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Stability and skill in driving

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Abstract

Two experiments addressed the relation between postural stability, perceptual sensitivity, and stability of driving performance. A vehicle was fitted with differential GPS for measuring position and speed, position sensors for measuring brake and accelerator depression, force transducers for measuring door, console and footrest bracing forces, and an accelerometer for measuring the 3D accelerations of the vehicle. In Experiment 1, we investigated whether the initiation of deceleration and the control of braking might be due to sensitivity to the perceptual variable tau, which specifies time-to-contact (TTC), and in particular, whether its first derivative, tau-dot, is used to maintain a constant deceleration profile. Using both untrained experienced drivers (EDs) and trained driving instructors from the Holden Performance Driving Centre (HPDC), results confirmed that, regardless of skill level, tau-dot was maintained at a value close to 0.5 and, as predicted by Lee [Perception 5 (1976) 437], braking was initiated when TTC $\approx$ 5 s. In Experiment 2, we wished to quantify the purported differences in driving behaviour between EDs and HPDC instructors during a variety of everyday manoeuvres. Results indicated that instructors utilised a different cornering trajectory, a different emergency braking strategy, and were able to perform a high-speed swerve and recovery task more effectively than the EDs. In general, the instructors applied greater bracing forces using the door and console compared with EDs. The instructors also applied greater footrest forces during emergency braking than did the EDs. The greater use of bracing by instructor drivers to resist g-forces represents a strategy of active stabilisation that enhances both postural stability, as well as overall stability and consistency of driving performance. Results are discussed with regard to the dynamics of perceptual-motor coordination, and how increased stability might improve sensitivity to relevant perceptual information. We conclude that driver-training programmes that focus on increasing driver stability (as a pre-requisite for increased control) show great promise as a means to improving one's attention during driving, and hence have the potential to dramatically improve road safety in general.

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1. Introduction

1.1. Driving as an information-based complex system

Locomotion, when considered as the ability to negotiate one's way in the world, is arguably the most fundamental property of any animate complex system. Central to a complex system's organisation and function is its reliance upon dynamical constraints. These both constitute and give rise to new properties of collective phenomena that are not necessarily encoded or explicitly represented in the device itself (Haken, 1977; Rosen, 1986). The coordinated movement underlying locomotion relies on information which an organism must detect if epistemic contact with the environment and subsequent control is to be possible (Gibson, 1979). Locomotion can therefore be considered as an emergent property of a goal-directed complex system consisting of the tripartite relation holding between organism, informational coupling, and environment (Warren, 1995, 1998; Warren & Wertheim, 1990). From the outset, the driver–vehicle–road relation can be considered as a complex system in the strict sense. Although multiple components at relatively microscopic levels (e.g., neural sensitivities, muscular control systems, vehicle mechanics) are necessary for the act of driving, it is the macroscopic emergent properties of the complex system (e.g., dynamic patterns of braking and steering) that are coupled to macroscopic informational patterns and are therefore controllable. Importantly, circular causality is a hallmark of complex systems such that the emergent behavioural properties in turn act back and constrain and coordinate lower level components of the system (Haken, 1977; Iberall & Soodak, 1986; Kelso, 1995; Pattee, 1977; Turvey, 1990; Yates, 1986).

Central to the identification of the governing dynamics of any complex system is determining the relevant *information* that constrains control. The primary constraint on balance, posture, and especially locomotion, is widely considered to be visual information and in many cases this over-rides other forms of information such as that detected and provided by the vestibular system (Fajen & Warren, 2000; Kim, Effken, & Carello, 1998a,b; Kim, Fajen, & Turvey, 2000; Kim & Turvey, 1998, 1999; Riccio, 1995; Warren, 1998). However, information such as that arising from a gravitoinertial field (GIF) is potentially critical for optimal control of a vehicle, not to mention for simulating (e.g., via immersive virtual reality techniques) the full experience that driving entails (Stanney, 2002; Stoffregen & Bardy, 2001). Indeed, significant advances in automobile driving theory have been gained from the approach of information-based perception as initiated by Gibson and extended by others (Fajen & Warren, 2000; Gibson, 1958, 1979; Gibson & Crooks, 1938; Hancock, Flach, Caird, & Vicente, 1995; Hildreth, Beusmans, Boer, & Royden, 2000; Kadar & Shaw, 2000; Kim et al., 1998a,b, 2000; Kim & Turvey, 1998, 1999; Schiff & Arnone, 1995; Stoffregen & Bardy, 2001; Warren, 1998; Warren & Wertheim, 1990). At the ecological (i.e., macroscopic) scale of analysis, organisms are surrounded by a richly structured environmental energy distribution known as the optic array. The ecological approach to visual perception investigates the vector flow-field characteristics of a streaming optic array that is actively generated due to the self-motion of a moving perceiver.

As a driver (actively) moves through the environment, optic flow is generated which can specify not only that the actor is indeed moving (self-motion specified via global optic flow), but also that one or more objects are moving extrinsically in the environment (object motion specified via local optic flow) (Anderson et al., 2001; Warren & Wertheim, 1990). Importantly, the direction of heading due to self-motion along both straight and curved paths can also be specified in the optics (Fajen & Warren, 2000; Kim & Turvey, 1998, 1999; Warren, 1998; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Thus, there may be sufficient information in the external optical environment to guide, constrain, and control locomotion. Rather than having to consider which action to perform next ("do I brake or shift gear?"), which takes significant time and effort, the skilled driver may have instead developed a high degree of interlimb coordination that is primarily "geared" to the relevant optical invariants of information (Lee & Young, 1985; Turvey, 1990; Turvey, Carello, & Kim, 1990). The issue of how actions become geared to optical structure is central in this approach and has been extensively investigated in research on interceptive actions (e.g., Bootsma & Peper, 1992). As one becomes more proficient at driving, conscious thinking about the road-scene decreases, and seamlessly coupled perception-action increases (Schiff & Arnone, 1995). To this extent, skillful driving may be largely considered to be a perceptual process.

1.2. Gravitoinertial information and the control of driving

Although the direction of heading of self-motion can potentially be specified in the pattern of optical structure available to the visual system, the extent to which optic flow alone can uniquely specify heading direction continues to be debated (Harris & Rogers, 1999; Rushton & Salvucci, 2001; Wann & Land, 2001). The issue of whether optic flow or some other information (such as that from head or eye movements) provides the basis for heading estimation may largely be secondary to a more primary concern regarding the sufficiency of visual information per se for the control of locomotion in general and heading in particular. It is clear that the posture that drivers adopt while cornering varies due to both centripetal acceleration acting on the body as well as personal preferences and what might be generally labelled as "driving style". Such variability in driving style has contributed to considerable debate and disagreement as to how best to provide driver education and driver training (Christie, 2001; Lund & Williams, 1985). Is there a recommended alignment of the head and body for the optimal perception of heading direction? Should the body remain upright, or is it best to "lean into" the corner? Or perhaps it is best that the body remains upright with the head tilted, or to tilt the body while keeping the head upright. Although these are important practical questions, there has been little experimental investigation into the consequences of driving posture on driving performance. Since the two main sources of perceptual information that facilitate the control of steering and heading direction during cornering are visual information due to optical constraint and vestibular information due to gravitoinertial forces (Gibson, 1966), the posture adopted by the driver is both a consequence of such informational constraints (e.g., the GIF during cornering can produce body tilt) and, in turn, can lead to an alteration in the information detected (e.g., body or head tilt can result in a tilted visual field). For example, during cornering the driver is required to balance the potentially competing demands of maintaining postural stability within an inertial frame of reference, and being receptive to relevant visual information (Rogé, 1996).

During cornering tasks such as running around an athletic track, performing a skiing turn, or motorcycle racing, the athlete leans inwards and towards the centre of the curve in order to align the body axis with the "direction of balance" (DOB) so that dynamic equilibrium can be maintained (Riccio, Martin, & Stoffregen, 1992). The DOB is defined from the direction of the gravitoinertial force (GIF) which is the vector sum of the gravitational force (acting vertically) and the centripetal force (acting laterally) and is normally co-parallel with the GIF (Riccio, 1995). The DOB is oriented vertically when driving in a straight line on a flat road at constant speed. However, in the presence of centripetal forces during cornering, the DOB is tilted in the direction of the corner and so it seems reasonable to assume that drivers "lean into the curve" in order to remain balanced. If this were true, the body and associated head tilt would be expected to be strongly correlated with the direction of the GIF.

Although the proprioceptive vestibular system has the ability to detect such centripetal forces during curvilinear translation at constant velocity, recent evidence suggests that head tilt is not correlated with GIF, and is instead correlated with an optical variable related to the visual curvature of the road (Zikovitz & Harris, 1999). It was shown that during cornering, drivers tilted their heads "into the corner" by angles of up to 20° but that the driver's head tilt was *not* significantly correlated with the magnitude of the GIF. Instead, magnitude of head tilt was correlated with the *visual* curvature of the road. Further, Zikovitz and Harris (1999) showed that the magnitude of a passive passenger's head tilt was correlated with the GIF. In addition, the direction of head tilt was in a direction opposite to that exhibited by the drivers (i.e., "out of the corner"), and was therefore probably subject to the experiential "centrifugal" force acting on the body. However no measurement was made of trunk movement, nor of hand, arm or shoulder movement, so it is unclear whether head tilt for the driver could have simply been a result of steering wheel turning (i.e., a right turn with fixed steering wheel hand posture would involve the left shoulder rising and the head consequently tilting to the right).

1.3. Specificity and multimodal information

The tendency to tilt the head toward the centre of the curve was noted in a driving simulator experiment (in the absence of any GIF), although the degree of head tilt was not quantified (Rogé, 1996). Although it was suggested by Rogé that the dominance of visual over GIF frames of reference may be subject specific, following the ecological premise that organisms have evolved to exploit the real properties of their environments (Reed, 1996), we hypothesise that a motor control system for locomotion could exist only if there were definite regularities in the patterning of energy (e.g., light, GIF, etc.), and that all individuals, to a similar degree, have developed and learned to exploit such regularities for the maintenance of balanced posture.

In contrast to studies demonstrating the generality of head tilt during cornering, Stoffregen and Bardy (2001) proposed that because gravitoinertial forces are generated during cornering, the driver's trunk will become tilted into the corner (aligned with GIF frame of reference), but the head will be actively kept upright (presumably to remain aligned with the extrinsic visual frame of reference of the road). Although, no data was presented to support their assertion, this would make good sense in practice – keeping the head and eyes aligned with the external environment would remove any requirement for additional (computational) processes presumed necessary for compensating for the optical tilt introduced by such head tilt. One conclusion to be drawn is that both visual information and GIF contribute to varying degrees to the perception and control of driving and that both may be necessary for accurately perceiving one's direction of heading. Indeed, it has recently been proposed that such multiple sources of information might better be conceptualised as being available for detection in a "global array" in some combined form (e.g., as a single abstract higher-order invariant; Stoffregen & Bardy, 2001).

1.4. The value of driver training

Given the potential existence of multiple contributory factors to the perceptual control of driving, the question arises as to whether driving performance can be improved through increased sensitivity to such perceptual factors. Although driving is an activity that the majority of adults have considerable experience in, many avoidable motor vehicle accidents still occur. Consequently, it has been proposed that a major reason for this is an inadequate level of skill in automobile handling techniques under both critical conditions as well as those encountered on an everyday basis (Schiff & Arnone, 1995) and that driver training is a valuable intervention for the improvement of road safety (Struckman-Johnson, Lund, Williams, & Osborne, 1989). Although a reasonable hypothesis, disagreement remains as to whether the main source of motor accidents is inadequate skill at vehicle control or rather extraneous factors such as excessive speed, over-confidence, bad attitude, or simply lack of "experience" (e.g., Christie, 2001).

It should be noted that recent research into the control and coordination of locomotion has demonstrated that perception-action behaviour is best considered as a tightly coupled dynamical system (Anderson et al., 2001; Hancock et al., 1995; Warren, 1998). If so, then if motor coordination skills during driving are to be better understood, then the necessary constraint on action – perceptual information – surely requires continued investigation (Schiff & Arnone, 1995). Furthermore, if inadequate attention and sensitivity to perceptual information is a key reason for driving accidents, then the potential exists that drivers can be re-educated to drive more effectively by learning to detect critical perceptual information about upcoming events and thus learn to gauge and control their actions better.

Our overall research programme investigates the potential of driver training to improve driving performance through examining the relation between biomechanics, the dynamics of perceptual-motor coordination, and the effects of cognitive demands on the control of a vehicle. Specifically, we are examining the driver-training programme as taught at the Holden Performance Driving Centre (HPDC; Ormeau, Australia) (Gardner, 1998). While many driver-training programmes purportedly emphasise the need to develop good driving skill (i.e., through controlled environments and repetition of critical driving situations (Lund & Williams, 1985), the HPDC approach offers a particular technique with a solid theoretical foundation that has as its ultimate goal the improvement of attention during driving. To achieve this outcome the strategy involves *active stabilisation* of potentially unstable states (Treffner & Kelso, 1999) through the application of appropriate bracing forces by the lower limbs against the foot-well of the vehicle (Gardner, 1998). This is in order to improve overall postural stability and thus provide the necessary physiological and dynamical basis upon which improved attention and perceptual awareness can be built (Foo, Kelso, & de Guzman, 2000; Gibson, 1979; Jeka, 1998; Jeka, Easton, Bentzen, & Lackner, 1996; Jeka, Ribeiro, Oie, & Lackner, 1998; Jeka, Schöner, Dijkstra, Ribeiro, & Lackner, 1997; Riccio, 1995; Riccio et al., 1992; Stoffregen & Bardy, 2001; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). Without such a prerequisite level of postural stability and corresponding control, perceptual and attentional training is likely to be of questionable worth. Indeed, a major factor underlying driving accidents is considered to be insufficient attention (Schiff & Arnone, 1995).

Given that the human motor coordination system is highly sensitive and responsive to changes in the magnitude and direction of attention (Amazeen, Amazeen, Treffner, & Turvey, 1997; Riley, Amazeen, Amazeen, Treffner, & Turvey, 1997; Treffner & Peter, 2002; Zanone, Monno, Temprado, & Laurent, 2001) it can be expected that driving performance might be improved if attentional processes are optimised (e.g., those acting at the level of interlimb coordination and pedal-steering control). In accordance with recent theoretical advances in the study of human posture and locomotion, increased postural stability during driving is expected to have a profound influence on vehicular control, and is likely to increase sensitivity and receptivity to relevant perceptual information about the body, vehicle dynamics, the driving environment, and the tripartite relation holding between them (Kelso, 1995; Stoffregen et al., 2000).

Through our collaboration with HPDC, we have instrumented a vehicle with biomechanical sensors in order to address the overall hypothesis that increased postural and vehicular stability engenders increased perceptual sensitivity to the relevant information for driving (Doyle, Treffner, Barrett, & White, 2000; Treffner, Barrett, Petersen, & White, 2002; Treffner, Doyle, & Barrett, 2001; Walker, 2001). Specifically, the purposes of the current study were twofold. First, we wished to evaluate the hypothesis that perceptual information plays a significant role in the control of driving. In particular, we wished to investigate whether the act of deceleration and the control of braking can be considered to be largely on the basis of the perceptual variable tau, τ, which specifies the time-to-contact (TTC), and in particular, whether its first derivative $\dot{\tau}$ (tau-dot) is used to control braking (Lee, 1976). Second, we wished to achieve initial quantification of the purported differences in driving behaviour between untrained but experienced drivers (EDs) and highly trained driving instructors from HPDC during a variety of everyday manoeuvres such as cornering, emergency braking, and swerve and recovery.

2. Experiment 1

2.1. Control of braking and tau-dot

Although many computer-simulation based studies have investigated the visual control of driving (e.g., Hildreth et al., 2000; Land & Horwood, 1995) and have supported the hypothesis that optic flow provides the necessary (if not sufficient) basis for visually guided behaviour (e.g., Kim & Turvey, 1999; Wann & Land, 2000; Warren, 1998), little research has attempted biomechanical or physiological measurements of the driver "in the field" (for an exception see Cavallo & Laurent, 1988). Specifically, we wished to evaluate driving performance with respect to Lee's hypothesised "constant tau-dot strategy" of deceleration (Kim, Turvey, & Carello, 1993; Lee, 1976; Lee, Young, & Rewt, 1992).

Extensive research into locomotion and vision has revealed a property of optic flow that is correlated with the instantaneous time remaining until contact with an approaching surface. This TTC variable, known as "tau" (τ), is an optical property defined as the inverse of the relative rate of optical expansion and lawfully specifies the time remaining until contact with a surface such as another approaching car or wall. The TTC therefore need not be explicitly "computed" by the nervous system (e.g., as a previously computed distance divided by a previously computed velocity). Experiments indicate that a variety of different organisms (e.g., cats, pigeons, bees, platypus, etc.) as well as humans (e.g., Bradshaw & Sparrow, 2001) are sensitive to τ and use it to "gear" their movements and to control the initiation of interceptive actions (see Bootsma & Peper, 1992; Lee & Young, 1985; Warren, 1998). Thus, it seems that animals are able to detect information about future events which implies that control is largely on the basis of anticipatory information (i.e., current information that, ceteris paribus, lawfully specifies future conditions). If a driver can become attuned to such future-specifying information sources, then perhaps he or she can learn to control a car more effectively by using task-specific information.

In addition to the information provided by τ, a higher-order invariant of τ also exists and specifies the *kind* of contact that will occur: either dangerous, safe, or appropriate (Kim et al., 1993; Yilmaz & Warren, 1995). This quantity, known as "tau-dot" ($\dot{\tau}$), the first temporal derivative of τ, is an optical property that specifies whether contact will be either "hard" ($\dot{\tau} > 0.5$; finite kinetic energy remains at contact and thus overshooting of target occurs); "undershoot" ($\dot{\tau} < 0.5$; kinetic energy is fully dissipated before contact and undershooting of target occurs); or "soft" ($\dot{\tau} = 0.5$; kinetic energy fully dissipated at contact and target and asymptotic contact with target achieved) (Turvey et al., 1990). Many experiments have shown that organisms maintain deceleration profiles such that $\dot{\tau} \approx 0.5$ – a value implying exact contact (e.g., Warren, 1998). Recent driving simulations have explored the ability to control steering on the basis of optic flow (e.g., Duchon, Kaelbling, & Warren, 1998; Kim et al., 2000; Kim & Turvey, 1998, 1999) and have supported the constant tau-dot hypothesis that deceleration is achieved through the active and continual adjustment of deceleration such that $\dot{\tau} \approx 0.5$ is maintained (Kim et al., 1993; Yilmaz & Warren, 1995). However, less evidence exists for such a tau-dot strategy in everyday tasks such as the control of an actual physical device (e.g., a vehicle) where the fundamental constraints are stability-based.

Recent experiments on the active stabilisation of unstable states have shown that stability is an achievement of the perception–action system rather than a given (Foo et al., 2000; Treffner & Kelso, 1999) and as such may require information sources other than from vision (e.g., gravitoinertial constraints). Since safe driving requires keeping a vehicle balanced at all times (Gardner, 1998), the current study forms part of an ongoing investigation into driving technique that evaluates the role of stability in the perception-action dynamics of locomotion (Doyle et al., 2000; Treffner et al., 2001; Walker, 2001).

2.2. Methods

2.2.1. Participants

Four instructors in safe driving technique from the HPDC (mean age = 42 years) and five individuals with at least five years of general driving experience (mean age = 30 years) constituted instructor driver (ID) and ED skill groups, respectively. No special considerations were given to the participants' anthropometric dimensions such that the participant groups yielded a range of heights typical of the Australian population.

2.2.2. Apparatus

A Mercedes C200 saloon car was fitted with a differential GPS receiver (Trimble DSM 212H; 10 Hz sample rate, sub-metre accuracy) and used to acquire vehicle position and speed. The antenna for the GPS was securely attached to the middle of the roof of the car. The GPS data were collected and stored on a laptop computer (Dell Latitude) using custom LabVIEW software (Barrett, 1998). Custom Matlab programs were used for subsequent data processing.

The car was driven around a 1.9 km closed driving circuit (Fig. 1) at the then Mercedes-sponsored Performance Driving Centre. The full width of the road (average width = 10 m) was used to negotiate straights and curves. For reasons pertaining to university ethics for experiments with human participants, an HPDC instructor sat in the passenger's seat at all times during testing. The instructor also checked via speedometer that the participant achieved the required speed during tasks. The experimenter sat in the back seat and monitored data-collection equipment.

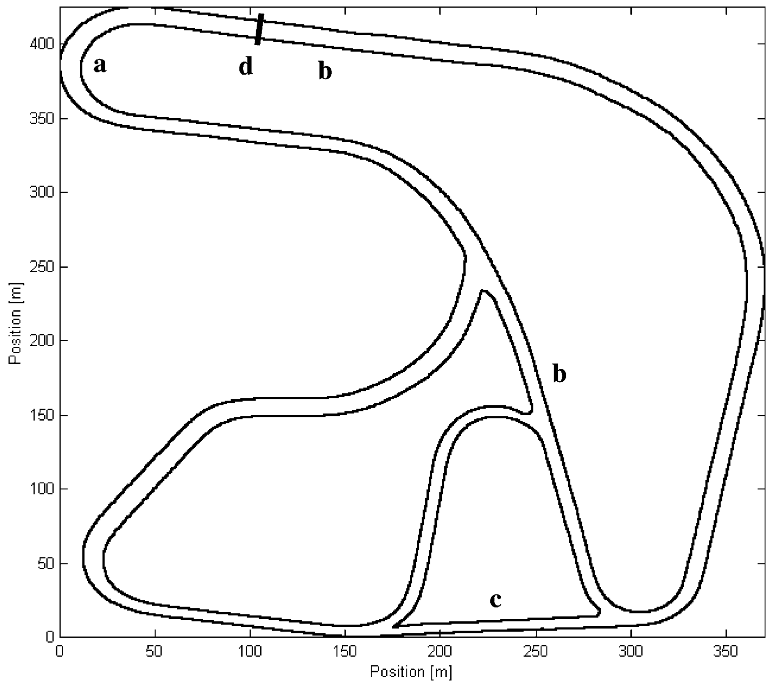

Fig. 1. The HPDC track. (a) Hairpin corner where the cornering task was performed, (b) straight sections of the track where the emergency braking task was performed, (c) section of track where the swerve and recovery task was performed, (d) location of the boxes in the controlled braking task. The outer perimeter of the track is 1.9 km and the track has an average width of 10 m.

Starting at location (d) in Fig. 1, drivers were required to complete two laps of the track in an anti-clockwise direction and to commence braking on the final approach to the boxes at location (d) in Fig. 1. During each lap, the driver was required to achieve a top speed of either 60, 80, or 100 $\text{km}\,\text{h}^{-1}$ (i.e., 37, 48, or 62 mph) on the final straight that preceded the final curve before the boxes, and/or on the corner or straight preceding the boxes.

Two potentially different intentional braking actions were required involving an approach to two potentially different kinds of targets. Drivers were required to brake as they normally would during an approach to: (a) a stop-line (e.g., at a T-intersection), or (b) a traffic light at which another car is already stationary. The stop-line was specified to lie between two large cardboard boxes (45 cm $\times$ 47 cm $\times$ 62 cm) perpendicular to the road and separated by 190 cm. A stationary car was simulated by three identical cardboard boxes with an overall width of 170 cm. Drivers were asked to brake normally as when decelerating and approaching a stop-line, or when decelerating and pulling up behind a stationary car. Three trials of each condition were completed. Trials were blocked by target (car vs. line) and counter-balanced between participants.

Dependent measures included the time required for the entire braking event (T_{brake}), the distance across which the entire braking event occurred (D_{brake}), and the distance before the target at which the car finally stopped (D_{target}). T_{brake} was computed as the time required to bring the vehicle to a complete stop from the time of peak velocity. Taken with respect to the final stopping point, the latter is in effect the time at which deceleration is initiated, T_{init}, and thus acts as a key landmark for computations involving the final approach to the target. D_{brake} was computed from the position at T_{init} to the position of the stopped vehicle.

In addition to the preceding dependent measures related to vehicle kinematics, dependent measures related to the purported perceptual control variable (i.e., TTC) were also computed. The tau-function (τ) is the time series of instantaneous TTC computed as the ratio of distance to velocity, where distance is computed from the position at T_{init} to the final position when the goal state is reached (typically when a moving actor comes to a standstill). However, two methods of computing tau-dot ($\dot{\tau}$) were adopted corresponding with two alternative intentional states potentially held by the participant. The first method required that $\dot{\tau}$ was computed as the slope of the linear regression of the "intrinsic" tau-function (τ_{int}) whereby τ_{int} was computed from T_{init} to the final position of the front of the car. In this case, the goal was considered to be intrinsic to the kinematics of the car alone. In the second method, $\dot{\tau}$ was based on the "extrinsic" tau-function (τ_{ext}) whereby τ_{ext} was computed from T_{init} to either the stop-line or the front of the boxes (in front of which the car was required to stop). In this case the goal was considered to be extrinsic to the kinematics of the car. Final segments of the tau-function in the case of τ_{ext} were eliminated from analysis since τ_{ext} ratios rapidly approach infinity during the final approach (i.e., velocity diminishes while distance remains finite). Analysis of variance (ANOVA) with repeated measures was used to assess the effect of one between-subjects factor of skill group (ID vs. ED) and two within-subjects factors of target (car vs. line) and speed (60, 80, or 100 km h^{-1}) on various dependent measures. For all multiple pairwise comparisons, alpha was set at the 0.05 level and Bonferroni correction was applied.

2.2.3. Results and discussion

ANOVA was conducted on T_{brake} with between-subjects factor of skill group (ID vs. ED), and within-subjects factors of target (car vs. line), and speed (60, 80, or 100 km h^{-1}). There was a significant interaction between group and target, $F(1,7) = 14.04$, $p < 0.01$ (ID: car = 8.31 s, line = 8.82 s; ED: car = 9.84 s, line = 8.91 s). Thus, for ED only, it took longer to stop before a stationary car than before a stop-line ($p < 0.01$). No other significant differences or interactions were found.

The ANOVA conducted on D_{brake} indicated that there was a significant effect of speed (87.8, 120.8, and 146.3 m, for 60, 80, and 100 km h^{-1}, respectively), $F(1,7) = 70.97, p < 0.001$, indicating that initiation of braking occurred increasingly farther from the target as speed increased. There was also a marginal interaction between group and target, $F(1,7) = 3.69$, $p = 0.09$. As with T_{brake}, only for ED was D_{brake} greater when stopping before a stationary car (128.1 m) than before a stop-line (118.2 m). No other significant differences or interactions were found.

For the ANOVA conducted on D_{target}, a significant interaction was found between target and group, $F(1,8) = 8.55$, $p < 0.05$, such that ID stopped farther from the stationary car (8.50 m) than from the stop-line (5.85 m). No other significant differences or interactions were found.

Overall, the results suggest that the ED were more cautious in braking (earlier and farther from target) than were the ID, but only when confronted with an object affording tangible negative consequences of collision (i.e., colliding with a substantial stationary object versus stopping on or near an intangible stop-line). Further, the ID allowed a larger buffer-zone in front of the stationary car than in front of the stop-line. The larger buffer-zone is consistent with an aspect of the HPDC driving technique which emphasises the importance of leaving sufficient space between one's own vehicle and a stationary vehicle in front such that evasive manoeuvres can be made if need be (e.g., avoiding an impending rear-end collision if an approaching vehicle from behind fails to decelerate sufficiently).

Separate ANOVAs conducted on the individual values of τ_{int} and τ_{ext} at T_{init} revealed no significant differences (grand means: $\tau_{int} = 5.07$ s, $\tau_{ext} = 4.91$ s). Thus, the conclusion can be drawn that regardless of skill, speed, or target, braking commenced at an invariant value of TTC (TTC $\approx$ 5 s). This was first predicted by Lee (1976) as the average TTC that could be expected for comfortable and tolerable g-forces across a range of speeds. Although recent research into the perceptual control of gait indicates that humans modify their coordination as a function of specific affordances (e.g., Bradshaw & Sparrow, 2001), the finding that a critical action such as deceleration initiation occurs at an invariant TTC suggests that certain aspects of locomotion are very robust and utilise key informational variables regardless of competing exigencies of the situation.

Interestingly, the slopes of the tau-functions were not always constant. Due to this $\dot{\tau}$ was estimated from the linear fit of both the complete trajectory, $\dot{\tau}_{all}$, and the last quarter of the approach, $\dot{\tau}_{qrt}$ (Fig. 2). Separate ANOVAs conducted on dependent measures of $\dot{\tau}_{all}$ and $\dot{\tau}_{qrt}$ yielded no significant differences for any of the conditions. However, mean values of $\dot{\tau}$ indicated that in several cases drivers did not maintain $\dot{\tau} = 0.5$, and either undershoot of the target (as required: $\dot{\tau} < 0.5$) or slight overshoot was specified ($\dot{\tau} > 0.5$) (Table 1). It was also found that $\dot{\tau}_{qrt} < 0.5$ during the final quarter phase of deceleration, implying that deceleration decreased ($\dot{\tau} < 0.5$) yielding a balanced and smooth control of stopping the car.

The results suggested that skill and perceived affordances influence braking, that drivers initiate braking at an invariant value of τ regardless of speed, and that although $\dot{\tau} \approx 0.5$, $\dot{\tau} \neq 0.5$ may obtain at different stages of braking. As predicted on the basis of theoretical considerations by Lee (1976), the findings confirm that across a range of speeds (and associated maximal tolerable decelerative g-forces) both IDs and EDs initiated braking at a point at which the TTC would have been 5 s if they had maintained a constant velocity. In short, drivers seem to exploit an invariance in the dynamics of the perception–action system (yielding a braking onset at TTC = 5 s). This provides confirmation that Lee's (1976) predicted TTC of 5 s for the intentional initiation of braking holds (for both trained and untrained drivers). Although it remains to be seen whether this is the case for novice drivers, it would be reasonable

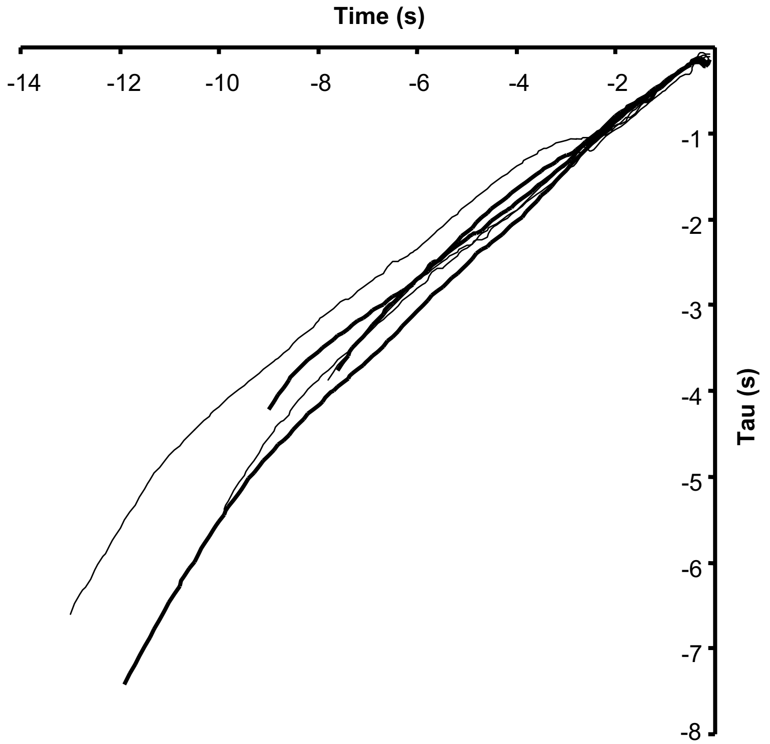

Fig. 2. Tau-functions for a car decelerating to a standstill showing actual TTC from T_{init} to the stationary position plotted against instantaneous TTC (τ_{int}) for an ID at 100 km h^{-1} and braking before a car (three trials; thick lines) or a stop-line (three trials; thin lines). Consistency is greatest during approximately the final 1/4 of the deceleration event. From the slope of the profiles (i.e., the rate of change of tau) a tau-dot of approximately 0.5 is derived.

Table 1
Mean values of tau-dot estimated as a function of section of tau-function fitted ($\dot{\tau}_{all}$ and $\dot{\tau}_{qrt}$), skill group (instructors and experienced), and intention (τ_{int} and τ_{ext})

Tau-fit	Instructors		Experienced	
	τ_{int}	τ_{ext}	τ_{int}	τ_{ext}
$\dot{\tau}_{all}$	0.487	0.498	0.515[a]	0.552[b]
$\dot{\tau}_{qrt}$	0.382[b]	0.337[b]	0.392[b]	0.350[b]

[a] Different from $\dot{\tau} = 0.5$, $p < 0.05$.
[b] Different from $\dot{\tau} = 0.5$, $p < 0.001$.

to conclude that tau provides a reliable basis onto which the perception–action system can be geared.

3. Experiment 2

3.1. Active stabilisastion and skill

In Experiment 1 it was shown that an in-vehicle data acquisition system based upon GPS kinematic data could provide insights into actual driving on an actual road in an actual car. In Experiment 2 we decided to further investigate the dynamics of driving through a comparison of the differences in performance in untrained but experienced drivers and so-called "skilled" drivers (i.e., driving instructors) from the HPDC. At HPDC, various techniques related to improving control of the vehicle are taught with the sole emphasis on *safety* rather than as an opportunity for increased driver adrenalin levels and associated exhilaration (Treffner et al., 2002). The major emphasis of HPDC training is on increased postural stability and improved visual attention through better scanning of road conditions. In order to maintain safety, the driver must keep the vehicle balanced at all times (Gardner, 1998). Specifically, at HPDC the technique of "switching-on" is taught as a way of increasing postural stability, awareness, and attention when road conditions potentially become critical. To summarise the technique, when faced with a potentially hazardous situation (e.g., another car approaching at an intersection), for a right-hand drive vehicle, switching-on involves the driver *bracing* with the left foot against the footrest while simultaneously *relaxing* slightly the grip of the wheel in order to maintain a sensitive grip and to avoid "tunnel vision" and the associated degradation of perceptual attention. Thus, the method increases postural stability in order to facilitate increased attention. Importantly, recent motor control research has recognised that dynamical stability is the foundation of well-coordinated perceptual-motor behaviour (Kelso, 1995; Riccio, 1995; Stoffregen et al., 2000; Treffner & Kelso, 1999; Turvey, 1990). We therefore conjecture that attentional switching-on is a necessary pre-requisite for increasing sensitivity to perceptual information for the control of driving (Gardner, 1998). In this experiment it was hypothesised that IDs would exhibit markedly different patterns of driving performance (e.g., greater stability of driving trajectories) than EDs, and that the instructors would achieve such outcomes through markedly different control actions such as the appropriate application and timing of postural bracing forces.

3.2. Methods

3.2.1. Participants

The EDs skill group consisted of four individuals (<25 years) whereby each had held a drivers license for more than five years but had not undertaken any formal driver training. The IDs group consisted of four HPDC instructors.

3.2.2. Apparatus

All testing was performed in a 6-cylinder Holden Commodore Executive supercharged VX series sedan (2000 model) with automatic transmission and power steering. Anti-lock braking (ABS) was engaged. The in-vehicle data acquisition system consisted of a differential GPS receiver (Trimble DSM 212H; 10 Hz sample rate, submetre accuracy) for measuring car position and speed, force sensors for measuring bracing forces against the footrest (Applied Measurements, S-beam load cell, ± 1 kN), console and door (LPS single point load cell), linear potentiometers for measuring brake and accelerator depression (Honeywell, 3″ stroke), and a triaxial accelerometer (Crossbow CXL02LF3, ± 2 g) for measuring 3D accelerations (vertical, side–side, and front–back) of the vehicle. The GPS receiver was connected directly to a laptop computer (Dell Latitude) via the serial port. A pair of strain gauge modules (DBK43A) connected to a DAQ Book (IOTECH DAQBook 200) were used to acquire data from the remaining analog sensors at 100 Hz. All data were synchronised with GPS data and stored on a laptop computer using custom LabVIEW software (Barrett, 1998). Custom written Matlab programs were used for subsequent data processing.

The three tasks chosen were designed to quantify performance during potentially critical events typically encountered during everyday driving. The cornering task was implicitly performed during circuit driving. This was conducted in an anti-clockwise direction whereby one of the corners was selected for further analysis (Fig. 1). Entry speed into and during the corner was specified as either 30, 35, or 40 $\mathrm{km\,h^{-1}}$. The emergency braking task was performed at a speed of either 60, 70, or 80 $\mathrm{km\,h^{-1}}$ at randomly selected straight sections of the track (Fig. 1). The signal to stop was given as a loud "Stop!" command by the experimenter sitting in the back seat of the vehicle. The swerve and recovery task involved negotiating a set of traffic cones placed on a straight section of the track (Fig. 1). The driver was required to maintain an approach to the right of the central marker at a speed of either 40, 45, or 50 $\mathrm{km\,h^{-1}}$ and then to swerve to the left (simulating an obstacle in the path of the vehicle) and then swerve to the right and back onto the original (right) side of the road. Three trials of each task were performed. The drivers were informed that they could use the full width of the track and thus treat it as a single lane road.

The dependent measures were categorised into those relating to vehicle motion, vehicle control, and postural stability (via the driver's active stabilisation). Vehicle motion variables consisted of vehicle speed, vehicle trajectory (e.g., braking distance and location of apex), variability of vehicle trajectory (during cornering), and anterior–posterior (AP), medio-lateral (ML) and vertical (V) accelerations of the vehicle. Vehicle control variables consisted of the amount and timing of accelerator and brake depression. The variables relating to postural stability and active stabilisation consisted of the footrest, console and door bracing forces.

ANOVA was used to assess the effect of one between-subjects factor (skill: ID vs. ED) and one within-subjects factor (speed) on various dependent measures for each task. For all multiple pairwise comparisons, alpha was set at the 0.05 level and Bonferroni correction was applied.

3.2.3. Results and discussion

3.2.3.1. Cornering. Representative data for an ID and ED performing the cornering task in the anti-clockwise direction (i.e., left-hand corner) at 40 $\mathrm{km\,h^{-1}}$ are displayed in Figs. 3 and 4. GPS trajectories revealed differences in the vehicle trajectory produced by ID and ED through the corner. In Fig. 3, the ID exhibits a definite apex (i.e., closest point of the trajectory to the inside edge of the track) whereas the ED (Fig. 4) does not exhibit such a definite apex and instead tends to follow the inside edge of the track from the point of entry to the corner until exit.

When performing the left-hand corner, the ID actively stabilised the upper body against leaning by bracing the right knee against the door in order to counteract the centrifugal force that would tend to tilt the head and body towards the door (Fig. 3f). It can also be seen that the onset of the active stabilising force applied to the door for ID coincided with the onset of ML accelerations (Fig. 3c and f). Although lesser than the magnitude of door bracing, there was force applied by the left knee to the console. Together, this bilateral bracing technique of the HPDC instructors results in a stabilisation of the head and torso against postural tilt and instability. In addition, the footrest force applied by the ID was steady but not excessive as in an emergency braking (Fig. 3e). Likewise, the application of a uniform and definite increase in accelerator pedal usage resulted in a smooth acceleration out of the corner (Fig. 3d and b).

In contrast, the ED depicted in Fig. 4 did not actively stabilise using the door. Instead, they may have attempted to counteract the lateral force by "leaning into" the

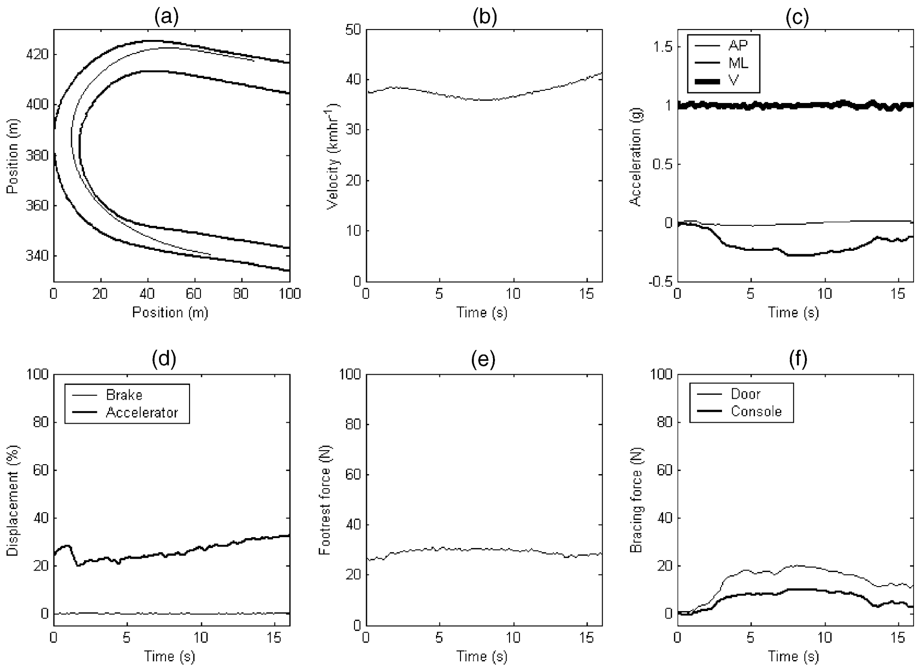

Fig. 3. Representative data for an ID performing a left-hand cornering task at 40 km h^{-1}. (a) GPS trajectory, (b) car velocity, (c) car acceleration in the AP, ML and V directions, (d) brake and accelerator pedal depression, (e) footrest force, (f) door and console bracing force.

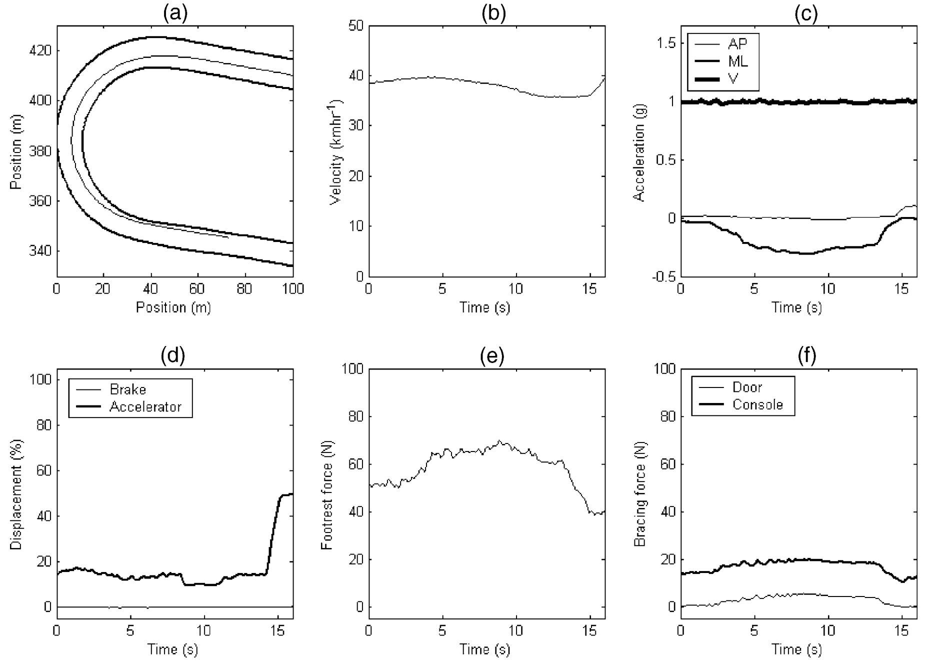

Fig. 4. Representative data for an ED performing a left-hand cornering task at 40 km h^{-1} (see Fig. 3 caption for details).

corner. This is suggested by the nominally larger console forces over the door forces (Fig. 4f). This strategy effectively aligns the body with the DOB and is one method, albeit non-optimal, for preventing the loss of postural stability under dynamic inertial frames of reference (Riccio, 1995; Riccio et al., 1992; Rogé, 1996; Zikovitz & Harris, 1999). However, the negative consequence of body-lean is typically a tilt (and thus alteration) of the visual frame of reference and can lead to misjudgement of direction of heading (Foque, Bardy, Stoffregen, & Bootsma, 1999; Warren, 1998). In addition, possibly because of leaning to the left, this driver may inadvertently have increased the asymmetric pressure applied by his left lower limbs resulting in a large but inappropriate footrest force (Fig. 4e). Such a left-directed footrest force would push the body further towards the right and would therefore amplify the already considerable centrifugal forces that are pushing his body outwards and rightwards. Asymmetric biases such as these, although inherent to the motor control system due to functional asymmetries and handedness (Treffner & Turvey, 1995, 1996), are to be minimised rather than accentuated if well-balanced locomotion (either with or without a locomotion device) is to be achieved. The ED also exhibited greater fluctuations in accelerator pedal depression (Fig. 4d) and together with the asymmetric application of forces due to bracing, it is clear that this driver is dynamically unstable and results in inappropriate (and potentially dangerous) coordination and control of the vehicle (Gardner, 1998).

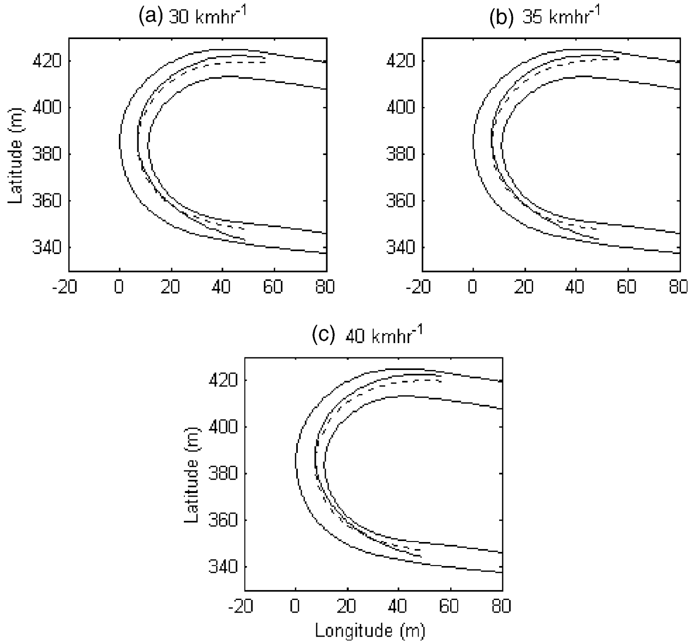

Fig. 5. Mean trajectories during cornering at (a) 30, (b) 35, and (c) 40 km h^{-1} for IDs (—) and EDs (– – –).

Differences in cornering trajectory between ID and ED are illustrated in Fig. 5 which depicts the mean trajectory through the corner for ID and ED. Clearly, different trajectories were adopted by the different groups and this difference was maintained regardless of speed.

To gain greater insight into the form and consistency of the trajectories taken, the corner was superimposed by 100 equally spaced "rays" which were drawn with each perpendicular to its corresponding segment (chord) from the inside of the track (Fig. 6a).

The distance from the inside of the track to the intersection of the vehicle trajectory with each ray was determined for each trial, was collapsed across speeds, and was used to calculate a mean inside track distance profile for both ID and ED (Fig. 6b and c). The apex is the location along the trajectory where the vehicle is closest to the inside edge of the track. When position of the apex within the corner is expressed as a percentage of the distance through the corner, results suggested that the apex was reached earlier by ID (77%) compared to ED (88%) $F(1,6) = 5.43$, $p = 0.06$ (see also Table 2). However, one must be circumspect in assuming the existence of an apex for the ED. Although the ID exhibited a definite apex with minimal variability in its location (Fig. 6b and d), the ED only exhibited a gradual and indefinite approach towards some point at which the distance to the inside of the track was a minimum (the so-called apex). However, this point necessarily occurred on exit from the corner and involved greater variability in its location (Fig. 6c and e) than that of the ID. That the ID had a definite approach to an apex is indicated by

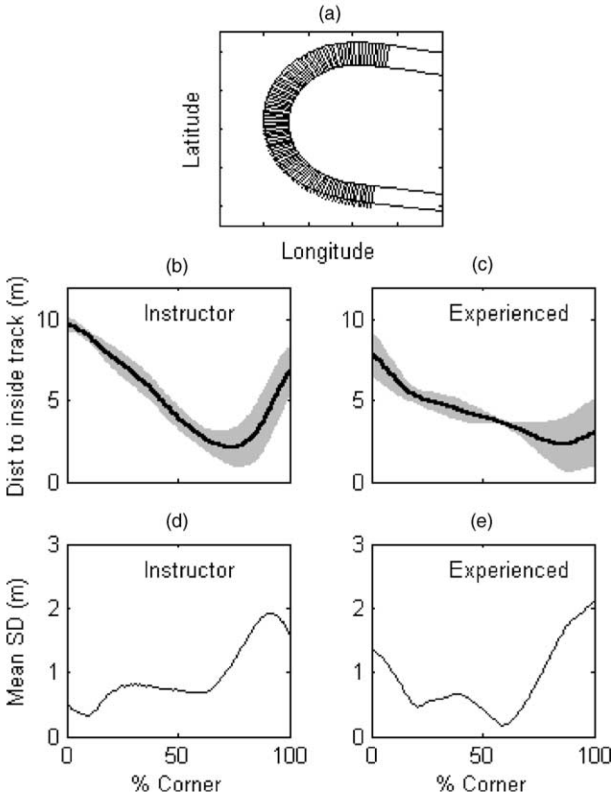

Fig. 6. (a) Corner divided into 100 equally spaced intervals perpendicular to the inside edge of the track from which the distance between vehicle trajectories and the inside of the track were calculated. (b, c) Mean distance between vehicle trajectories and the inside of the track collapsed across all speeds for IDs and EDs, respectively. Shaded region represents ±1 standard deviation. (d, e) Mean standard deviation of vehicle trajectories collapsed across all speeds for IDs and EDs, respectively.

the steepness of the profile of the distance to the inside track prior to and following the apex (Fig. 6b). By contrast, the distance profile for the ED was flatter than for the ID, especially prior to the apex (Fig. 6c). In general, the ID maintained a position far from the inside of the track when entering and exiting the corner. Relative to ED, this indicates that the ID used a cornering strategy that maximised effective use of the width of the road. The ID exhibited more consistent (less variable) cornering trajectories compared to ED as indicated in the flatter profile of the average standard deviation of the distance to the inside of the track (Fig. 6d and e). The latter suggests that the ED tended to maintain the vehicle at a fixed distance from the inside edge of the track. The overall mean of the standard deviation of the distance to the inside track (calculated across the entire corner) was significantly lower for ID (0.31 m) compared to ED (0.57 m), $F(1,6) = 8.67, p < 0.05$, thus confirming that ID had developed a definite and repeatable strategy for negotiating the corner.

Table 2
Means (and standard deviations) for the cornering task as a function of skill group (experienced and instructor) across three speeds (30, 35, and 40 $\mathrm{km\,h^{-1}}$)

	Experienced			Instructor		
	30	35	40	30	35	40
Average speed ($\mathrm{km\,h^{-1}}$)[a]	30.4 (1.3)	34.7 (1.2)	38.4 (1.1)	31.6 (1.3)	36.1 (1.0)	39.2 (1.8)
Peak door force (N)[b]	3 (1)	4 (1)	4 (1)	20 (10)	23 (7)	25 (6)
Average door force (N)[b]	1 (0)	2 (0)	2 (0)	13 (8)	15 (6)	17 (5)
Peak console force (N)	13 (9)	12 (7)	13 (9)	17 (8)	17 (8)	18 (8)
Average console force (N)	7 (6)	5 (3)	6 (3)	10 (5)	9 (7)	8 (7)
Peak footrest force (N)	64 (48)	60 (36)	59 (37)	74 (39)	59 (18)	52 (22)
Average footrest force (N)[c]	58 (48)	54 (33)	49 (32)	39 (14)	39 (12)	38 (13)
Peak lateral acceleration (g)[a]	0.19 (0.01)	0.26 (0.01)	0.30 (0.02)	0.21 (0.03)	0.27 (0.03)	0.31 (0.04)
Average lateral acceleration (g)[a]	0.11 (0.03)	0.11 (0.03)	0.18 (0.05)	0.11 (0.01)	0.12 (0.01)	0.19 (0.02)
Apex of corner (% corner)[c]	87 (11.5)	92.4 (7.0)	85.9 (9.3)	76.7 (5.6)	77.8 (5.6)	76.4 (6.3)
SD of cornering trajectory (m)[c]	0.69 (0.66)	0.60 (0.27)	0.80 (0.64)	0.47 (0.12)	0.23 (0.09)	0.24 (0.03)

[a] Significant main effect due to speed.
[b] Significant group by speed interaction.
[c] Significant main effect due to group.

It can be concluded from the above that the cornering trajectories for ID were well-defined and less variable (i.e., more stable) than those of the ED, both at entry into, during, and exit from the corner. These results are consistent with a theoretical perspective on perceptual-motor control which states that as an end result of the learning process, minimisation of variability is achieved and consistency of behaviour is exhibited not because of reprogramming or the strengthening of a pre-existent motor program, but because of the strengthening of the attractors or stable states that engender coordinated perception-action phenomena (e.g., Kelso, 1995; Newell, 1996; Newell & Corcos, 1993; Strogatz, 1994; Turvey, 1990).

Summary data for the cornering task are presented in Table 2. The average door forces were significantly greater for ID (15 N) than for ED (2 N), $F(1,6) = 18.24$, $p < 0.01$. Similarly, peak door forces were greater for ID (22 N) than for ED (3 N), $F(1,6) = 25.84$, $p < 0.01$. The effect of speed was also significant for both average door force (7, 8, and 10 N, for 30, 35, and 40 $\mathrm{km\,h^{-1}}$, respectively), $F(2,12) = 12.07$, $p < 0.05$, and peak door force (11, 13, and 15 N, for 30, 35, and 40 $\mathrm{km\,h^{-1}}$, respectively), $F(2,12) = 8.11$, $p < 0.05$. There was also a significant interaction between group and speed on both average door force $F(2,6) = 5.42$, $p < 0.05$, and peak door force $F(2,6) = 3.93$, $p = 0.05$, indicating a greater effect of speed for ID than for ED.

In contrast to the preceding significant effects for the door force, there was no difference between ED and ID on either average or peak console force indicating that the important difference between groups involved a bracing force applied in a direction to counteract the destabilising centrifugal force (i.e., towards the door). This was confirmed by the finding that there was a significant effect of speed on both average lateral acceleration (0.11, 0.11, and 0.19 g, for 30, 35, and 40 km h^{-1}, respectively), $F(2,12) = 121.32$, $p < 0.001$, and peak lateral acceleration (0.20, 0.27, and 0.31 g, for 30, 35, and 40 km h^{-1}, respectively), $F(2,12) = 210.99$, $p < 0.001$.

Interestingly, there was a marginally larger average footrest force applied by the ED (54 N) than by the ID (39 N), $F(1,6) = 21.47$, $p = 0.09$. Since it was a left-hand corner, a footrest force may be counter-productive to the goal of increasing postural stability as it would tend to accentuate the rightward force already present due to the lateral accelerations from the GIF (e.g., see Fig. 4e).

3.2.3.2. Emergency braking. Summary data for the emergency braking task are presented in Table 3. Although group differences did not reach significance, the mean braking distances were uniformly less for ID (40.42 m) compared to ED (42.70 m). A significant main effect for speed was detected (32.39, 41.81, and 50.48 m, for 60, 70, and 80 km h^{-1}, respectively), $F(2,12) = 23.54$, $p < 0.001$. Thus, at 80 km h^{-1} the difference between ED (52.7 m) and ID (48.3 m) was 4.4 m – equivalent to one car length. Such a difference would be sufficient to influence the probability and severity of a collision, and is therefore of practical significance. Although there was an effect of speed on braking time (3.03, 3.47, and 3.81 s, for 60, 70, and 80 km h^{-1}, respectively), $F(2,12) = 21.23$, $p < 0.001$, there was no group effect.

The effect of speed on the average magnitude of deceleration was significant (−0.54, −0.56, and −0.58 g, for 60, 70, and 80 km h^{-1}, respectively), $F(2,12) = 4.79$, $p < 0.05$. Consequently, there was a marginal effect of speed on the time taken to reach peak deceleration (2.04, 2.34, and 2.60 s, for 60, 70, and 80 km h^{-1}, respectively), $F(2,12) = 3.28$, $p = 0.07$.

Interestingly, when the time at which peak deceleration was reached is expressed as a percentage of the total braking time, then speed had no effect (67%, 68%, and 67%, for 60, 70, and 80 km h^{-1}, respectively), $F < 1$. Thus, drivers appeared to invoke an *invariant* control strategy in their production of resultant decelerative forces, regardless of speed. This is supportive of the hypothesis that coordinated driving, deceleration (both controlled and emergency braking) and locomotion in general may primarily be on the basis of higher-order invariants of ambient energy distributions that constitute the relevant prospective information for coordinated perception–action phenomena (e.g., optical and/or GIF-based TTC information) (Doyle et al., 2000; Gibson, 1979; Stoffregen & Bardy, 2001; Warren, 1995, 1998).

In contrast to the above invariance of peak deceleration with respect to speed, there was a group difference in that peak deceleration was postponed by the ID (80%) in comparison to the ED (55%), $F(1,6) = 43.35$, $p < 0.01$. The results are consistent with the finding that the relevant control action of the driver, the time to peak

Table 3
Means (and standard deviations) for the emergency braking task performed as a function of skill group (experienced and instructor) across three speeds (60, 70, and 80 $km\,h^{-1}$)

	Experienced			Instructor		
	60	70	80	60	70	80
Pre-braking speed ($km\,h^{-1}$)[a]	59.3 (6.7)	68.8 (5.5)	80.8 (4.4)	61.2 (4.6)	69.2 (3.1)	78.6 (3.0)
Braking distance (m)[a]	33.0 (8.6)	42.4 (13.9)	52.7 (7.8)	31.8 (4.2)	41.2 (5.0)	48.3 (6.5)
Braking time (s)[a]	3.10 (0.65)	3.64 (0.76)	4.20 (0.76)	2.96 (0.18)	3.30 (0.24)	3.42 (0.18)
Average footrest force (N)[b]	84 (25)	81 (21)	92 (29)	173 (73)	171 (30)	184 (71)
Peak footrest force (N)[b]	103 (30)	101 (26)	112 (37)	241 (108)	238 (48)	263 (108)
Average deceleration (g)[a]	−0.52 (0.07)	−0.54 (0.08)	−0.53 (0.08)	−0.56 (0.04)	−0.57 (0.05)	−0.63 (0.04)
Peak deceleration (g)	−0.81 (0.14)	−0.81 (0.14)	−0.78 (0.13)	−0.91 (0.05)	−0.89 (0.04)	−0.92 (0.05)
Time to peak deceleration (s)[a]	1.71 (0.70)	2.08 (1.00)	2.41 (0.56)	2.36 (0.15)	2.60 (0.45)	2.78 (0.13)
Time to peak deceleration (%)[b]	55 (11)	56 (20)	53 (10)	80 (5)	79 (9)	81 (3)
Time to peak brake depression (s)[a]	1.54 (1.02)	1.47 (1.11)	1.67 (1.11)	2.51 (0.15)	2.43 (0.78)	2.90 (0.20)
Time to peak brake depression (%)[a,b]	47 (20)	38 (20)	37 (19)	85 (6)	73 (18)	85 (2)

[a] Significant main effect due to speed.
[b] Significant main effect due to group.

brake depression, was later for ID (81%) compared to ED (41%), $F(1,6) = 15.44$, $p < 0.01$. There was also a marginal effect of speed on the time to peak brake depression (66%, 55%, and 61%, for 60, 70, and 80 $km\,h^{-1}$, respectively), $F(2,12) = 3.55$, $p = 0.06$.

Importantly, there were group differences with respect to bracing forces required to resist the AP g-forces tending to push the body forward during braking. The average footrest force was greater for ID (176 N) than for ED (85 N), $F(1,6) = 8.55$, $p < 0.05$, as was peak footrest force (ID = 247 N; ED = 105 N), $F(1,6) = 10.66$, $p < 0.05$.

The preceding differences in braking style can be seen in the acceleration and braking profiles displayed for a representative ID and ED in Figs. 7 and 8. From Fig. 7c and e it may also be seen that the onset of the application of the footrest force for the driving instructor tended to coincide with the onset of the deceleration of the vehicle. In contrast, the ED represented in Fig. 8e did not increase the footrest force during braking. Instead this driver probably relied on the passive restraint provided by the seatbelt or pushed harder against the steering wheel in order to provide postural stability in the AP direction. Since standard 3-point diagonal set belt design

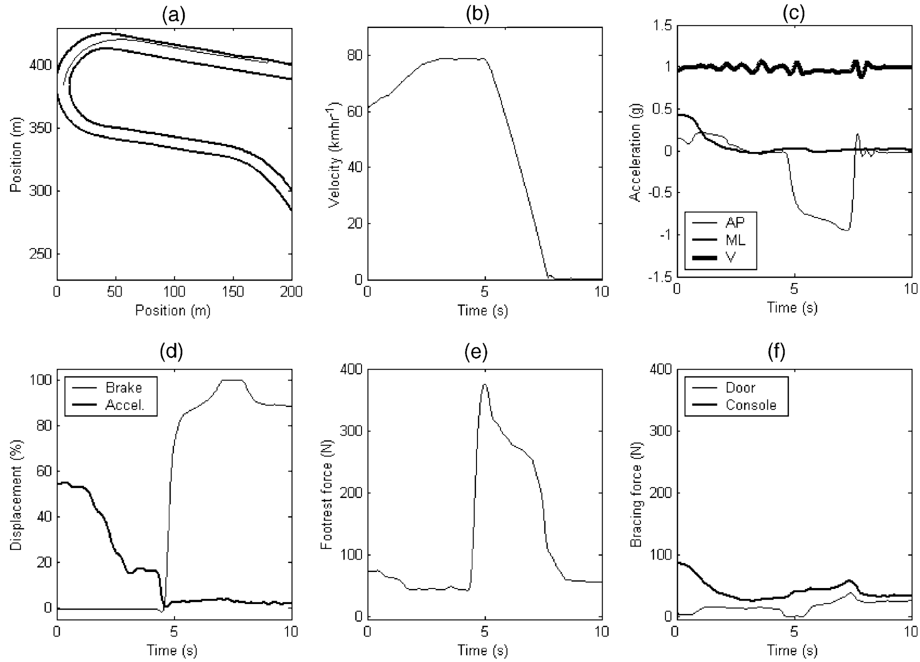

Fig. 7. Representative data for an ID performing the emergency braking task at 80 km h^{-1}. (a) GPS trajectory with respect to track (braking occurred on the straight after exiting the curve), (b) car velocity, (c) car acceleration in the AP, ML and V directions, (d) brake and accelerator pedal depression, (e) footrest force, (f) door and console bracing force.

reflects a compromise between providing stability and allowing mobility, the seatbelt does not fully stabilise the upper body in critical manoeuvres such as emergency braking. Active stabilisation via the footrest is the preferred means of providing postural stability during braking since the use of the steering wheel to stabilise the body (through increased grip pressure) would significantly compromise the sensitivity to and control of steering.

3.2.3.3. Swerve and recovery. Representative data for an ID and an ED performing the swerve and recovery task at 50 km h^{-1} are displayed in Figs. 9 and 10. Each driver was required to approach the marker grid at the required speed, pass between two entry markers on the right-hand side of the lane, swerve to the left and around the centre marker, move quickly back onto the right side of the road and exit between two exit markers. The ED were able to reduce the destabilising lateral accelerations acting on the body and the vehicle by applying the brake (Fig. 10d) and consequently decreasing speed and magnitude of the g-forces during the swerve. In contrast, the ID avoided braking suddenly, and could tolerate significantly greater lateral accelerations than the ED because the ID invoked active bracing using the footrest, door, and console (Fig. 9c and f).

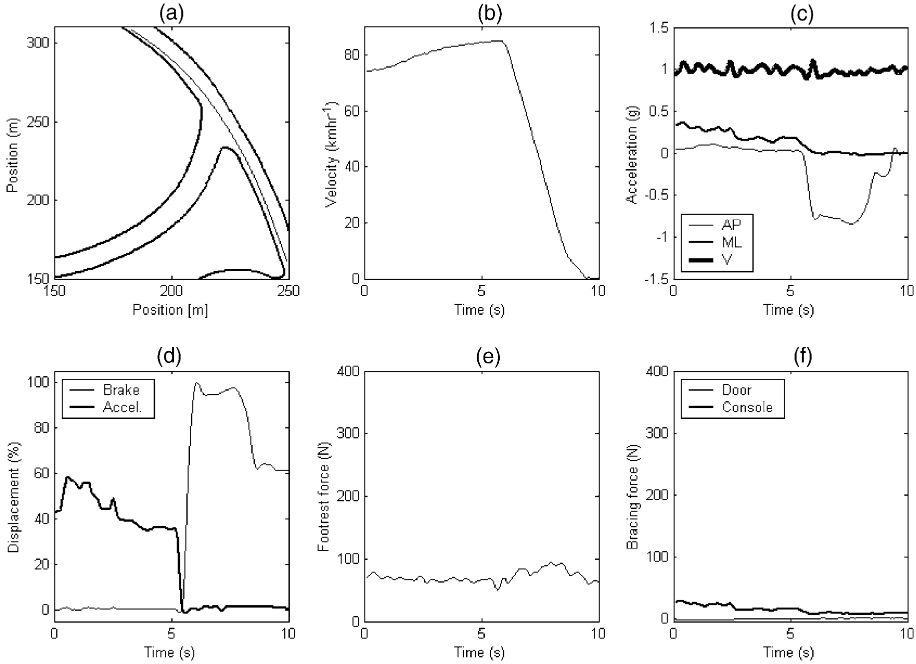

Fig. 8. Representative data for an ED performing the emergency braking task at 80 km h^{-1} (see Fig. 7 caption for details).

Summary data for the swerve and recovery task are presented in Table 4. Actual entry speed was significant (39.84, 44.31, and 48.25 km h^{-1}, for 40, 45, and 50 km h^{-1}, respectively), $F(2,12) = 81.82$, $p < 0.001$, and was higher for ID (45.53 km h^{-1}) compared to ED (42.74 km h^{-1}), $F(1,6) = 5.69$, $p = 0.05$, thus indicating a more cautionary approach by the ED to the potential hazard to be avoided. Actual exit speed was significant (38.72, 41.88, and 45.39 km h^{-1}, for 40, 45, and 50 km h^{-1}, respectively), $F(2,12) = 34.20$, $p < 0.001$, and was higher for ID (43.44 km h^{-1}) compared to ED (40.55 km h^{-1}), $F(1,6) = 10.24$, $p < 0.05$. As ID were able to complete the task without using the brake, this meant that the velocity of the car at exit was maintained closer to both the required and actual entry speed compared to ED.

For peak rightward lateral acceleration around the entry marker, there was a marginally significant interaction between group and speed (ID = 0.29, 0.35, 0.36 g; ED = 0.17, 0.18, 0.21 g, for 40, 45, and 50 km h^{-1}, respectively), $F(2,12) = 18.27$, $p = 0.07$. This suggested that the peak lateral acceleration at entry was less affected by speed in ED than in ID. Overall, there was a significantly larger lateral acceleration for ID (0.34 g) than for ED (0.19 g), $F(1,6) = 21.62$, $p < 0.01$. Peak lateral acceleration at entry also increased across speeds (0.23, 0.27, and 0.29 g, for 40, 45, and 50 km h^{-1}, respectively), $F(2,12) = 18.27$, $p < 0.001$.

For the corresponding door force at entry (at the time of peak lateral acceleration), there was a marginally significant interaction between group and speed

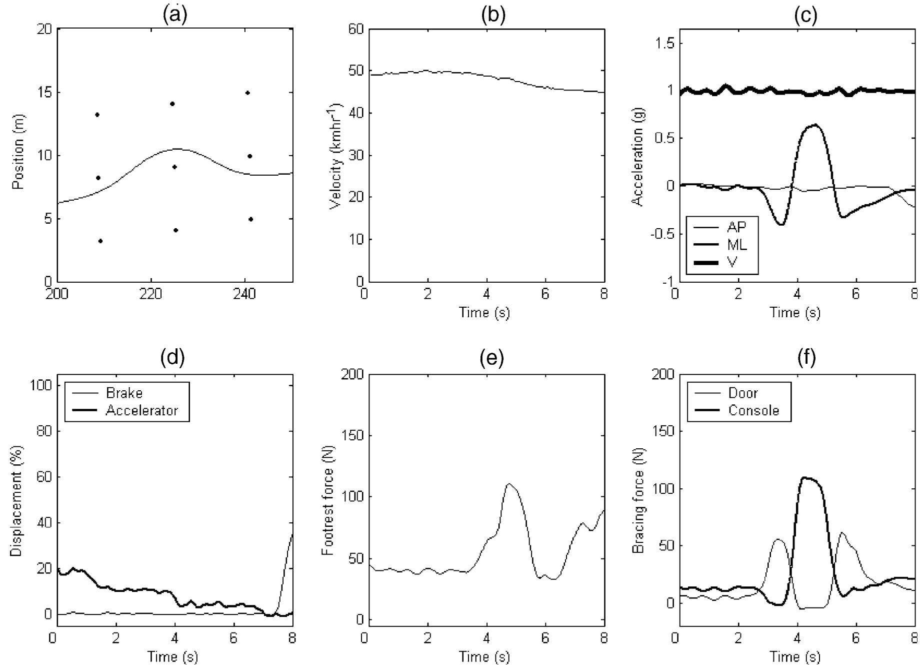

Fig. 9. Representative data for an ID entering from the right and performing the swerve and recovery task at 50 $\mathrm{km\,h^{-1}}$. (a) GPS trajectory with respect to markers, (b) car velocity, (c) car acceleration in the AP, ML and V, (d) brake and accelerator pedal depression, (e) footrest force, (f) door and console bracing force.

(ID = 39, 52, 46 N; ED = 2, 2, 3 N, for 40, 45, and 50 $\mathrm{km\,h^{-1}}$, respectively), $F(2,12) = 4.20$, $p < 0.05$. This suggested that the bracing forces against the door for the ED were unaffected by speed in comparison to the ID. The door force was greater for ID (46 N) than for ED (2 N), $F = 40.04$, $p < 0.001$, but the effect of speed was only marginally significant, $F(2,12) = 4.27$, $p = 0.08$.

Around the central marker, the peak leftward lateral acceleration for ID (0.54 g) was marginally greater than for ED (0.41 g), $F(1,6) = 4.73$, $p = 0.07$. However, as speed increased, so did peak leftward lateral acceleration (0.42, 0.49, and 0.52 g, for 40, 45, and 50 $\mathrm{km\,h^{-1}}$, respectively), $F(2,12) = 16.70$, $p < 0.001$. The corresponding console force around the central marker was greater for ID (96 N) than for ED (28 N), $F(1,6) = 33.80$, $p < 0.001$, and as speed increased, so did console force (49, 65, and 71 N, for 40, 45, and 50 $\mathrm{km\,h^{-1}}$, respectively), $F(2,12) = 6.84$, $p < 0.05$.

The peak lateral acceleration around the exit marker for ID (0.28 g) was not significantly different from that for ED (0.20 g), although the corresponding door force at that time was greater for ID (43 N) than for ED (2 N), $F(1,6) = 32.49$, $p < 0.001$, again indicating that active bracing was invoked as a stabilisation strategy. Speed

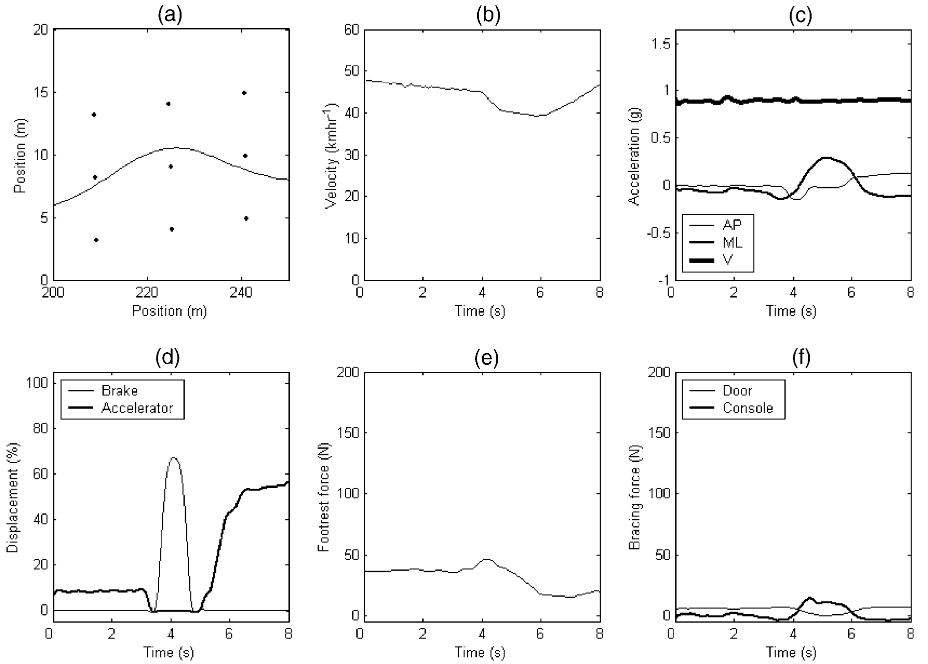

Fig. 10. Representative data for an ED entering from the right and performing the swerve and recovery task at 50 $\mathrm{km\,h^{-1}}$ (see Fig. 9 caption for details).

had a significant effect on peak lateral acceleration at exit (0.21, 0.24, and 0.28 g, for 40, 45, and 50 $\mathrm{km\,h^{-1}}$, respectively), $F(2, 12) = 8.08$, $p < 0.05$, but had no effect on door force at exit.

4. General discussion

4.1. Time-to-contact information in driving

The current study constitutes the outcome of initial attempts to use in-field data acquisition techniques to evaluate key hypotheses from the ecological/dynamical systems perspective on the control and coordination of locomotion. Specifically, we considered that driving in general and skilled driving in particular is founded upon the detection of information (i.e., higher-order invariants of ambient energy distributions) that provides a constraint on the underlying information-based dynamical system. Through the use of GPS technology, it is now possible to compare the extensive results of previous computer simulations on the perceptual control of locomotion with data from actual driving. In Experiment 1 we used GPS data on vehicle trajectory to evaluate Lee's (1976) tau and tau-dot hypotheses of controlled braking. The

Table 4
Means (and standard deviations) for the swerve and recovery task as a function of skill group (experienced and instructor) and across three speeds (40, 45, and 50 $\mathrm{km\,h^{-1}}$)

	Experienced			Instructor		
	40	45	50	40	45	50
Speed at entry marker ($\mathrm{km\,h^{-1}}$)[a,b]	38.6 (2.4)	42.8 (1.7)	46.8 (3.1)	41.0 (0.4)	45.8 (1.5)	49.7 (1.7)
Speed at exit marker ($\mathrm{km\,h^{-1}}$)[a,b]	37.6 (1.2)	40.0 (1.9)	44.0 (3.1)	39.8 (0.7)	43.8 (1.6)	46.7 (1.6)
Peak lateral acceleration around entry marker (g)[c]	0.17 (0.06)	0.18 (0.05)	0.21 (0.06)	0.29 (0.04)	0.35 (0.04)	0.36 (0.04)
Door force at peak lateral acceleration around entry marker (N)[c]	2 (0)	2 (1)	3 (1)	39 (10)	52 (20)	46 (13)
Peak lateral acceleration around central marker (g)[a,b]	0.37 (0.08)	0.41 (0.10)	0.45 (0.12)	0.48 (0.07)	0.57 (0.08)	0.59 (0.08)
Console force at peak lateral acceleration around central marker (N)[a,b]	20 (10)	29 (29)	36 (29)	79 (15)	101 (12)	107 (9)
Peak lateral acceleration around exit marker (g)[b]	0.18 (0.06)	0.19 (0.08)	0.23 (0.11)	0.24 (0.07)	0.29 (0.04)	0.33 (0.03)
Door force at peak lateral acceleration around exit marker (N)[a]	1 (1)	2 (1)	2 (2)	36 (12)	48 (20)	46 (14)
Peak footrest force (N)	61 (26)	64 (35)	68 (33)	58 (19)	55 (15)	61 (13)

[a] Significant main effect due to group.
[b] Significant main effect due to speed.
[c] Significant group by speed interaction.

results provide data and confirmation, to our knowledge for the first time, that during actual driving vehicle deceleration profiles are consistent with a control strategy whereby a driver strives to maintain $\dot{\tau} \approx 0.5$ and in doing so achieves a braking strategy that maintains constant deceleration.

The findings also confirm that across a range of speeds both IDs and EDs initiated braking at a point at which the TTC would have been 5 s if they had maintained a constant velocity. The suggestion therefore is that given a range of initial speeds together with reasonable and tolerable decelerative g-forces from which to select a deceleration strategy from, drivers gauge the time at which to initiate braking similarly – they act in accord with Lee's (1976) prediction that braking will be geared to an invariant value of the optical information (tau), specifically when tau indicates TTC = 5 s. Although this was the case for both trained and untrained drivers (i.e., both groups were EDs), it will be of interest whether novice drivers act similarly or whether controlled perception-action coupling is a learned phenomenon (future experiments aim to verify this).

Whether the TTC information is provided by global optical tau or some other ambient energy distribution remains an open question. For example, GIF information about deceleration is potentially available in the patterning of the decelerative forces in the antero-posterior direction. If $\dot{\tau} \approx 0.5$ and thus constant deceleration is achieved through appropriate modulation of braking forces (e.g., by varying traction forces of the tyres via modulation of brake pressure) (Yilmaz & Warren, 1995), then the absence of antero-posterior forces (at constant deceleration) would in itself be informative about braking strategy and would thus constitute information about braking performance (e.g., as detected by the vestibular and haptic perceptual subsystems; Gibson, 1966). Whether conjoint optical and GIF information might provide the unique and specific information for braking by being related at a higher-order and more abstract level (e.g., in the "global array"; Stoffregen & Bardy, 2001) remains an intriguing possibility and will be explicitly addressed in our future experiments both on the driving track and in simulations.

Although numerous, many of the extant studies of TTC have involved driving simulators or monitor-sized visualisations which, although permitting precise control of optically presented information, must compromise visual information due to the size of the display. The current study, because it occurred using an actual car in an on-road environment, meant that normal peripheral vision was potentially available to the driver for the detection of optic flow-based global tau information. This would have been in addition to more accurate optical expansion information detected foveally and would have helped support optimal detection of any purported tau variable (Caird & Hancock, 1994; Manser & Hancock, 1996; Tresilian, 1991). Indeed, it has been argued that the sometimes incongruous results (e.g., underestimations) of TTC are due to inappropriate use of a *spontaneous disappearance paradigm* in simulations where experiment participants must indicate when an object would have collided with the viewpoint if the simulated approach of the object had continued. In cases where a more relevant control action is required by using a *collision-avoidance paradigm* (e.g., actual steering to avoid collision rather than pressing a button in a simulation) such misjudgements are less prevalent. Further, in simulations of locomotory approach, when optical information in addition to an optically expanding object is presented (e.g., information due to occlusion behind a natural object or the addition of adjacent roadside texture), then estimates of TTC are significantly improved (Hancock & Manser, 1997; Hesketh & Godley, 2002). This further reinforces the possibility that higher-order invariants – either in a multimodal global array or in a unimodal but embellished array – exist in natural driving situations, and that such information constrains driving. It also supports the tenet that such information is often profoundly relational in nature (Gibson, 1966), and that further ecologically inspired research into the nature of visually perceived collision events should strive to incorporate such multiple sources of information.

4.2. *Affordances and prospective control*

That a larger buffer-zone was maintained in front of the stationary car by the instructors but not by the EDs may be evidence for information-based direct perception. That is, it is the meaningful consequences of an action that are directly apprehended via perception during an activity such as driving. The concept of a buffer-zone is similar to the "field of safe travel" of Gibson & Crooks (1938) who long ago speculated that perception (and control) during driving must be based upon prospective information available in the global optical field that can potentially specify upcoming events and their consequences for action (see also Kadar & Shaw, 2000). Indeed, it has long been proposed (and debated) that the relevant objects of perception must be functionally defined and must be with reference to both the organism and the environment (e.g., Gibson, 1966, 1979; Turvey, 1992; Warren, 1995). Specifically, the perceived properties of an object (or event) are related to the possibilities for action that the object (or event) affords an intentional agent. In the case of driving, it is the *affordances* of the road environment (co-defined relative to the driver) that are directly apprehended as a function of an intentional perceptual process (Gibson, 1979; Hancock et al., 1995; Reed, 1996). The buffer-zone that was maintained by the instructors (but not the EDs) suggests that for the instructors, the affordance of approaching a car stationed at a traffic light is different to (and consequently is perceived differently from) the affordance of a stop-line with no stationary vehicle present. Theoretically, after Gibson, an information-based explanation notes that different visual information is available in these two situations. The instructors, because of their greater perception–action skills of driving, were sufficiently sensitised to relevant visual information and were able to differentially act resulting in different stopping distances for the two scenarios. In contrast the EDs failed to detect information differentiating the two scenarios and consequently acted similarly leaving no buffer-zone in both the stationary vehicle and the stop-line cases. Arguably, across the two scenarios, the instructors perceived two different affordances whereas the EDs perceived the same affordance. The EDs perceived the same affordance – a stopping place – even though the physical environment was different (i.e., stationary car vs. stop-line). The instructors, however, perceived two different affordances. The first affordance involving the stop-line might be defined as "a place that affords bringing a vehicle to a standstill nearby a target". The second affordance involving the parked car at the traffic light might be defined as "a place that affords bringing a vehicle to a standstill such that one can still manoeuvre forward and out of the way of other vehicles if an emergency arises". For the EDs, the ontological status of the latter affordance remains an intriguing theoretical question: Did the affordance involving the parked car exist for the untrained but EDs in the same way it existed for the IDs? Although the parked car affordance was not perceived by the EDs (since it was not acted upon in the same way as by the instructors), this does not imply that it did not exist. Due to the fact that an ED can be *trained* to act towards a parked-car-at-traffic-light scenario in a similar fashion to an instructor (e.g., HPDC training technique), this implies the existence of a real possibility for action (i.e., an affordance) towards which behavioural modification can be directed, and about which information is available to be detected.

4.3. Active stabilisation and skill

In addition, results indicated that untrained EDs acted differently from instructors when confronted by the prospect of braking before an apparently solid stationary object (i.e, the parked vehicle) rather than an intangible stop-line. Consistent with an interpretation based on the concept of affordances, the EDs initiated braking earlier and farther from the target when having to stop before the substantial object than before the insubstantial stop-line. In sum, such results support both a realist perspective on prospective control, and a further examination of affordances as the ontological basis for coordinated perception and action (Turvey, 1992).

From the results of Experiment 2 it can be concluded that HPDC driving instructors use dramatically different driving strategies to untrained but well-experienced drivers when performing cornering, emergency braking, and swerve and recovery manoeuvres. Differences were observed in the path taken by the vehicle as well as in the manner in which the body was stabilised via the use of bracing forces. IDs found a definite apex in their progress through the corner and made greater use of the width of the road and so were able to "straighten out the corner". The results indicated that instructors maintained postural stability during cornering by bracing and actively applying lateral forces to counteract destabilising "centrifugal" forces. The postural stabilisation strategy used by IDs is consistent with the discovery that active stabilisation and postural stability increases one's sensitivity to visual and vestibular information (Foque et al., 1999; Jeka, 1998; Jeka et al., 1996, 1998, 1997; Patterson, Cacioppo, Gallimore, Hinman, & Nalepka, 1997; Riccio, 1995; Riccio et al., 1992; Smith, Cacioppo, & Hinman, 1997; Stoffregen et al., 2000; Treffner & Kelso, 1999). In contrast to IDs, EDs did not use the knees to brace appropriately against lateral accelerations and therefore had either less postural stability, gained their postural stability by leaning and aligning with the DOB, or used other means such as increasing grip pressure and "hanging off" the steering wheel in order to use it as a postural anchor-point. However, the use of the steering wheel to enhance postural stability should be strongly discouraged. Excessive grip force can lead to oversteering in emergency situations, as well as being completely inappropriate given its prime function which is to steer a steady and unbiased course (Gardner, 1998). Overall, the results indicate that, compared with the instructors, the EDs were dynamically less stable – both in posture and (consequently) in driving performance.

In the emergency braking task, the instructors stopped in a shorter distance than the experiencing drivers by using a gradual rather than sudden braking strategy (i.e., the "brush-and-bury" braking technique) (Gardner, 1998). Whereas EDs tended to reach peak brake depression and hence peak vehicle deceleration rapidly (i.e., a "slam-on-the-brakes" strategy), the IDs tended to apply force to the brake pedal in two distinct phases. In the first phase the brake was depressed to about 80% of maximum, which was followed by a second phase whereby increasing pressure was gradually applied to the brake so that maximum depression occurred as the car came to a stop. The graduated application of the brake in the manner used by the IDs minimises sudden weight transfer to the front wheels associated with sudden braking. Maintaining a relatively equal weight distribution between the front and rear tyres through gradual application of the brakes enhances braking performance since the rear brakes can contribute to a much greater extent compared to when they are unweighted during sudden braking.

As speed increased in the emergency braking task, so also did the distance required to bring the car to a standstill. Since the EDs tended to engage ABS with their slam-on-the-brakes emergency braking strategy (or lack thereof), it would seem that prospective information about stopping target was not utilised. In contrast, the instructors never engaged ABS and through their "brush-and-bury" technique, tended to bring the vehicle to a standstill in a shorter distance than did the EDs. This suggests that even supposedly "ballistic" manoeuvres such as the knee extension of emergency braking can be controlled through the use of appropriate perceptual information. Further evidence that such actions are constrained via perceptual information comes from the finding that peak deceleration was reached at the same proportion of total braking time regardless of speed. Again, the nature of such information requires further investigation into whether it involves visual, gravitoinertial, acoustic, or a higher-order relation involving all three modalities (cf. Stoffregen & Bardy, 2001). Experiments involving driving simulators (e.g., where GIF information is absent or acoustic information can be added and controlled) will therefore have an important role to play in further studies of information-based control of driving (cf., Hesketh & Godley, 2002).

The results of the swerve and recovery task suggest that the lack of appropriately timed door and console bracing forces amongst normal EDs may be a limiting factor in resisting lateral accelerations associated with a critical avoidance manoeuvre. Although braking helps to decrease lateral accelerations during swerve and recovery, this could be dangerous (especially at high speeds and on dry road without ABS) since sudden braking can result in the tyres "biting" the road surface resulting in dramatic destabilisation of the vehicle with an increased likelihood of collision. In contrast, the coordinated bilateral bracing technique of the HPDC instructors, together with the appropriate scaling of force with speed and associated g-forces, provides an effective counter-measure against the destabilising forces and ensuing skidding that potentially accompanies the majority of single-vehicle collisions.

The driving technique used by the IDs of the current study can be characterised as one of dynamic balance through active stabilisation (Kelso, 1995; Treffner & Kelso, 1999). During tasks where the destabilising g-force was sideways to the vehicle (e.g., in cornering and in swerve and recovery), the instructors applied greater bracing forces against the door and console than did the EDs. Although postural stability was not explicitly measured in this study, results indicate that the use of lateral bracing forces by the instructors represents an attempt of the motor control system to achieve and maintain postural stability. A similar strategy was used by the instructors during emergency braking and involved resisting the g-forces associated with vehicle deceleration by applying pressure with the left foot against the footrest.

Importantly, since pressing with the foot and lower leg would also create co-contraction of the upper body musculature (e.g., the core stabilising muscles of the abdomen and pelvis; Richardson, Jull, Hodges, & Hides, 1999) this technique not only improves postural stability by preventing forward movement of the body but also improves lateral stability of the trunk. In addition, the lower body is more symmetrically braced by using both feet instead of only a single foot on the brake pedal. This would result in a greater base of support and permit the driver to rely less upon the steering wheel as a postural anchor-point.

The manner by which EDs achieved postural stability is not completely clear from the current study. Frank Gardner, who is largely responsible for developing the technique, suggests that untrained drivers may use the steering wheel to provide postural stability during critical manoeuvres to the detriment of their steering performance (Gardner, 1998). The specific means by which drivers achieve postural stability during driving is the subject of ongoing research by our research group and involves simultaneous measurement of head and body movement and steering wheel grip force (Doyle et al., 2000; Treffner et al., 2001).

In summary, the results indicated that the HPDC instructors used a consistent cornering trajectory, a consistent braking strategy and were able to perform the swerve and recovery task more effectively than the EDs. During the cornering and swerve and recovery tasks IDs applied greater bracing forces against the door and console than EDs. IDs also applied greater forces to the footrest during emergency braking than EDs. The greater use of leg bracing by IDs to resist g-forces represents an attempt to enhance postural stability and maintain a balanced base of support. Bracing with the legs also reduces the need to stabilise the upper body via steering wheel grip force and may therefore help reduce the risk of oversteering in emergency situations.

5. Concluding remarks

Recent theoretical advances in perceptual-motor control research supports the HPDC approach of improving postural stability in order to heighten sensitivity to perceptual information (and vice versa) (e.g., Foque et al., 1999; Jeka, 1998; Jeka et al., 1996, 1998, 1997; Patterson et al., 1997; Stoffregen et al., 2000; Riccio, 1995). Importantly, the particular driver-training programme of the current study is not an opportunity for individuals to "have fun and throw the car around" in a controlled environment. Rather, the sole purpose of the HPDC technique is improved driver attention to car and road conditions, better vehicle control and coordination skills, and therefore potentially increased safety in driving. It is crucial to recognise that not all advanced driving courses are the same (Lund & Williams, 1985; Struckman-Johnson et al., 1989). Some recent critiques have prematurely concluded that driver training may be counter-productive and even a waste of resources. A popular reason given for such purported counter-productivity is that advanced driver-training engenders "over-confidence" in the driver (e.g., Christie, 2001). There is, however, little evidence in the peer-reviewed literature to support such a contention. Therefore, any well-founded attempt to improve driving skill should be viewed with considerable interest (rather than disinterest), and those that claim to actually *have* a technique to teach, should welcome careful examination and evaluation through scientific means. Our investigations of the HPDC technique thus far confirm that it is indeed worthy of attention, especially because of its emphasis on dynamic stability as a prerequisite for improved attention and control (Doyle et al., 2000; Treffner et al., 2001, 2002). That the learning and creation of new patterns of perceptual-motor coordination can now be well-addressed and understood using the theoretical framework of stability-based dynamical systems (e.g., Kelso & Zanone, 2002; Schmidt, Treffner, Shaw, & Turvey, 1992) is further reason for investigating a driver-training programme that both explicitly and tacitly utilises dynamic stability as the foundational concept.

It is now becoming clear that higher-order cognition (e.g., attention and thought processes) can modulate the level of biarticular links (or synergies) that provide the basis of functionally stable motor coordination patterns (Amazeen et al., 1997; Pellecchia & Turvey, 2001; Riley et al., 1997; Treffner & Peter, 2002; Zanone et al., 2001). Our most recent experiments at the HPDC track address the discovery that the use of a mobile phone (both hands-held and hands-free) while driving is strongly correlated with a degradation in driving performance and increased likelihood of an accident (Haigney & Westerman, 2001; Redelmeier & Tibshirani, 1997). We are also conducting an examination of the efficacy of HPDC technique through measuring the influence of closed-circuit driver-training on driving performance prior to, following, and at extended intervals after initial training. Through a joint collaboration with HPDC and Vigil Systems (Brisbane, Qld), we are determining the efficacy of driver-training by comparing driving performance with long-term data gained from extended driving episodes on the open road (e.g., for a week of typical driving). As Vigil Systems can provide in-car data-loggers for the collection of long-term driving data not unlike the data herein presented, and since they can be installed at relatively low cost in numerous vehicles, it will be possible to obtain a unique insight into the relation between stability-based training and driver performance. Of particular concern will be the nature of driving variability. Already apparent in the present results is an increased variability of performance for experienced drivers in comparison to instructors. Recent developments in perceptual-motor control research have emphasised the centrality of variability as a prominent categorical signature of the differential stability of the underlying dynamics of individuals under different circumstances (Bassingthwaighte, Liebovitch, & West, 1994; Collins, De Luca, Burrows, & Lipsitz, 1995; Kelso, 1995; Riley & Turvey, 2002). Through the use of fractal time series techniques and long-range correlation analysis (e.g., Chen, Ding, & Kelso, 2001; Collins et al., 1995; Treffner & Kelso, 1999) it may be possible to quantify the degree to which driver-training improves the stability of the underlying dynamical system that constitutes coordinated driving performance. Such results would confirm the wisdom behind designing training strategies that, first and foremost, target the improvement of the foundational basis of successful locomotion – postural stability – before attempting to modify higher-order aspects of driving such as visual attention, general awareness, and cognition. For the moment, the current results confirm that active stabilisation through postural bracing is a straightforward and effective strategy for improving the dynamic stability of driving performance.

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