Exp Brain Res (2007) 180:1–14
DOI 10.1007/s00221-006-0839-2

RESEARCH ARTICLE

Eye–steering coordination in natural driving

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Received: 27 April 2006 / Accepted: 28 November 2006 / Published online: 26 January 2007

Abstract When driving along a winding road, eye movements and steering are tightly linked; the driver looks across to the inside kerb of an approaching bend some time before turning the steering wheel. With the eyes leading, the oculomotor controller assists the neural centres controlling steering; prevention of any eye movements correlated with steering impairs driving, so the coordination is crucial for safety. A key question is therefore what are the limits of acceptable variation in timing and degree of coordination. Over a period of continuous driving on the open road, how much does the relative timing and degree of coordination between eye and steering movements vary? A related question is how brief a period of driving will suffice to measure these coordination parameters. Drivers' eye movements and steering were measured over different time periods ranging from 15 s to 6 min epochs of natural driving along a winding country road to establish the variability in coordination and the minimum time period required to characterise it. We show here that brief periods of driving, 30 s or less, are inadequate for describing eye–steering coordination. But a minute of driving yields an accurate description much of the time; and 2 min is sufficient both to accurately describe this relationship and to show that it is highly consistent for a given individual, and for different people driving the same route.

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Keywords Eye movements · Steering · Driving · Coordination

Introduction

Driving is an everyday example of visually guided behaviour in which the eyes move just before and coordinated with another action (steering). The degree of coordination and relative timing in such situations seriously affects performance of the action (Miall and Reckess 2002); individuals who cannot move their eyes appropriately perform badly (Van Donkelaar and Lee 1994; Crowdy et al. 2000) but can improve their performance if they first improve their eye movements (Crowdy et al. 2002).

Eye movements and fixation patterns when driving have been studied for several decades (Mourant and Rockwell 1970; Shinar et al. 1977; Cohen and Studach 1977; Kito et al. 1989; Land and Lee 1994). These studies show that during normal driving, eye movements and the task of steering are closely related. On approaching a bend, the driver looks across to the inside kerb half a second or more before turning the steering wheel (Land and Lee 1994); the horizontal component of gaze is attracted to and lines up on this 'tangent point'. All experienced drivers naturally adopt this coordination without instruction (or being aware of it). This suggests both that it represents 'optimal' coordination, and that it reflects and yields insight into the way in which the CNS has solved the problem of steering along a winding road.

'Tangent point steering' was convincingly demonstrated by Land and Lee (1994). Their study revealed that a driver tends to use the tangent point of an up-coming corner to direct the car, with gaze over or within 3° of the tangent point almost all (>75%) of the time, although other features of interest or importance were also sometimes fixated. Technological advances in spatial accuracy and sampling rate of car-based eye trackers have now enabled us to undertake a full quantitative analysis of the relationship between eye movements and steering using powerful signal processing and statistical techniques. Importantly also our eye tracker is remote from the driver (non-intrusive) and so less likely to affect their driving; although this benefit comes at the cost of a narrower range of eye movements that can be tracked, which would mean a head-mounted device might be preferable if studying for example gaze behaviour at junctions.

The tangent point on a bend is displaced from the direction the car is heading by an angle that reflects the curvature of the road. Land points out that fixating it might permit computation within the CNS of that visual angle which will relate directly to how much the steering wheel should be turned. Fixating the tangent point therefore yields *visual information* that could guide steering (Land and Lee 1994; Land and Horwood 1995; Land 1998). During most driving situations the driver is constrained to a 'line' around a corner that involves keeping the car in a lane and safely on the road. As the driver moves into the bend the road margin or kerb therefore forms a relevant and obvious point of reference for any steering. Marple-Horvat et al. (2005) found in a realistic driving simulation that if drivers' usual, optimal coordination was disturbed by making them look straight ahead their driving performance was seriously damaged or impaired, again indicating that this usual pattern of eye movements correlated with steering is crucial for driving performance; disruption of coordination impairs driving ability.

The observation that eye movements precede actions in many situations, including driving, suggests an alternative or additional explanation beyond Land's framework as to how fixating the tangent point assists steering, in terms of *motor control mechanisms* underlying coordinated actions. We have proposed (Marple-Horvat et al. 2005; Wilson et al. 2007) a movement centred framework which, regardless of precisely which visual cues are used to guide movement, acknowledges and identifies the benefit of moving one body part—the eyes—for moving another. Because the eyes lead, the oculomotor controller represented by the collected neural centres controlling eye movements can assist the neural centres controlling steering. Thus, the varying left–right rotation of the eyes-in-orbit as they move to bring the horizontal component of gaze to the tangent point and maintain fixation by smooth pursuit also defines the evolving left–right angle required for steering, and so is a useful driving input to the steering controller. That horizontal eye movement signal could be provided in several ways; either by sensory feedback from the external ocular muscles, or by efference copy of oculomotor controller output (Sommer and Wurtz 2002), or by predictive estimation from an internal forward model of the eye. The idea of linked controllers and a beneficial influence from the oculomotor controller onto other controllers fits well with current frameworks for understanding coordinated movement involving different parts of the body and the role of the cerebellum, where such coordination is most likely established (Miall 1998; Miall et al. 2000; Miall and Reckess 2002).

If eye–steering coordination is as crucial as experimental observations and this theoretical framework suggest, and indeed closely reflects the way in which the CNS solves the problem of steering along a winding road, with the eyes leading, and the oculomotor controller assisting the neural centres controlling steering, then we might expect this coordination to be relatively invariant, or well-preserved and consistent during natural driving. We therefore present here quantitative measures of eye–steering coordination over driving epochs spanning the range 15 s to 6 min.

Our perspective is therefore that coordinated eye and steering movements represent much more than just the preferred solution to the motor control problem of steering along a winding road; they are crucial for driving performance. We seek to confirm during natural driving our evidence from a realistic driving simulation that moving the eyes (or the act of looking) contributes as much benefit for steering as the visual information the eyes move to acquire (Wilson et al. 2007).

We present here evidence that eye–steering coordination is consistent in natural driving on the open road. It is important to be able to define this *usual or optimum* eye–steering coordination while driving as a precursor to identifying *unusual or impaired* coordination, which may be as a result of pharmacological factors such as alcohol, illegal or prescription drugs, or physical factors such as fatigue.

Methods

Subjects

Ten individuals took part in the study (5 male, 5 female), ranging from 21 to 23 years of age (mean 21.3;

SD 0.54). All were qualified drivers, had not committed any road traffic offences that resulted in penalty points being placed on their licence, and were able to drive without any restriction due to a medical condition. All could also drive without the use of corrected vision (i.e. spectacles, contact lenses or sun glasses). Local ethical committee approval and written informed consent were obtained prior to testing.

Driving task

The task involved driving a 5 mile section of a 'B' designated road between Alsager and Crewe (B5077 Cheshire, UK). Each participant completed a familiarisation drive before undertaking the recorded test drive; this consisted of a 20 min drive around an area close to the test route. Once the participant was familiar with the car's handling he or she was asked to drive to the start point of the test and commence the route that had been earlier discussed. The subject was asked to drive to a certain point (a roundabout 2.5 miles away) and then return along the same road in the opposite direction, following the traffic laws, including speed limits, at all times. Testing was conducted during the hours of daylight (street lights off) and never in adverse weather conditions (ice, snow, sleet or fog).

Data acquisition

During driving, the horizontal and vertical components of subjects' eye movements were monitored using an ASL ETS PC II car-based eye tracking system (Applied Science Laboratories, Bedford, Massachusetts, USA) mounted in the dashboard of an Alfa Romeo 156: Fig. 1. The eye position signals (horizontal and vertical) provided by the ASL system as supplied were digital data streams at 50 Hz. We took these outputs and D/A (digital to analog) converted to produce true analog signals (but of course with zero frequency content above the Shannon frequency of 25 Hz). These analog signals representing horizontal and vertical component of any eye movements, were calibrated to 1° accuracy before driving using 21 equally spaced calibration points covering an area of 2 m × 8.5 m

Fig. 1 A montage of pictures showing the equipment inside the car and their positions relative to the driver. **a** The optics module of the ASL ETS PCII, situated in the dash board. **b** CCTV scene camera that provides a view of the road ahead. **c** View of an eye recognition file. The *red circles* are the inner and outer boundaries set by the eye tracker pattern recognition software for acceptance of a dark disc as the pupil. The *green circles* define the acceptable boundaries for the size of left and right bright corneal reflections. The *coloured rectangles* define the areas within which the pupil and right (as seen in this image) corneal reflection must be found in order to be accepted. The location and size of these bounded regions can be changed by the experimenter to tailor to an individual subject's eye and exclude stray reflections. **d** Position of researcher and data collection equipment in the test car. **e** Position of infra-red illuminators and optics module relative to the driver

(height × width) and viewed by the driver (in driving position with hands on the steering wheel) at a distance of 13 m, so subtending visual angles of 8.8° and 36.2°, respectively.

During driving, the analog eye movement signals, together with analog signals from other sensors measuring steering, acceleration and braking, were fed into a CED 1401 A/D converter (Cambridge Electronic Design, Cambridge, UK) sampling at 200 Hz. This was to maintain consistency with earlier studies and to provide timing accuracy (e.g. onset of braking) to 5 ms if needed. The eye movement signal was therefore safely over-sampled; indeed analysis subsequently revealed (see "Results") that no signal had much power above 10 Hz.

In summary, all signals were fed with the same sampling rate from the CED 1401 into the on-board computer for subsequent cross-correlation and Fourier analysis (using Spike 2 CED software). All signals were safely over-sampled to ensure no loss of signal content. Following cross-correlation and Fourier analysis it became clear that the power in both steering and eye position signals was confined to much lower frequencies. (This was confirmed by re-analysing after first down-sampling all raw data files to 50 Hz; cross-correlation and time lead values were identical to three significant figures, and Fourier transforms were identical up to 25 Hz).

The ASL eye tracker control unit also generated on a flat screen monitor attached to the rear of the front passenger seat head rest and so visible only to the experimenter (in the rear near-side seat: Fig. 1) cross-hairs representing the horizontal and vertical coordinates of gaze superimposed on the driver's view of the road through the windscreen. This scene plus gaze output was recorded on videotape. The picture of the scene ahead was collected by a forward pointing CCTV camera placed next to the drivers head, to the left of and just behind the driver's tracked left eye (Fig. 1). The calibration process incorporated defining the rear view mirror and top of the dashboard so that a parallax correction error could be applied when the driver looked anywhere other than through the windscreen (in the mirror, or at the car's instruments).

A drawstring potentiometer was attached to the steering column to measure steering wheel rotation. A similar device monitored the accelerator pedal, and the voltage across the brake lights indicated onset and offset of braking.

Real-time analog signals representing eye movements, steering wheel movements, use of accelerator pedal and onset/offset of braking were displayed on a laptop computer sitting on the passenger seat behind the driver, so that the experimenter could check that all signals were being successfully acquired, but without them being visible to the driver. Figure 2 shows a portion of the horizontal eye movement and steering signals overlaid for comparison.

Analysis

Pre-treatment of the eye movement signal: interpolation

During the drive, subjects were seated in the car in their normal driving position. As they travelled along the route it was normal to see a small amount of head movement. The ASL system was designed to compensate for these movements and for the great majority of the drive the system maintained an accurate lock on the driver's eye. On occasions when the eye was briefly lost (mainly due to blinks) drop-out occurred in the horizontal eye movement trace until the system acquired the eye again. This was removed by manual interpolation. Typically, a 1 min portion of a complete drive required interpolation of only a few seconds in total. The horizontal and vertical eye movement signals provided by the in-car eye tracker were therefore very reliable, and the gaze cross-hairs superimposed on the scene of the road ahead accurate and stable.

Time-domain analysis

Cross-correlation (r value and time lead) Signals representing the horizontal component of eye movements

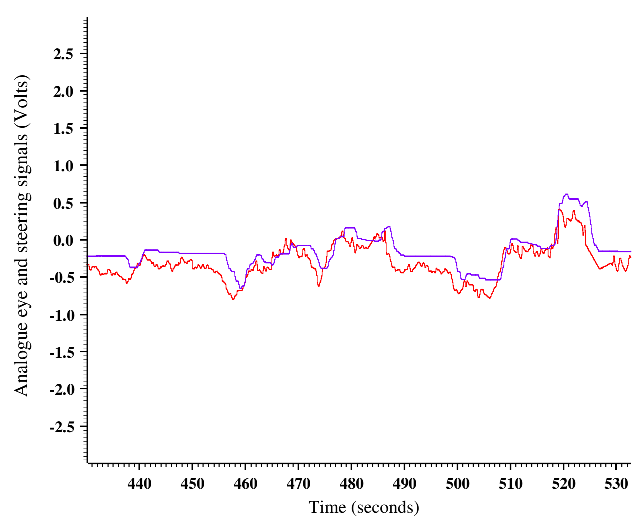

Fig. 2 Raw data, with eye movements and steering overlaid for comparison. The high level of correlation, and time lead of eye movements (*red*) over steering (*blue*), are both clearly visible (subject KW). For the eye movement signal, 1 V = 23.1° of visual angle; the signal ranges over approximately 1.2 V, or 28°

and steering wheel rotation were analysed within the CED Spike 2 environment. Cross-correlation of the two signals over the time taken to complete a drive yielded a cross-correlogram, the peak of which identified the correlation coefficient (r) which is a measure of the covariation of the two signals: Fig. 3. Calculation of ($r^2 \times 100$) yields the percentage of variance in steering wheel movement that is attributable to covariation with horizontal eye movement.

This analysis of horizontal eye movements and steering action therefore gives a quantifiable insight into how a driver controls the car when steering along a winding road. This study of actual driving used the same analytical techniques as previously used in a realistic simulated driving task (Cooper 2004; Marple-Horvat et al. 2005, Wilson et al. 2007).

Minimum signal length Signal analysis texts (Beauchamp 1973; Lynn 1982) state that the accuracy of estimation of the cross-correlation function between two signals improves with increasing signal length, which should therefore be as long as practical, and contain a number of cycles of the lowest frequency component (or fundamental frequency) in the signals. We identified this component by generating Fast Fourier transforms (FFTs; see below) and considered as a working estimate a minimum acceptable signal length to be five cycles. The fundamental frequency in both eye movement and steering signals was very similar, and typically 0.073 Hz, yielding a cycle time of 13.7 s and an adequate signal length of 68.5 s.

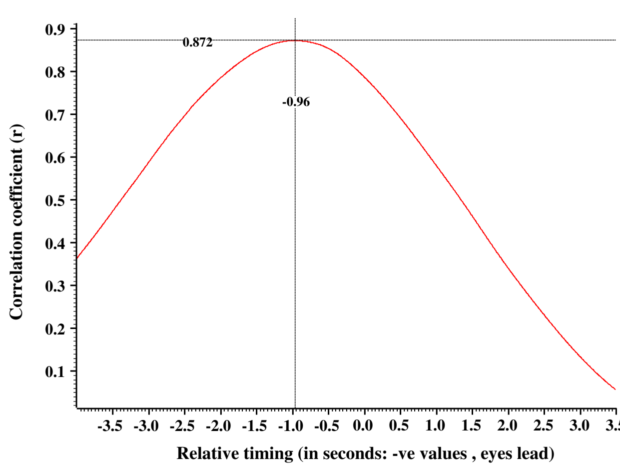

Fig. 3 Correlation between eye movements and steering during natural driving. Cross-correlation of the horizontal eye movement and steering signals, in this instance over a 1 min epoch, yields a cross-correlogram from which correlation coefficient (r), and time lead (t) are obtained (subject KW)

Frequency-domain analysis

FFT and fundamental frequency All FFT analysis was conducted on the whole drive (not on shorter epochs) using an FFT size of 16,384 blocks with a Hanning window setting. The minimum length requirement for this FFT analysis is 81.92 s, which was greatly exceeded by each data file. The lowest or fundamental frequency in the horizontal eye movement and steering signals was determined as the first peak in the FFT after the initial drop from asymptote. Inversion of the fundamental frequency yielded the longest cycle time for each signal; i.e. the time taken for the driver to move through one left and one right hand bend.

Minimum signal length Having identified the rate at which bends in the road were encountered, and with one bend in each direction constituting a single cycle, the period required to complete five such cycles was thus determined; this was taken to be a working estimate of the minimum acceptable signal length for analysis (see detailed consideration in "Minimum signal length" under the section "Time-domain analysis").

Comparison of horizontal eye movement (X eye) FFT and steering FFT The coherence of two waveforms is the measure of their similarity in frequency content. Coherence is a function of frequency and ranges from 0 for totally incoherent waveforms to 1.0 for totally coherent waveforms. For two waveforms to be completely coherent at a particular frequency over a given time range, the phase shift between the waveforms at that frequency must be constant, and the amplitudes of the waves at that frequency must have a constant ratio. The coherence is calculated from the cross spectral density (CSD) between the two waveforms normalised by the power spectral density (PSD) of each waveform. The coherence at some frequency f is given by:

$$\mathrm{coh}(f) = \frac{|\sum csd_{ab}(f)|^2}{\sum psd_a(f) \sum psd_b(f)}.$$

Coherence of the horizontal eye movement and steering signals was calculated for each drive.

Results

Analysis of subjects' eye movements and steering revealed that these were highly coordinated. This was immediately evident in the live video feed showing the view of the road with gaze crosshairs superimposed. When approaching a left hand bend in the road, all subjects looked across to the inside kerb almost a second before turning the steering wheel, and gaze remained fixed on this tangent point until they were emerging from the bend. For right hand bends, gaze settled on the tangent point of the central white line. Figure 4 presents typical video still frames showing gaze fixed on these features, which define the left and right lane margins, whilst approaching four left and right hand bends of various character along the route.

Figure 5 shows all correlation coefficient and time lead values obtained from all drives of different epochs plotted together. Values obtained for 60, 120, 240 and 360 s epochs were normally distributed (Kolmogorov–Smirnov test of normality, all $P > 0.05$), and the results from the 120–360 s periods of driving were closely

Fig. 4 Video frames showing gaze superimposed on the view of the road. *Left* gaze crosshairs fixed on the left (*inside*) road margin on approach to left hand bends. *Right* gaze crosshairs fixed on the centre white line, which is the right hand margin of the lane, on approach to right hand bends (subject KW)

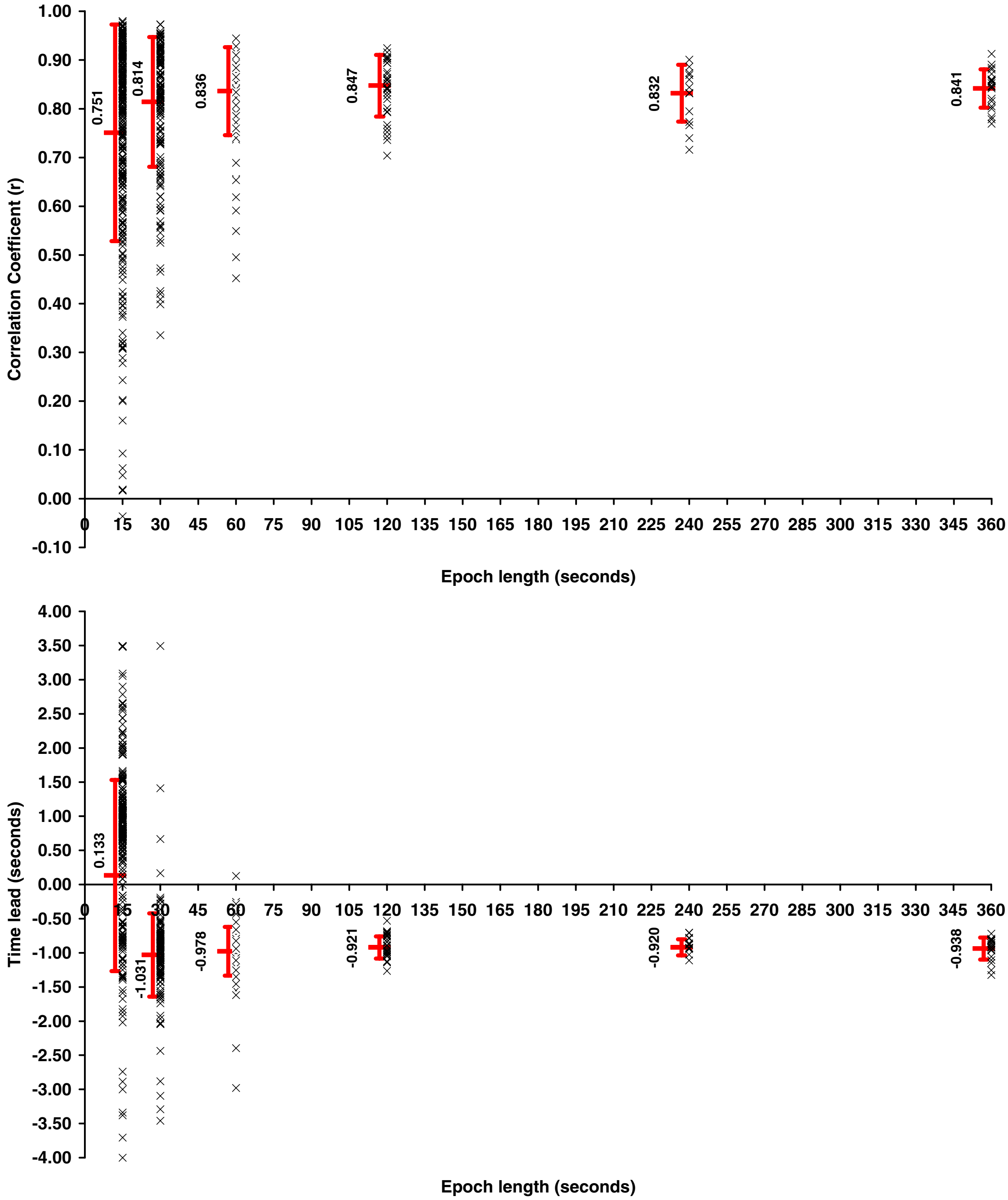

Fig. 5 Correlation coefficient and time lead values obtained from all drives with epochs ranging from 15 s to 6 min. *Top* correlation coefficient values with mean and SD bar shown for different epochs. *Bottom* time lead values with mean and SD bar for each epoch length. Data from all drivers are shown

bunched and very similar. There was a progressive widening of the spread of values with progressively shorter driving epochs, visible both from the individual points (one from each drive) and in the increasing SD bar.

The mean value of all points at any epoch was highly consistent for the 6, 4 and 2 min epochs, varied a little at 1 min and 30 s but changed much more for 15 s epochs. The distribution of points was also progressively skewed for shorter periods of driving with increasing numbers of 'outliers'; the 60 s data were normally distributed, but the 30 and 15 s results were not (Kolmogorov–Smirnov, $P < 0.05$).

The mean of all r values changed from 0.841 at 360 s to 0.751 at 15 s, a drop of 11% in the correlation between the horizontal eye and steering signals. The change in mean was also paralleled by an increase in the SD from 0.040 in the 360 s epoch to 0.222 in the 15 s epoch, a 5.55-fold increase. Figure 5 (top) also highlights that at the 15 s level of analysis we saw some extremely low (near-zero) correlations.

Figure 5 (bottom) illustrates a similarly increasing spread in the data values as epoch length reduced when examining time lead data. The mean values were very stable or consistent between 360 and 30 s epochs, but there was a large change in mean in the 15 s data, resulting in a positive time lead value (i.e., steering leading eye movements by 0.133 s). The SD also showed a modest progressive change in the same range of 360–30 s epochs, but an 8.69-fold increase when comparing 360 s epochs to the 15 s group.

No significant differences could be identified between individuals. Correlation coefficient (r) and time lead values from different drivers were compared using ANOVA for 1 min epochs of driving (the shortest period that we found to be acceptable—see results below and "Discussion") for which we had 12 sections of driving per individual. There were no significant differences ($P > 0.05$). The same result was obtained when 2, 4 and 6 min epochs were compared (with correspondingly fewer sections of driving available per driver).

Figure 6 shows frequency-domain data from a single drive by one individual, fast fourier transforms (FFTs) obtained using the horizontal eye and steering wheel position signals, together with the coherence plot which defines the similarity of the eye and steering signals in their frequency content. As can be seen, there were high coherence values, all but one above 0.8 in the lower bands of frequency, the range 0–0.1 Hz. This high coherence in horizontal eye signals and wheel position signals was seen in all ten subjects. The FFTs for this driver had a notable peak at 0.073 Hz in both eye and steering wheel power spectra, this lowest frequency peak identifying the fundamental frequency of the signal analysed. The coherence trace confirmed both signals shared the same fundamental component; there is a 0.935 score for this frequency bin.

Figure 7 shows the result of averaging the individual power spectra obtained from all ten subjects, in order to examine the underlying fundamental frequency across all drivers. There is a peak in the range 0.061–0.073 Hz in both average FFT plots for horizontal eye and steering wheel data.

Analysis of individual subjects' fast fourier transforms revealed that there was a great deal of consistency in the fundamental frequency. Figure 8 shows the distributions of fundamental frequency values obtained in all 20 4-min driving epochs (outward and return route for all 10 subjects). Both distributions have corresponding peaks at 0.073 Hz.

As explained above, a coherence plot was obtained from the FFTs of eye and steering signals for each participant. All 20 individual coherence plots were averaged together to obtain a coherence profile across all participants; Fig. 7 (bottom). A high coherence value of 0.93 in the frequency bin of 0.073 Hz confirms the similarity of the fundamental frequency distributions in Fig. 8.

Discussion

In recent years there have been a number of studies of driving as an everyday example of visually guided skilled behaviour. Many have been undertaken in simulated driving environments which to varying degrees approximate reality. Since the aim is, however, to understand driving in the real world, this study has examined driving behaviour in its true setting, using equipment that allows for minimal disruption of a driver's environment in a car on the open road.

Eye movements and steering are highly coordinated; drivers use tangent point steering

Land and Lee (1994) first demonstrated that eye movements and steering are highly coordinated when driving in a relatively simple environment (the route was a one-way system). Most of the time, gaze is directed to and fixated upon or very near to successive tangent points of upcoming corners, with brief interruptions to look at other objects of interest. There is therefore fundamentally a high degree of coordination between the eye movements and steering action of a driver negotiating a winding road, in which eye movements lead and are highly correlated with steering.

We have seen the same tangent point steering and tight eye–steering coordination in several studies in a realistic driving simulation; in all, 86 subjects and more than 30 h of driving under various conditions have been analysed. Using standard signal processing and statistical techniques, we have obtained quantitative measures both of the eye–steering coordination and of the benefits for driving performance that the optimal coordination confers (Marple-Horvat et al. 2005).

Land and co-workers (Land and Lee 1994; Land and Horwood 1995; Land 1998) interpreted tangent point steering in terms of acquiring *visual information* for

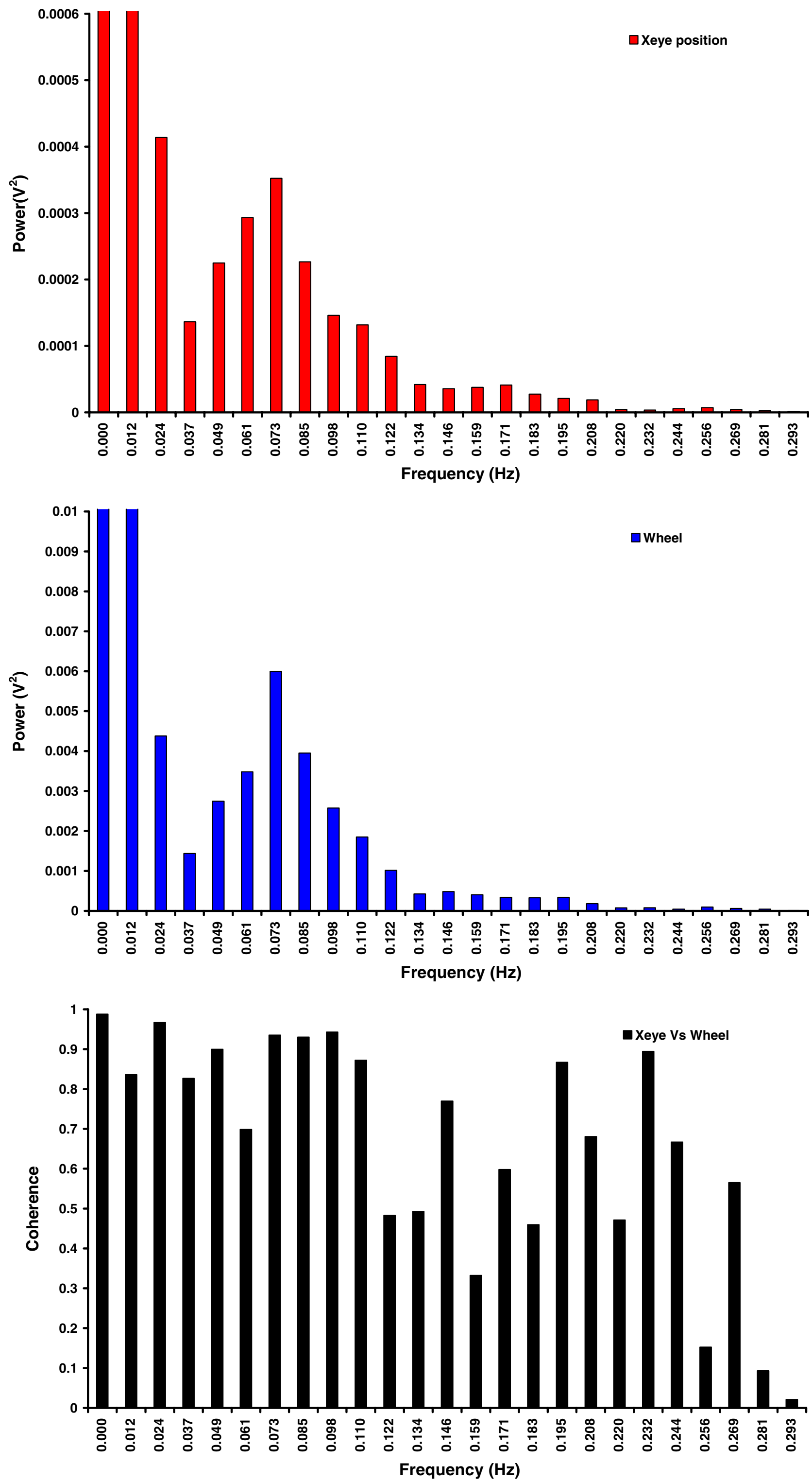

Fig. 6 Frequency domain analysis of a single drive by an individual subject. *Top* FFT of the horizontal eye movement signal. *Centre* FFT of the wheel position signal. *Bottom* graph showing the coherence between the two signals (subject KW)

control purposes, so stressing sensory aspects. However, we have recently demonstrated in simulated driving that tangent point steering, which involves *moving the eyes* to fixate the turning point on successive bends, confers a benefit even when it results in looking into a part of the visual world where vision is denied by a translucent (but almost opaque) mask (Wilson et al. 2007). Thus, drivers responded to a critical level of reduced visibility in the left visual hemifield in one of two ways: some persisted in looking into the masked area so preserving their eye–steering coordination, some did not. Those who preserved their

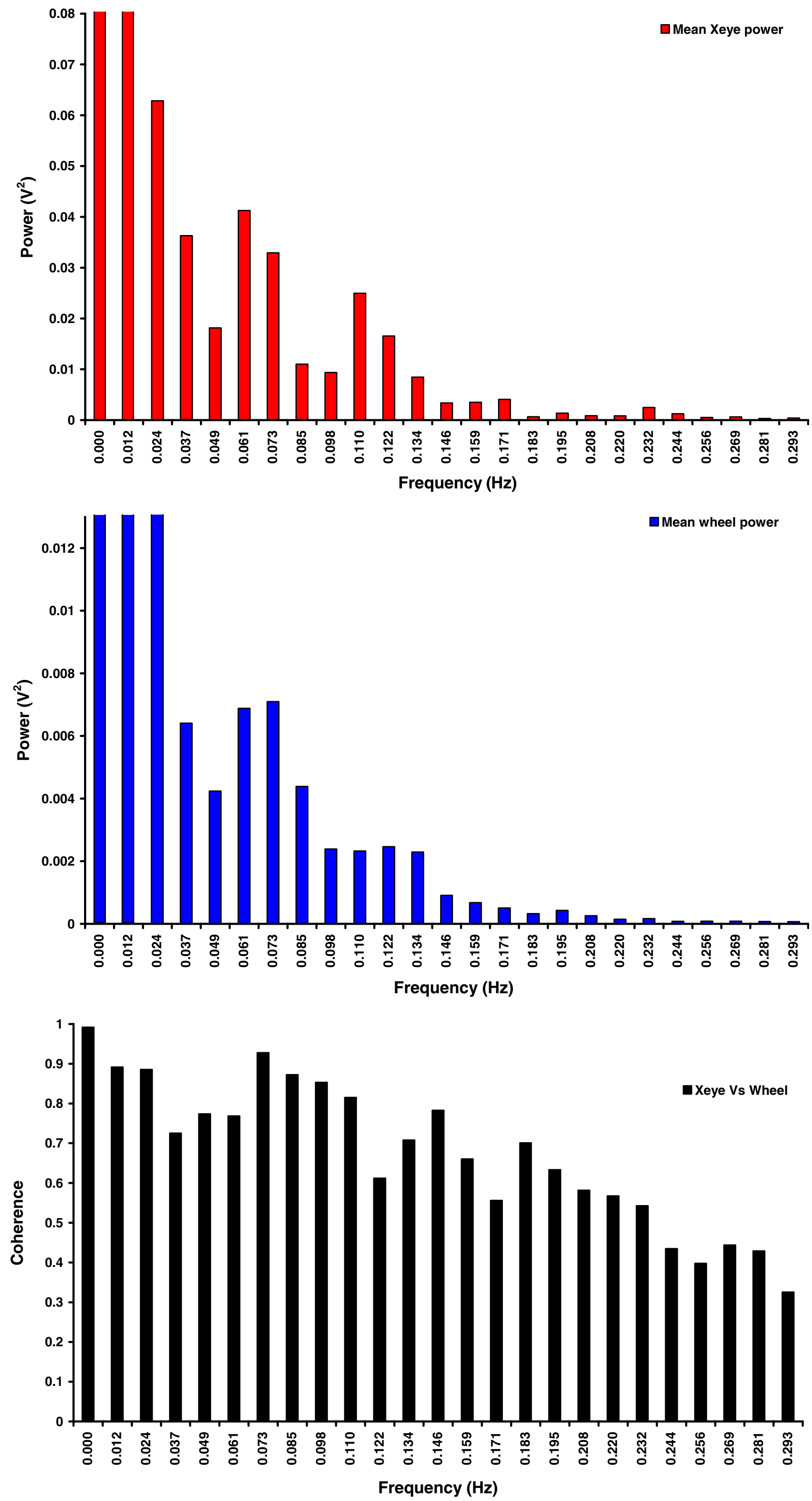

Fig. 7 Frequency domain analysis averaged across all subjects. *Top* average FFT for horizontal eye position. *Centre* average FFT for the wheel position signal. *Bottom* graph of the average coherence values obtained across the whole group of drivers

coordination performed better than those who did not. We have therefore previously suggested a different explanation in terms of *motor control mechanisms* underlying coordinated actions. We proposed a movement centred framework which, regardless of precisely which visual cues are used to guide movement, stresses and identifies the benefit of moving one body part—the eyes—for moving another. Because the eyes lead, the oculomotor controller can assist the neural centres controlling steering; their

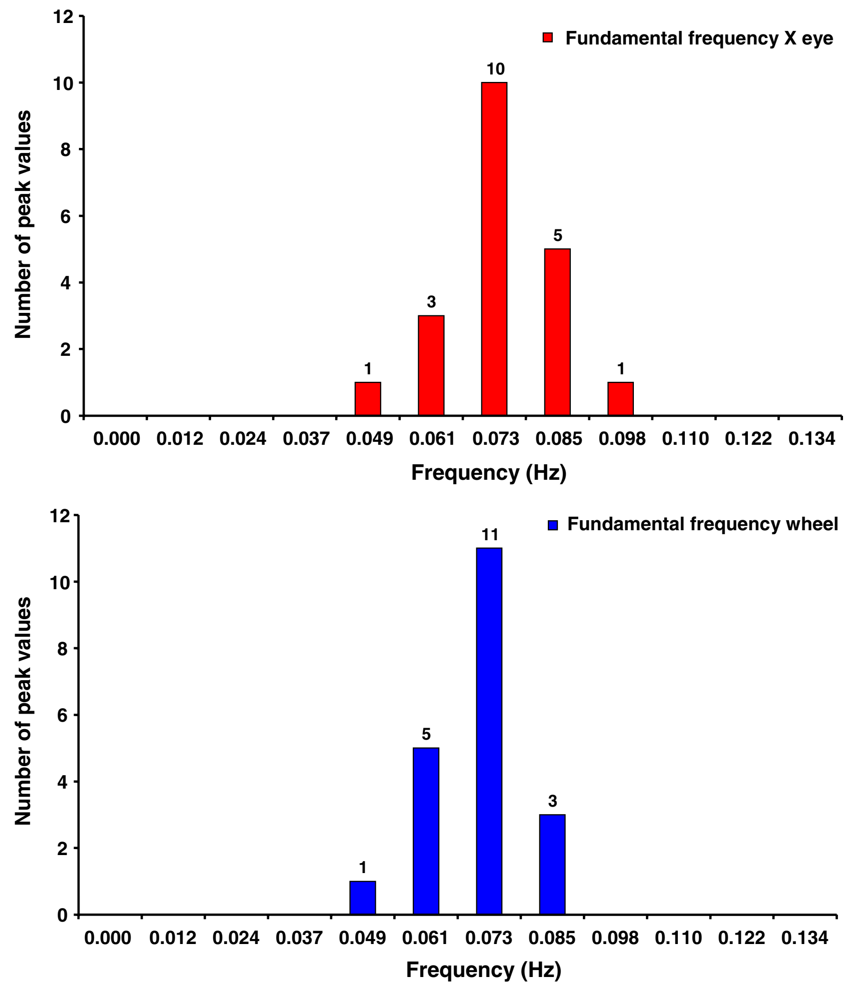

Fig. 8 Distribution of fundamental frequency values seen in all 4-min drives by all drivers. *Top* distribution of fundamental frequency values seen within the horizontal eye movement FFTs. *Bottom* distribution of fundamental frequency values seen within the steering wheel FFTs

left–right rotation as they move to bring gaze to and fixate successive tangent points defines the evolving left–right angle required for steering, and so can be a useful control or 'driving' input to the steering controller. Just how useful is revealed when it is taken away; preventing any eye movements, which can be done safely only in a driving simulation, has a substantial effect. Subjects racing a well-practised stage of the World Rally Championship took on average 30 s (12%) longer when eye movements were denied. This impairment of driving performance is dramatic; actual race times (WRC 2003) reveal that such an increase in time to complete the course is equivalent to slipping 19 places down the leader board in the real rally stage. Just as telling, preservation of eye movements correlated with steering, even when this means looking into a region where the visual information sought is obscured, still benefits performance; indeed it seems as much benefit accrues from moving the eyes (or the act of looking) as from the visual information they move to acquire (Wilson et al. 2007). The usual pattern of eye movements correlated with steering is therefore not just a preference, it is both optimal and crucial for driving performance.

We hypothesised that if eye–steering coordination is as crucial as our conceptual framework and previous simulator studies suggest, and the CNS solves the problem of steering along a winding road by the eyes leading, and the oculomotor controller assisting, even 'driving' the steering controller, then we should expect this coordination to be relatively invariant, or well-preserved and consistent during natural driving. We obtained here quantitative measures of eye–steering coordination over driving epochs spanning the range 15 s to 6 min to test this prediction.

Eye–steering coordination is relatively invariant, and highly consistent

Our evidence is that eye–steering coordination is highly consistent in natural driving on the open road, both for an individual driver in successive driving epochs, and for different drivers travelling the same route, between whom we have identified no significant differences. Provided that adequate lengths of data are involved (and definition of the minimum drive time for accurate characterisation is dealt with in a separate section below) the mean values and scatter (expressed as SD) of correlation coefficients and relative timing behave very simply with increasing data lengths. The reduction in scatter with increasing signal length might seem obvious or trivial, but this is not the case. Firstly, it is not something that could be confidently predicted beforehand, so required demonstration. Secondly, it tells us something important about the data, which is that it has the same character throughout the drive along the route. Any non-stationarity, for example, would result in very different behaviour. The fact that everything behaves simply is therefore in itself an important result.

The ability to closely and quantitatively define this *usual or optimal* eye–steering coordination while driving is important, since that is a precursor to identifying *unusual or impaired* coordination, which may be as a result of pharmacological factors such as alcohol, illegal or prescription drugs, or physical factors such as fatigue. We have evidence in driving simulation (Cooper 2004) that low to moderate alcohol intoxication (breath alcohol levels below the current UK legal limit for driving, 35 μg/100 ml) changes the coordination, and are currently seeking evidence of this in actual driving, under carefully controlled conditions (a private road with no other vehicles or pedestrians present, no roadside obstacles, and with safety run-offs and speed limited to 40 mph).

In different driving environments, other competing requirements (than just steering) might impinge upon eye movements and gaze distribution. Thus, at very high speed racing, head movements are related to steering (Land and Tatler 2001). This might simply reflect the mechanical advantage of keeping the resultant force vector, due to gravity acting vertically on the head mass and centrifugal force acting horizontally, aligned through the axis of the neck vertebrae, to avoid neck muscle fatigue or horizontal shear forces on the brain in the cranium. It may also, however, betray a broader version of the motor control framework we have proposed in which additional control inputs (to those provided by eye movements) are provided from neck muscle proprioceptors which will be stimulated when cornering at high speeds. There is no reason why controllers for the eyes, head and trunk should not be able to influence steering under appropriate conditions [see Miall (1998) and Kawato and Wolpert (1998) for example concerning multiple coupled controllers].

At very low speed, in a cluttered urban environment, driving and steering probably become intermittent, with the necessity to sample many other features than the road ahead, such as other vehicles, traffic signals and pedestrians. On a winding open road, however, steering and driving involve a simple, well-established, continuous pattern of eye–steering coordination. Essentially, drivers kept their head still while driving along the winding rural road used in this study. We realise that in more complex urban situations, including in particular junctions, substantial head movements do occur, and we intend in future to investigate the relative contributions of eye and head movements to steering control in such situations. In this study, however, covariation with eye movements ($r = 0.84$, see Fig. 5) explains 71%, which is the great majority, of steering movements. Eye movements are therefore a powerful explanatory variable for steering; any head movement could only explain some of the relatively smaller (in comparison) 29% residual unexplained variance in a multiple regression model.

We stress here that this observed coordination arises from the way in which the brain solves problems involving coordinated movements under visual guidance in general. Thus, a strategy in which the eyes move with a time or phase lead over other body movements provides for the oculomotor controller to assist the neural centres controlling voluntary limb movements in diverse situations (van Donkelaar and Lee 1994; Crowdy et al. 2000; Miall and Reckess 2002). Such an influence is demonstrable in patients who have been able to improve their limb movements by improving their eye movements (Crowdy et al. 2002), is likely established within the cerebellum which is known to be crucial for motor coordination (Miall et al. 2000), and is evident in tight, relatively invariant, timing relationships (Hollands and Marple-Horvat 2001).

This relationship between horizontal eye movement and steering can be seen and analysed in both time and frequency domains. In the time domain, cross-correlation analysis yields highly consistent correlation coefficients (as long as adequate signal lengths are involved—see below). In the frequency domain there are high levels of coherence visible in the lower frequency range, i.e., highly similar frequency content of both the horizontal eye and steering signals, particularly around the area of the lowest or fundamental frequency. This frequency reflects the rate at which bends in the road are encountered, and indeed in the absence of other information could be used to estimate that quantity. Finding this same fundamental frequency in both the eye movement and steering records is therefore not surprising. There is of course some power at higher frequencies (above 1 Hz) in the eye movement signal that steering wheel movements would be unable to match; moving a steering wheel at these rates would be both mechanically difficult and perhaps result in loss of control.

Minimum drive time for accurate characterisation of eye steering coordination

Accurate measurement of eye–steering coordination requires at least a minute and preferably 2 min of driving. Driving epochs less than 1 min, which have sometimes been used in simulations [Wilkie and Wann (2003), for example, studied just 10 s of driving] are inadequate for quantitative description of eye–steering coordination. This is immediately evident from inspection of the results obtained by analysing different length epochs of natural driving (Fig. 5). One of our aims for this study was to discover how much time was needed to derive a true picture of the coordination between eye and steering movements. Signal analysis texts state that (not surprisingly) reliability of cross-correlation estimation improves with increasing signal length, which should therefore be as long as practical. Specifically, a number of cycles of the lowest frequency component in the two signals should be obtained. In our data, five cycles of this fundamental component (a little over a minute) yield a reliable result, and should therefore be obtained regardless of any factors, i.e., road type, driver, weather conditions and other environmental factors. However, the rate at which a driver moves through one cycle (one left and right hand bend) is clearly dependent on the road the subject is driving which at least partly determines the speed of the car. The fundamental frequency found in this study, on the road that these subjects drove, was 0.073 Hz meaning that a left and right bend was passed on average every 13.7 s. For five cycles to be present, this would mean that on this particular road, at the speed driven a total of 68.5 s of data must be acquired. Future work will examine different road sections of different types to confirm that determination of fundamental frequency, and hence of acceptable data length, is possible under the range of driving conditions commonly encountered.

This study provides the firm foundation for quantitative description of eye–steering coordination during natural driving; future work will assess the robustness of that coordination in different driving situations and the effect on driving performance when that optimal coordination is challenged by alcohol, drugs and fatigue.

Acknowledgments Mark Chattington is supported by an IRM PhD studentship. Mark Wilson is an IRM research fellow. Steve Gilbey provided expert technical assistance, and Jill Harrison took part in experimental sessions. Photographs in Fig. 1 were provided by (and copyright owned by) Richard Stanton.

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