. All drivers were paid for their participation.

2.2. *Apparatus*

After a familiarization drive that used rural, suburban and dual-carriageway sections of road, and that lasted up to 20 min, the drivers were fitted with the head-mounted NAC EyeMark VII eye-tracker and then taken through a new route consisting of the same three road types. The output from the EyeMark was stored on NTSC video. All drivers used the same Ford Escort saloon vehicle used in the Crundall and Underwood (1998) study.

2.3. *Procedure*

Drivers generated eye fixation data on three types of roads, and a 1-min section was taken from each driver's recordings, to correspond with the same section of road used by Crundall and Underwood (1998). The video recordings were analysed frame by frame, after dividing the visual scene into 11 non-overlapping areas of interest: road near ahead; road near right; road near left; road mid ahead; road mid right; road mid left; road far ahead; road far right; road far left; mirror; other (including dashboard instruments, other objects inside the car, and roadway objects such as road signs, other vehicles and pedestrians). Liu's definitions of near, middle and far distance (up to 1 s ahead; 1 – 2 s ahead; more than 2 s ahead) were used in the analysis. As the study was conducted in the UK, in the following descriptions 'left' refers to the nearside relative to the car, and the 'right' refers to the offside.

3. Results

The output from the EyeMark eye-tracker consisted of a video-recording of the scene as viewed by each driver, together with a marker on the scene that indicated the location of the current fixation. These recordings were the subject of a frame-by-frame analysis to identify the subject of the driver's attention. The 1-min sections of recording were transcribed into a series of codes that corresponded to the locations of the fixations, to determine the frequency of fixating objects in the driver's scene on each of the roads. Table 1 indicates the mean number of fixations within each of the 11 specific areas of the scene during the sampling period.

The inspection data summarized in table 1 were entered into a mixed-design analysis of variance with three factors: driving experience (novices and experienced drivers), inspection zones (11 possible fixation locations) and road type (dual-carriageway, and rural and suburban roads). Experienced drivers did not differ from novices ($F < 1$), and there was no difference attributable to road type ($F < 1$). There was a reliable variation over inspection zones (F (10, 300) = 37.7, $p < 0.001$). The only reliable interactions involved the inspection of different parts of the scene on the three different roads (F (20, 600) = 3.18, $p < 0.001$).

The main effect of inspection zones was analysed using Scheffé comparisons. Only comparisons that were reliable at $p < 0.05$ or better will be mentioned here. The road far ahead (RFA) received more fixations than any other zone. A group of four zones did not differ from each other: road near left (RNF), road near right (RNR), mirrors (M) and other objects (OO). These four zones received fewer fixations than other

Table 1. The mean number of fixations in each of the 11 non-overlapping areas of the scene on each of the three roads during 1 min of sampling for each driver. *[Standard deviations of means are in brackets.]*

Road:	Rural		Suburban		Dual-carriageway	
Driver:	Novice	Experienced	Novice	Experienced	Novice	Experienced
Road near left	2.56	0.75	1.31	1.63	2.20	1.07
	[3.03]	*[1.24]*	*[1.74]*	*[2.31]*	*[3.30]*	*[1.28]*
Road near ahead	8.88	6.56	7.25	4.06	7.81	4.47
	[5.43]	*[9.09]*	*[6.36]*	*[4.36]*	*[6.97]*	*[3.70]*
Road near right	1.13	0.94	1.38	2.31	1.25	3.53
	[0.96]	*[1.48]*	*[1.45]*	*[2.21]*	*[1.06]*	*[3.74]*
Road mid left	10.63	11.56	14.38	19.13	9.19	12.67
	[5.81]	*[10.60]*	*[8.59]*	*[9.69]*	*[7.79]*	*[4.98]*
Road mid ahead	10.38	11.88	12.00	9.06	11.88	11.73
	[7.68]	*[10.73]*	*[8.95]*	*[7.78]*	*[7.53]*	*[7.69]*
Road mid right	7.75	8.38	11.13	14.63	8.56	11.27
	[6.38]	*[5.86]*	*[5.90]*	*[7.46]*	*[4.82]*	*[6.57]*
Road far left	9.94	8.94	7.13	11.56	8.56	9.67
	[7.30]	*[7.45]*	*[4.50]*	*[8.34]*	*[6.00]*	*[7.33]*
Road far ahead	21.94	16.75	19.56	23.56	19.50	22.13
	[13.58]	*[9.01]*	*[10.46]*	*[12.33]*	*[11.85]*	*[12.68]*
Road far right	6.94	9.75	10.06	14.00	9.69	11.93
	[3.60]	*[8.10]*	*[8.88]*	*[8.10]*	*[6.96]*	*[8.28]*
Mirrors	5.50	4.75	6.00	4.88	8.38	12.40
	[4.05]	*[3.84]*	*[3.48]*	*[3.93]*	*[5.07]*	*[7.07]*
Other objects	3.69	8.31	1.44	2.44	3.69	4.13
	[4.94]	*[22.02]*	*[1.79]*	*[3.35]*	*[3.38]*	*[4.85]*

zones. A second group of zones did not differ from each other: road near ahead (RNA), road mid left (RML), road mid ahead (RMA), road mid right (RMR), road far left (RFL), road far right (RFR), and mirrors (M). The overall pattern of differences of fixation on different parts of the scene is as follows, using a convention whereby zones that are joined by a common line did not differ in their frequency of inspection. In the following representations of the patterns of differences, the zone attracting the greatest number of fixations is listed on the left.

RFA RMA RML RMR RFR RFL RNA M OO RNL RNR

The interaction between zones and roads was first inspected with an analysis of simple main effects which found that zones varied on each road type (for rural, suburban and dual-carriageway respectively (F (10, 900) = 25.14, F (10, 900) = 27.38, and F (10, 900) = 20.11, all $p < 0.001$) and that roads produced variations in the inspection of four of the zones: RML (more fixations on suburban roads, F (2, 660) = 8.87, $p < 0.001$), RMR (more fixations on suburban roads, F (2, 660) = 3.84, $p < 0.05$), RFR (more fixations on suburban roads, F (2, 660) = 3.60, $p < 0.05$), and mirrors (more fixations on the dual-carriageway, F (2, 660) = 3.26, $p < 0.05$). The pattern of inspection differences on each road was similar to the overall pattern described above. RFA gained more inspections than any other zone, except on the suburban road when RML also attracted a large number of fixations. The pattern of differences for rural roads is represented as follows, where zones joined by a common line did not differ in the frequency of inspection:

RFA RML RMA RFL RNA RMR RFR M OO RNL RNR

The pattern of differences for suburban roads was as follows:

RFA RML RMA RMR RFR RNA RFL M OO RNR RNL

The pattern of differences for the dual-carriageway was as follows:

RFA RMA RFR RML RMR RFL M RNA OO RNL RNR

3.1. *Identifying two-fixation scanpaths*

A first-order Markov matrix was calculated for each road/driver combination using the fixation data, to indicate the location of the next fixation given that the current fixation is in a specified area of the scene. Six such matrices were calculated to reflect the two factor design, with drivers (novice/experienced) and roads (rural/suburban/dual-carriageway) as the factors. The transition probabilities within each matrix were evaluated by using a binomial test to calculate the z-score associated with each possible transition. This assumes that each part of the scene has an *a priori* equal probability of being inspected. The probability of each transition was determined as a proportion of all fixations within each area, and the expected probability of inspecting each part should be 0.1 given that there are 10 areas available when refixations within the same zone are excluded. The z-score describes the difference between this expected probability of fixation and the observed probability. Only the reliable transitions (two-tailed) will be mentioned here, and they are shown in figures

1–6. Transitions that are significant at the $p < 0.05$ level or better are shown by arrows between the first and second fixation locations. The assumption of equal probability of fixation can be questioned on the basis of slight variations in the distribution between zones shown in table 1. Although the analysis of variance indicated that these are not reliable variations, a second analysis of transitions was also performed using the actual distribution of fixation rather than an assumed equiprobable distribution. The same pattern of results was obtained when the observed distribution was used rather than an assumed equiprobable distribution.

On the rural road the novice drivers showed a simple pattern of fixations, whereby, in almost every case, whatever they look at on fixation N, then on fixation N + 1 they look at the road far ahead. The only exception to this generalization was when they were currently looking at the road far ahead. No other transitions were reliable. The experienced drivers showed a more variable scan pattern. There was less evidence of the dominance of the road far ahead, and inspection of other parts of the scene did occur contiguously. Reliable transitions are shown in figure 1 (novice drivers) and figure 2 (experienced drivers), where one of the striking features is the small overlap between the transitions common to the two groups of drivers. Both groups of drivers fixate the road far ahead having looked to the far right or to the far left, and having looked in the mirror they look far ahead, and having looked to the left they also look far ahead, but these are the only four transitions that they share.

The novice drivers again showed dominance of the road far ahead when driving on the suburban roads, but other sequences of fixations also emerged (see figure 3). The reliable two-fixation transitions involved inspection of the road far ahead after fixating the road near left/ahead/right, the road mid left, the road far left/right,

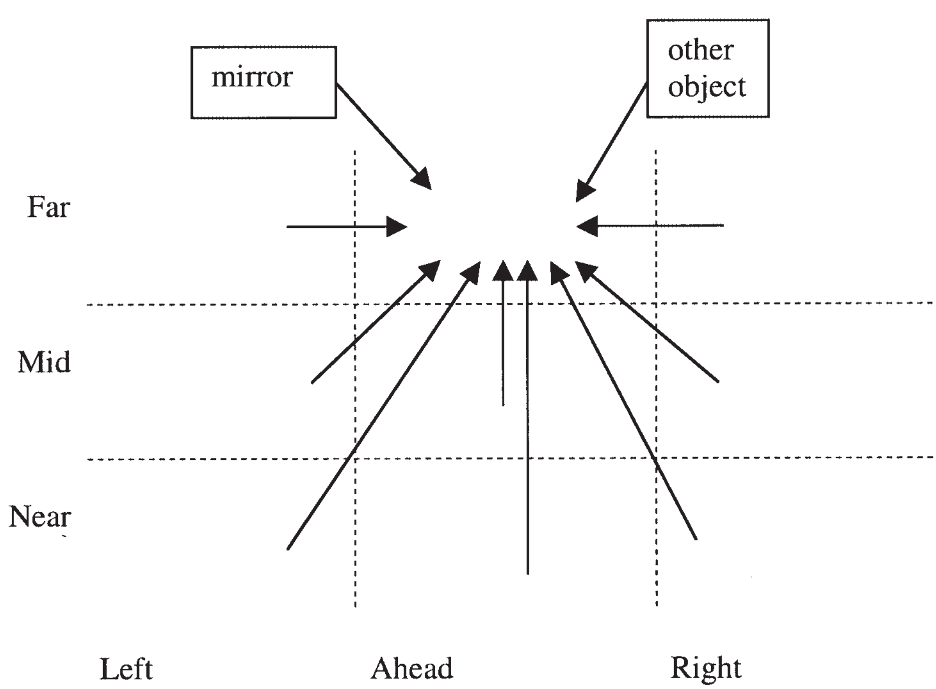

Figure 1. Rural road: Novice drivers

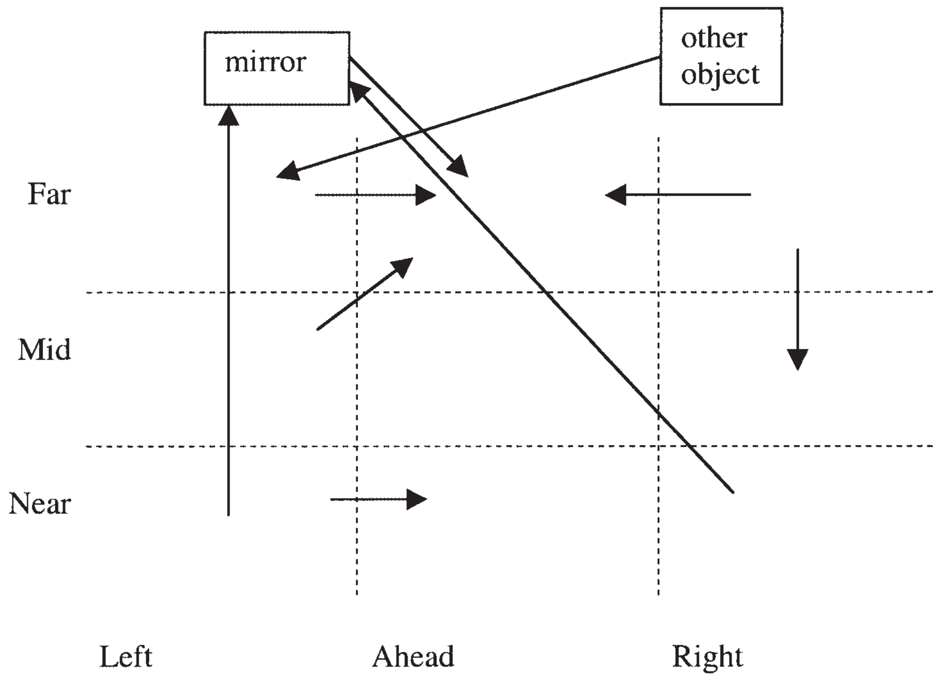

Figure 2. Rural road: Experienced drivers

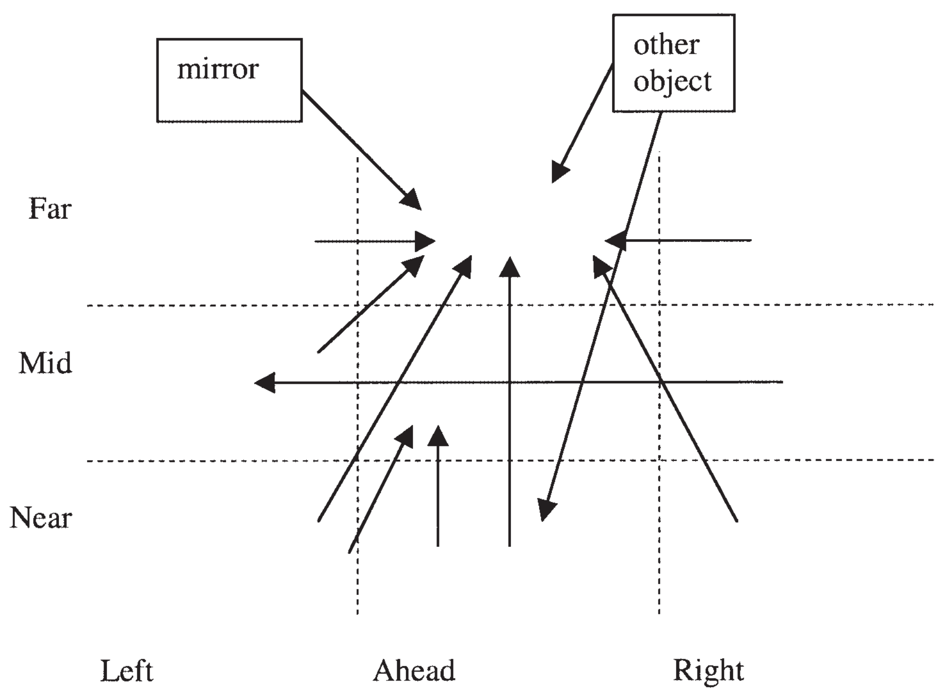

Figure 3. Suburban road: Novice drivers

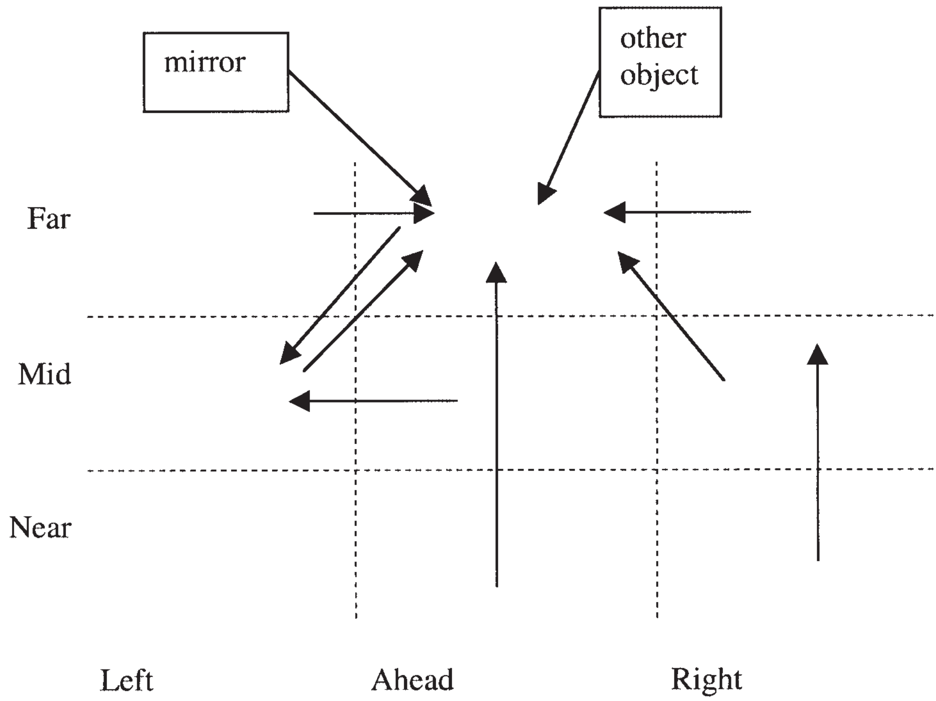

Figure 4. Suburban road: Experienced drivers

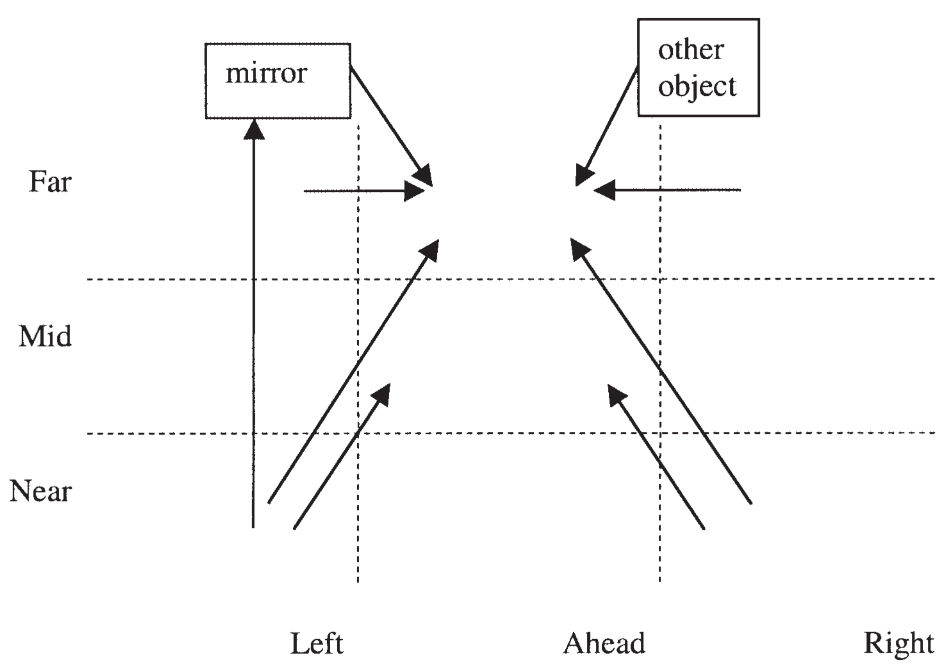

Figure 5. Dual-carriageway: Novice drivers

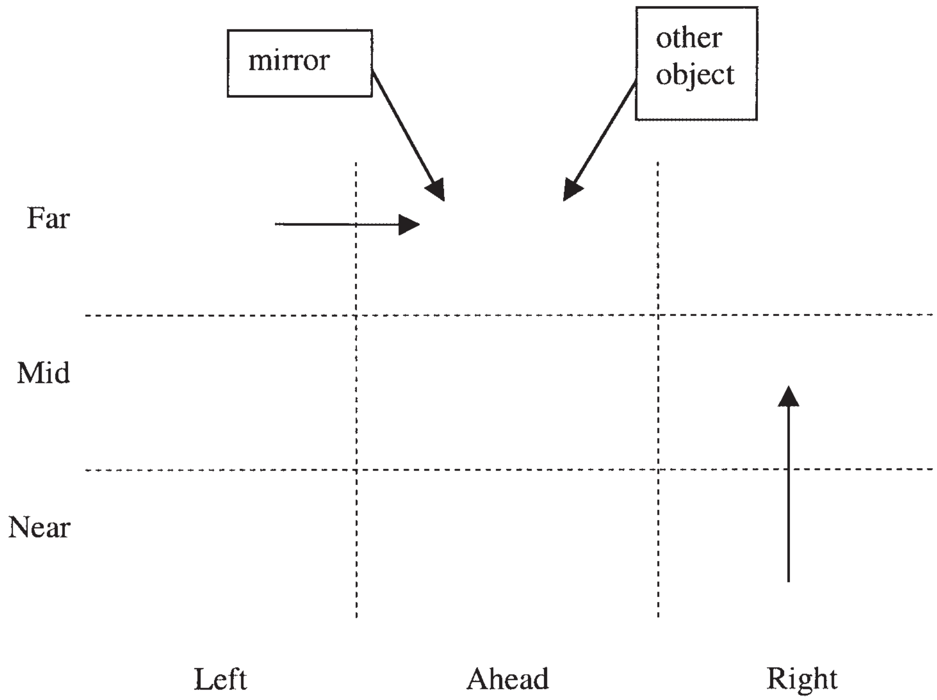

Figure 6. Dual-carriageway: Experienced drivers

mirrors, and other objects. This pattern is similar to that seen on the rural road, with minor differences including a horizontal sweep from the road mid right to the road mid left, and fixation upon the road mid ahead following fixation upon the road near left/ahead.

The fixation sequences of experienced drivers were more varied on suburban roads (see figure 4), but with a dominance of the road far ahead again in evidence. This preview or focus of expansion zone was fixated reliably after fixating the road near ahead, the road mid left/right, the road far left/right, mirror, and other objects. Apart from transitions to the road far ahead, there were also transitions between the road near right and the road mid right, from the road mid ahead to the road mid left, and from the road far ahead to the road mid left. In addition, it should be noted that the transitions between the road far ahead and road mid left were reciprocated. This indicates the significance of these two locations for the experienced drivers, with multiple transitions between them.

The novice drivers again showed dominance of the road far ahead when driving on the dual-carriageway (see figure 5). The fixation sequences of experienced drivers on the dual-carriageway are notable by their absence, relative to the other roads (see figure 6). There were just four two-fixation sequences, relative to 10 on suburban roads and nine on rural roads for these drivers. This indicates the variability of their search patterns on dual-carriageways, with no dominant sequences.

3.2. *Identifying three-fixation scanpaths*

Three-fixation sequences could be identified from combinations of the two-fixation transitions described above, but this would have no theoretical or statistical basis.

Suppose drivers fixated Zone N followed by Zone P on a regular basis, and they also fixated Zone P followed by Zone Q on a regular basis. It would seem likely therefore that they would show a three-fixation scanpath between Zones N, P and Q. It is quite possible, however, for frequent N-P transitions and frequent P-Q transitions to be not associated with N-P-Q transitions, if P-Q never occurs immediately after N-P. Rather than relying upon combinations of two-fixation sequences, it is necessary to identify the three-fixation sequences separately. The procedure for comparing potential scanpaths in the fixations of the novice and experienced drivers was to identify scanpaths reported by Liu *et al*. (1998), and in addition any that were shown by at least one group of drivers on at least one of the road types. Liu and his colleagues have identified a preview scanpath involving glances to the road far ahead, and lateral transitions in which deviations from an optimal inspection position are made to the right and to the left. The following comparisons are of three-fixation scanpaths that appeared most frequently, and the purpose is to compare their selection by novice and experienced drivers rather than to catalogue all possible scanpaths that could appear.

Five scanpaths involving three fixations were identified by this procedure. The first three of these start and end with fixation on the road ahead at middle distance, and can be characterized as fixation from an optimal viewing position to another part of the road scene and then back again. These three scanpaths are:

(road mid ahead ⇒ road far ahead ⇒ road mid ahead)
(road mid ahead ⇒ road mid left ⇒ road mid ahead)
(road mid ahead ⇒ road mid right ⇒ road mid ahead)

The other two scanpaths involved inspection of the rear view mirror:

(mirror ⇒ road far ahead ⇒ mirror)
(mirror ⇒ road far ahead ⇒ road mid ahead)

The one-minute samples of fixations were used to determine the frequencies of these scanpaths for the two groups of drivers on the three types of roads, and these frequencies are presented in table 2. These frequencies were entered into a series of separate analysis of variance calculations, to determine differences between drivers in the use of the five scanpaths on the three different roadways. Each of these mixed-design analyses had two factors: driving experience (novice and experienced drivers) and road type (dual-carriageway, and rural and suburban roads).

The analysis of the number of 'road mid ahead ⇒ road far ahead ⇒ road mid ahead' (RMA-RFA-RMA) scanpaths showed no effect of driving experience ($F < 1$), but there was an effect of road type (F (2, 60) = 4.05, $p < 0.05$). The interaction was not reliable ($F < 1$). Scheffé tests were used to identify the differences between road types in the frequency of this scanpath, with the only difference being that they were more frequent on rural rather than suburban roads ($p < 0.05$).

Driving experience did not influence the frequency of the 'road mid ahead ⇒ road mid left ⇒ road mid ahead' (RMA-RML-RMA) scanpath (F (1, 30) = 1.18), and neither did road type appear as a main effect ($F < 1$), but the interaction between these two factors was reliable (F (2, 60) = 4.75, $p < 0.05$). An analysis of simple main effects was used to inspect this interaction. Driving experience was a reliable factor, but only on rural roads (F (1, 90) = 8.69, $p < 0.01$), where experienced drivers used

Table 2. Mean frequencies of the reliable three-fixation scanpaths during 1-min sampling periods. *[Standard deviations of means are in brackets.]*

Road:	Rural		Suburban		Dual-carriageway	
Driver:	Novice	Experienced	Novice	Experienced	Novice	Experienced
RMA⇒RFA⇒RMA	0.63	0.94	0.06	0.25	0.63	0.63
	[0.72]	*[1.57]*	*[0.24]*	*[0.45]*	[1.15]	*[1.09]*
RMA⇒RML⇒RMA	0.63	2.00	1.25	1.28	1.4	1.13
	[0.88]	*[1.37]*	*[1.57]*	*[1.38]*	[1.26]	*[1,36]*
RMA⇒RMR⇒R-MA	1.00	3.13	0.69	1.06	0.56	1.68
	[1.03]	*[1.56]*	*[0.70]*	*[1.65]*	[0.81]	*[0.96]*
M⇒RFA⇒M	0.13	0.06	0.00	0.06	0.63	1.38
	[0.50]	*[0.25]*	*[0.00]*	*[0.25]*	[1.15]	*[1.68]*
M⇒RFA⇒RMA	0.63	1.5	1.12	0.56	0.69	1.38
	[0.72]	*[1.71]*	*[1.06]*	*[1.03]*	[0.70]	*[1.50]*

Key: M, mirror; RMA, road mid ahead; RML, road mid left; RMR, road mid right; RFA, road far ahead; RFR, road far right.

this pattern of fixations more than novices. No other simple main effects were reliable.

The analysis of the 'road mid ahead ⇒ road mid right ⇒ road mid ahead' (RMA-RMR-RMA) scanpaths showed a number of differences. Driving experience appeared as a main effect (F (1, 30) = 21.20, $p < 0.001$) with experienced drivers using the scanpath more often than novices. Road type also influenced the use of this scanpath (F (2, 60) = 10.18, $p < 0.001$). The interaction between experience and road type was also reliable (F (2, 60) = 6.17, $p < 0.01$), and was inspected with an analysis of simple main effects. Only experienced drivers showed differences between road types (F (2, 60) = 14.53, $p < 0.001$), and Scheffé tests indicated more of these scanpaths on rural roads relative to suburban and dual-carriageways (both comparisons at $p < 0.01$). The novices showed no variation between roads. Simple main effects comparisons between experienced and novice drivers showed experienced drivers using the scanpath more than novices on the rural road (F (1, 90) = 32.16, $p < 0.001$) and on the dual-carriageway (F (1, 90) = 7.38, $p < 0.01$), but no difference between drivers on the suburban road ($F < 1$).

Two scanpaths involved use of the rear view mirror. The analysis of the 'mirror ⇒ road far ahead ⇒ mirror' (M-RFA-M) scanpath indicated a main effect of road type (F (2, 60) = 13.10, $p < 0.001$) but no effect of driving experience (F (1, 30) = 1.85) and no interaction (F (2, 60) = 2.15). Scheffé tests indicated that the effect of road type resulted from increased use of the scanpath on the dual-carriageway. On this road there were more M-RFA-M transitions than on rural roads and on suburban roads (both comparisons at $p < 0.001$).

The 'mirror ⇒ road far ahead ⇒ road mid ahead' (M-RFA-RMA) scanpath showed no differences between drivers (F (1, 30) = 1.35) or roads ($F < 1$), but there was an interaction between these two factors (F (2, 60) = 4.39, $p < 0.05$). An analysis of simple main effects showed greater use of the scanpath by experienced drivers in comparison with novices on the rural road only (F (1, 90) = 4.38, $p < 0.05$). For novice drivers there were no differences in the use of the M-RFA-RMA scanpath on different roads ($F < 1$), but experienced drivers used the scanpath selectively according to the road they were using (F (1, 90) = 4.38, $p < 0.05$). Scheffé tests were used to inspect this selective use of the scanpath by experienced drivers, and showed that it was used more on rural roads than on suburban roads ($p < 0.05$), with no other reliable contrasts.

4. Discussion

When comparing the parts of the scene inspected by novice and experienced drivers different conclusions are drawn according to whether the analysis is conducted using single fixations, two-fixation transitions, or three-fixation scanpaths. The scene available to the driver was divided into nine areas of the roadway, plus the rear view mirror, and a category of other objects within and outside the vehicle that included the driving instruments and other road users. Comparisons of the single fixations made on these 11 parts of the scene, and on the three types of roads, revealed no systematic differences between drivers. On the different roads different parts of the scene attracted the driver's attention to different extents. The road far ahead (RFA) and mid ahead (RMA) attracted more fixations than any other part of the scene, and the road near left (RNL) and road near right (RNR) tended to attract fewer fixations than other parts of the scene. Mirror inspections increased on the dual-carriageway. However this simplistic analysis fails to capture the complex behaviour of driving, in which moment-to-moment actions are strongly influenced by events in the immediate past. The analysis of sequences of fixations determined those transitions that appeared most frequently, and those that distinguish the behaviour of novices and experienced drivers.

The two-fixation transitions often included these components of the scene, but differences between drivers are also apparent. The dominance of the road far ahead is especially noticeable in the behaviour of the novices. Two stereotypical sequences appeared on all roads. First, having looked in the mirror both groups of drivers then looked at the road far ahead (RFA). Fixation of other objects such as other road users also terminated with fixation of the RFA on many occasions. Whenever drivers looked away from the road it is then invariably refixated at the point that delivers maximum preview. Novices had more transitions that resulted in fixation of the RFA, suggesting that they were more concerned about the amount of time spent looking elsewhere. Alternatively, perhaps the experienced drivers were able to use peripheral vision to monitor events on the road ahead, allowing them to fixate elsewhere for longer. The second invariant transition was from the road far left (RFL) to the RFA, again reflecting the important of maximum preview of the road way ahead and the objects that may require further attention.

In the analysis of the three-fixation transitions the road far ahead again appears as a destination location, but also as a starting location. One group of transitions showed the significance of the road mid ahead rather than the road far ahead. The road mid ahead—the section of road that the driver would encounter one or two seconds later—was the starting and finishing point for a number of transitions that might be characterized as being a scanning strategy. Between fixations on the road mid ahead, there were fixations on the road far ahead, the road mid left and the road mid right. There was a tendency for experienced drivers to use this strategy more than novices, and also for the strategy to be used less on suburban roads. The other two scanpaths involved inspection of the rear view mirror followed by the road far ahead. Having checked the mirror, the drivers then checked the road, and then looked either in the mirror again or at the road mid ahead. Drivers returned to the mirror more frequently on the dual carriageway, and experienced drivers were more likely than novices to terminate the sequence by looking at the road mid ahead.

Liu and his colleagues found a dominance of the road ahead in their analyses of fixation sequences made in a driving simulator, with frequent fixation of the road a few seconds ahead (Liu, 1998, 1999, Liu *et al*. 1998). Drivers negotiated straight and curved roads with and without leading cars, but the view was restricted to the simulated road ahead. Two-fixation sequences between the road near ahead and the road far ahead were attributed to a preview strategy, and there was some evidence of transitions from side to side that were attributed to being necessary for steering control. When a lead vehicle was displayed there were also transitions to and from that vehicle as well as preview transitions. The significance of preview transitions is confirmed in the present study in which actual roads were travelled. However, a number of other transitions were observed, and these are associated with the complexity of the road scene and with natural events and objects that are found on different types of roads. The appearance of a richer number of two- and three-fixation sequences in the present study must be attributed to the use of natural driving and of course to the availability of the rear view mirror in the present study. Liu also reported frequent lateral transitions in his studies, but it was only on suburban roads that they appeared with regularity in the present study. The unfamiliar environment of the simulator, with unknown vehicle handling characteristics, may have induced more reliance upon road markings for steering than is observed on actual roads. The appearance of lateral transitions on the suburban roads, in the absence of these patterns on the other roads, suggests that they are not necessary to collect information for steering. They are more likely to be responses to the appearance of pedestrians near to the road edge.

The dominance of a preview strategy is indicated in table 1, which shows the number of fixations on different parts of the visual scene, during a 1-min sampling period. Both novice and experienced drivers made approximately twice as many fixations on the road far ahead as they did upon anything else in view. The two-fixation transitions represented in figures 1 – 6 confirm the significance of the road far ahead. More than twice as many eye movements resulted in a fixation in this zone, in contrast with any other part of the scene. Of the reliable two-fixation sequences, 37 of them resulted in a fixation on the road far ahead, and the remaining 16 resulted in fixations elsewhere (four of which were on the road mid ahead). An extreme example of this strategy is shown in figure 1, where the transitions of novices on rural roads are dominated by fixation of the road far ahead. There are 10 two-fixation transitions in the analysis of the distribution of attention of these drivers, and each one of them results in fixation of the preview zone. The novices were generally more extreme than the experienced drivers in their preference to fixate the road far ahead, with 24 of the significant transitions to the road far ahead, in comparison with 13 transitions in the fixation behaviour of the experienced drivers. In contrast with the dominance of the far preview, Mourant and Rockwell (1972) found that novices tended to fixate the road immediately in front of the car. The novices in the present study fixated this part of the scene infrequently (see table 1). The difference between these conclusions is perhaps attributable to different drivers tested. Mourant and Rockwell observed very naïve drivers who did not have a driving licence, and who had no more than 15 min of driving experience, whereas all of our drivers possessed a licence. Novices unfamiliar with vehicle handling characteristics would need to attend closely to the position of the vehicle relative to the road markings, and this would be achieved by regular fixation of the road directly in front of the car. The greater variety of scanning behaviour of the experienced drivers is illustrated by the differences in the figures showing the two-fixation transitions. On the rural road the transitions terminated with fixation upon five different parts of the scene, in contrast with the novices terminating in just one zone.

On the dual-carriageway, the novices continued to show a dominance of the road mid ahead and the road far ahead, whereas the experienced drivers showed relatively few transitions. This helps to clarify the pattern reported by Crundall and Underwood (1998), who analysed the present data for overall measures of fixation durations and variance of locations without analysing the objects of the drivers' fixations in the scene available to them. On the dual-carriageway, for example, the experienced drivers showed more extensive scanning in the horizontal plane, with extensive left/right fixation patterns indicated by increased variance of fixation locations. The present analysis of fixated objects, found remarkably few reliable sequences of fixations. The global measure of horizontal variance appears to be an indication of the variability of the fixation behaviour of these drivers. Their scanning behaviour is perhaps best characterized as being sensitive to whatever traffic conditions prevail on this section of roadway that has fast-moving vehicles merging from both left and right. Stereotypical behaviour is not appropriate on this road, given that the behaviour of other road users is not particularly predictable. The analysis of single fixations showed an increase in mirror use on the dual-carriageway, but no interaction with experience. This is important, since it suggests that the greater fixation variance reported by Crundall and Underwood (1998) was not due solely to mirror checking by the experienced drivers.

Novice drivers often fixated the road mid ahead (RMA) after fixating the road immediately to the left (RNL) or to the right (RNR) of the car on the dual-carriageway. These transitions may result from perceptual narrowing under high cognitive load. The novices may have been less able than the experienced drivers to read the lane markings with peripheral vision, thereby necessitating fixation on the markings directly. The central scene, with fixation and refixation of the road ahead, dominated the attention of the novices. Novices are less able than experienced drivers to detect peripheral targets under demanding conditions (Miura 1990, Crundall *et al.* 1999), and this limitation may prompt them to refixate the central field rather than to rely upon their peripheral vision.

The three-fixation scanpaths again involved inspection of the road far ahead but provided a more sensitive measure of road and driver differences. For novices, there were fewer three-fixation scanpaths evident on rural roads, where drivers tended to look straight ahead. The experienced drivers checked the road ahead after looking in the rear view mirror on these roads. The transitions of novice and experienced drivers were most similar on suburban roads, where Crundall and Underwood (1998) reported similar durations of fixations for the two groups. On rural roads they reported experienced drivers to have longer fixations than novices. The shorter fixations of novices were possibly a result of the continuing need to refixate the RFA after looking at anything else, with fixation away from the RFA curtailed after a critical interval that was shorter for these drivers

Liu's simulator studies found fixation sequences characterized as a preview strategy, and the present analyses confirm the appearance of these sequences in natural driving. Fixation sequences involving mirror inspections also appeared in the present analyses, whereas the simulator did not have a driving mirror available. There was more variability in the two-fixation sequences of experienced drivers, especially on the dual-carriageway, suggesting that the monitoring of other road users is a production of experience and that novices have little ability to switch the focus of their attention as potential hazards appear. The eye movements of the experienced drivers were prompted by events as they occurred, with a meaningful search for other vehicles as they interweaved and entered the driver's own zone of activity. The two-fixation transitions of novices are dominated by a preview strategy, with the next fixation on the road ahead wherever they are looking at the present time.

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