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Hands-free mobile phone speech while driving degrades coordination and control

Paul J. Treffner [a,*], Rod Barrett [a,b]

[a] *Complex Active Visualisation (CAV) lab, Institute for Integrated and Intelligent Systems, Griffith University, Australia*
[b] *School of Physiotherapy and Exercise Science, Griffith University, Australia*

Abstract

Using a closed-circuit driving track environment, we investigated the influence of using a hands-free mobile (or cell) phone on various biomechanical and perceptual factors that underlie the control of driving. Results showed that in three tasks representative of everyday driving conditions, the perceptual control of action was compromised when compared to a control condition where no mobile phone conversation was present. While conversing, critical control actions related to braking were postponed on approach to a corner. During controlled braking, as when approaching a stationary car at a traffic light, the degree of braking was reduced and braking style was altered in a non-optimal manner. During an obstacle avoidance task, car dynamics were affected as a result of the conversation. Interpretation of the results is motivated by the ecological approach to perception–action and the theory of affordances. It is concluded that a driver's sensitivity to prospective information about upcoming events and the associated perception and awareness of what the road environment affords may both significantly be degraded when simultaneously using a hands-free mobile phone. Implications for intervention and policy are discussed.

Keywords: Mobile (cell) phones; Perception; Affordances; Driving; Information; Ecological approach

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[*] Corresponding author.
E-mail address: L84sky@hotmail.com (P.J. Treffner).

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1. Introduction

It is well known that a major factor underlying the cause of driving accidents is insufficient attention to the relevant dimensions of the optic array (Schiff & Arnone, 1995; Warren & Wertheim, 1990). The antecedent of inattention—adverse cognitive activity—can detrimentally affect concurrent driving performance. This is nowhere more dramatic than in cognitive activities such as concurrent mobile (or cellular) phone use during the largely perceptual task of driving (Haigney & Westerman, 2001). Although manual handling of the mobile phone can lead to pronounced distraction while driving (Salvucci & Macuga, 2002), and although speech articulation has evolutionary origins in manual gestures (Corballis, 2002; McNeill, 2000; Treffner & Peter, 2002), a more subtle effect of mobile phone use involves the fact that coordination can be degraded if directed attention or other cognitive activity is introduced in addition to the primary task (Pellecchia & Turvey, 2001; Spence & Read, 2003). For example, if one focuses attention on one's dominant (preferred) hand in a bimanual coordination task, then an increased asymmetry results which may be detrimental to performance (Amazeen, Amazeen, Treffner, & Turvey, 1997; Riley, Amazeen, Amazeen, Treffner, & Turvey, 1997). In sum, there appears to be an inherent relation between cognitive activity, speech, and motor coordination.

1.1. Mobile phones

Although use of hand-held mobile phones is increasingly becoming illegal in states world-wide, hands-free usage (using either speaker or earphone) remains legal in most countries. Speaker-based phones have been shown to create greater cognitive workload and frustration (due to acoustic interference) than earphone-based systems (Matthews, Legg, & Charlton, 2003) but this fact has not yet been recognised by manufacturers or users. Indeed, the availability of mobile phones has been considered an asset to road-users (e.g., to call emergency services; Chapman & Shofield, 1998; Nunes & Recarte, 2002). However, cost benefit analysis fails to indicate a definite advantage for mobile phone use in driving situations (Cohen & Graham, 2003). Consequently, hands-free mobile phones may still pose a serious health risk due to the behavioural consequences of their use during driving (Dreyer, Loughlin, & Rothman, 1999; Haigney & Westerman, 2001; Rothman, 2000; Strayer & Johnson, 2001).

The mechanisms that underlie the influence that speaking on a mobile phone has on driving are complex. However, both epidemiological and experimental studies agree that degraded attention plays a pivotal role. An epidemiological study of New York drivers who had experienced an accident revealed that the likelihood of an accident was increased by a factor of 4 (similar to being legally drunk) compared to when not using the phone (Redelmeier & Tibshirani, 1997). Importantly, no difference was found between hand-held and hands-free devices, and the increased risk was not relative to driving with no distractions; it was relative to normal driving circumstances complete with distractions (e.g., car radio, passenger conversation, etc.; Redelmeier & Tibshirani, 2001). Another epidemiological study showed that New York drivers who spoke for more than 50 min per month on a mobile phone while driving increased their likelihood of an accident occurring by at least 5-fold (Violanti & Marshall, 1996). It has been confirmed that the heaviest users of mobile phones have more than double the risk of an accident compared to the lightest users (Dreyer et al., 1999; Laberge-Nadeau et al., 2003).

Results from driving simulators indicate that simultaneous mobile phone use decreases a driver's ability to detect a car ahead decelerating with an increase of 0.5s in reaction time and 1s in time to contact (Lamble, Kauranen, Laakso, & Summala, 1999). Likewise, braking reaction times to a simulated car that suddenly slows down ahead of a driver were increased by 19% compared to when not speaking using a mobile phone (Consiglio, Driscoll, Witte, & Berg, 2003). Concurrent phone use decreases speed adopted (Haigney, Taylor, & Westerman, 2000) and increases by 30% the failure to respond to critical traffic situations (Hancock, Lesch, & Simmons, 2003; McKnight & McKnight, 1993). Most dramatically, in an emergency stopping scenario at 70mph, use of a mobile phone increased reaction time and distance travelled by 8m for a hands-free phone, 14m for a hands-held phone, with both conditions more detrimental than being legally drunk (which resulted in only a 4m extension of braking distance; Direct Line Insurance, 2002). Indeed, although more numerous than studies involving actual road driving, simulator studies consistently report that mobile phone usage degrades driving performance (Alm & Nilson, 1994, 1995).

1.2. Dynamics of speech-hand coordination

Speaking using a mobile phone is expected to strongly influence manual control and because of the increased attentional load due to simultaneous thought and speech, neural structures supporting the right hand (dominant in approximately 90% of the population) are expected to become significantly activated when (predominantly) left cerebral speech mechanisms are involved. Since hand movements can become strongly synchronised with speech articulation (Treffner & Peter, 2002), and because complex systems are primarily governed by *dynamical* (not mechanical) constraints, this can lead to ubiquitous emergent properties such as resonances—preferred coordination states based on increasingly stable bimanual coordination patterns (e.g., drumming rhythms consisting of frequency ratios between the hands of 2:5; 2:3, 1:2, 1:1) (Treffner & Turvey, 1993; Wannier, Bastiaanse, Colombo, & Dietz, 2001). With regards to speech–hand interaction, there are clear dynamical interactions between the two moving components (hand and jaw) and this can lead to entrainment and transitions between patterns (Treffner & Peter, 2002). Clearly, the opportunity for interaction between hand movements and concurrent speech is strong. Thus, in a study of mobile phone use while driving, such experimental evidence should be considered.

How can one evaluate or quantify the difficulty of speaking while driving? Posner's "information reduction" methodology (Posner & Rossman, 1965) has recently been used to quantify the complexity of cognitive tasks and the degree to which such tasks can influence bimanual coordination. For example, reporting the sum of two digits yields 2.8bits of information reduction, whereas counting backwards from 200 by 3 yields 3.8bits of information reduction. In a conversation, there is less information provided in the utterance "seven" compared to "four and three" since there are many different combinations (more uncertainty) of how two single-digit numbers could produce a sum of 7. In contrast, "four and three" is definite with regards to its sum (i.e., 7). Building upon prior work on functional asymmetry, handedness, and attention (Amazeen et al., 1997; Riley et al., 1997), and employing straightforward motor coordination tasks (e.g., in-phase or anti-phase bimanual coordination patterns), Pellecchia and Turvey (2001) showed that the location of the dynamical attractors (stable points) of bimanual coordination patterns are shifted when concurrent cognitive activity is required. This was remarkable in that the shift in coordination states was not explainable by previously understood mechanisms such as imposed physical asymmetries (e.g., differential weighting of the pendula) or inherent asymmetries (e.g., due to handedness; Treffner & Turvey, 1995, 1996). Importantly, Pellecchia and Turvey (2001) showed that the degree of pattern shift was a linear function of cognitive task difficulty (measured in bits of information reduction) and that stability of coordination reduced (variability increased) under conditions of increased cognitive loading. These results have significant implications for our ability to quantify the effects of mobile phones on the dynamics and coordination of driving.

1.3. Ecological information, coordination, and control

The current experiment involved an examination of the perceptual-motor coordination underlying driving on a closed circuit driving track and investigated how anticipatory control of driving is compromised while maintaining a hands-free mobile phone conversation. Which aspects of the perception–action cycle for driving might be affected by concurrent speech on a mobile phone? Much research has been devoted to the role that optic flow and its higher-order derivatives have on the control and coordination of locomotion. Of particular interest is the property of optic flow that is correlated with the instantaneous time remaining until contact with an approaching surface. The quantity abstracted from such optic flow, known as "tau" (τ), is an optical property that can lawfully specify the "time (remaining) to contact" (TTC) with a surface such as a stationary car. Tau is defined as the inverse of the relative rate of optical expansion. Extensive experimentation has indicated that many biological systems appear to be sensitive to tau and use this quantity to "gear" their self-movements and to control the initiation of intentional actions such as a bird's leg extension in preparation for landing (Bootsma & Peper, 1993; Bradshaw & Sparrow, 2001; Lee & Young, 1985; Warren, 1998). Tau can therefore potentially provide a manner in which an organism can have its action directly coupled to environmental properties via the optic array. Further, such optical variables specify *future* conditions and so can be harnessed for prospective control of behaviour. Indeed, such anticipatory control is the hallmark of biological organisms that must continually be prepared for upcoming events rather than merely reacting to them once they occur.

Driving simulator studies have confirmed the ability to control steering on the basis of optic flow and tau (e.g., Duchon, Kaelbling, & Warren, 1998; Kim & Turvey, 1999). We recently demonstrated that tau information may be exploited under real driving conditions such as during prospective control of approach to a stationary car at a traffic light. It was shown that drivers initiate braking at an invariant TTC of approximately 5 s regardless of approach speed (60, 80, or $100\,\mathrm{km\,h^{-1}}$) (Treffner, Barrett, & Petersen, 2002). This five seconds rule was first predicted as the TTC for brake initiation that could be expected to provide comfortable and tolerable decelerative forces across a range of speeds (Lee, 1976).

In addition to tau, the first temporal derivative (rate of change) of tau can be defined which has the property of yielding numerical constants. Such a higher-order invariant can specify the *kind* of contact that will occur with a surface, that is, whether the current approach affords the driver, for example, a harsh collision or a soft contact. This quantity is known as "tau-dot" ($\dot{\tau}$), and specifies the *style* of contact (Lee, 1976; Lee, Young, & Rewt, 1992). If $\dot{\tau} > 0.5$ then a "hard" contact occurs with finite kinetic energy remaining at contact and overshooting of the target occurring. If $\dot{\tau} < 0.5$ then "undershoot" of the target occurs since all kinetic energy is fully dissipated before contact. If $\dot{\tau} = 0.5$, then ideal, smooth braking (i.e., constant deceleration) occurs since all remaining kinetic energy is dissipated as asymptotic approach to the target is achieved (Turvey, Carello, & Kim, 1990). Provided current conditions continue, tau-dot provides an appropriately attuned organism with anticipatory information that specifies whether an upcoming collision is likely to be dangerous (hard), safe (undershoot), or appropriate (Kim, Turvey, & Carello, 1993; Yilmaz & Warren, 1995). Research has shown the efficacy of exploiting this higher-order invariant of optic flow when decelerating and that organisms seem to behave in a manner consistent with a "constant tau-dot strategy" whereby $\dot{\tau} \approx 0.5$ and is achieved through continual and *intentional* control via small adjustments in the decelerative forces applied (e.g., via the foot and brake pedal; Warren, 1998). Note that any inanimate smooth object (e.g., a ball), when rolled along a flat surface, will exhibit a constant deceleration that corresponds to a tau-dot of *exactly* 0.5. However, organisms cannot simply "roll to a halt"; organisms have muscles, not wheels. They must intentionally *control* their decelerative forces, via the skeletomuscular system. Smooth braking (with a tau-dot of 0.5) is an *achievement* for a perceptually guided organism, not a trivial consequence of the laws of kinetics. That information such as tau is potentially available for the perceptual guidance of such intentional control actions, and since measured performance corresponds to a tau-dot of 0.5, this provides supportive evidence that the organism may have harnessed an optical informational invariant available in the ecology that would result in concomitant smooth decelerative behaviour.

The purpose of this experiment was determine whether speaking on a hands-free mobile phone will affect a driver's ability to control a vehicle compared to when driving with no conversation. There were three specific hypotheses tested: (1) Conversing on a mobile phone, regardless of conversation type, will detract from a driver's ability to control a vehicle compared to when driving in silence, (2) conversation level will differentially degrade a driver's ability to control a vehicle, and (3) driving while engaged in a categorisation conversation will affect driving the most.

2. Methods

2.1. Participants

Nine novice drivers (average age = 18.4 years) holding provisional licenses (average driving experience = 19 months) volunteered to participate in the study, which was approved by the Griffith University Ethics Committee. Following provision of written informed consent, each subject completed a series of driving tasks on a closed circuit driving track in an instrumented vehicle while simultaneously speaking on a hands-free mobile phone.

2.2. Equipment

A 2002 model 6 cylinder Holden Commodore VX series vehicle with automatic transmission, ABS brakes and power steering was instrumented to measure vehicle position, speed and 3D acceleration, and accelerator and brake depression. The in-vehicle data acquisition system consisted of an IOtech data logger (DAQBook 200) with voltage input module (DBK80) connected to a laptop computer. Vehicle position and speed were sampled at 10 Hz using a differential global positioning system (Trimble DSM 212H) that had sub-metre accuracy for latitude and longitude and measured speed with ±0.16 $\mathrm{km\,h^{-1}}$ accuracy. Acceleration of the vehicle was measured using a triaxial accelerometer (Crossbow CXL02LF3 ±2 g) attached to the centre console. Accelerator and brake depression were measured using a pair of linear potentiometers (Honeywell LTS03, 45 kΩ) attached to the pedals. The global positioning system (GPS) was connected directly to the laptop computer via the serial port. All other devices were connected directly to the voltage input module on the DAQ Book and data were sampled at 100 Hz.

2.3. Procedure

Three driving tasks were chosen to represent essential aspects of driving. The tasks assessed were cornering, controlled braking, and obstacle avoidance. For the cornering task participants approached a right-hand hairpin corner at 80 $\mathrm{km\,h^{-1}}$, which required the driver to brake, turn, and then accelerate. The controlled braking task simulated stopping before a stationary car at a set of traffic lights by braking from an approach speed of 80 $\mathrm{km\,h^{-1}}$ to stop behind a row of boxes. For the obstacle avoidance task participants were required to approach a set of traffic cones on the left-hand side of the road at 50 $\mathrm{km\,h^{-1}}$ and then swerve to the right-hand side of the road to avoid hitting the traffic cones and then return to the left-hand side of the road as soon as possible. Three trials in each condition were completed, task order was randomised, and drivers were informed that they could use the full width of the track. A driving instructor remained in the passenger's seat during testing (Figs. 1 and 2).

Four levels of hands-free mobile phone conversation (C1, C2, C3 and NC) that differed in conversation complexity were assessed. Participants listened to a track-side researcher via a

Fig. 1. Aerial view of the Holden Performance Driving Centre (HPDC, Queensland, Australia).

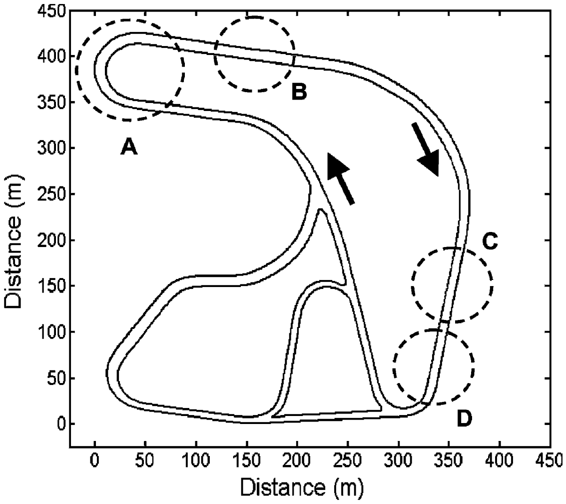

Fig. 2. HPDC track digitised using GPS coordinates. Circles represent regions of the track where driving tasks were performed. (A) Cornering, (B, C) obstacle avoidance, and (D) controlled braking.

microphone/earphone attached to the right ear and dialogue was maintained for the full length of each lap. Conversations involved presenting two numbers to the driver, which required an immediate appropriate reply. The relations between "input" (from the experimenter at base to the driver) and response or "output" (from driver to base) were quantified according to information reduction existing between input and output (see Pellecchia & Turvey, 2001).

The four conditions (NC, C1, C2, C3) were as follows. C1 involved 2-digit reversal (e.g., Base: "one, two" ... Driver: "two, one"), C2 involved mathematical summation (e.g., Base: "one, two" ... Driver: "three"), and C3 involved a categorisation task requiring the combination of two digits and then categorisation of the resultant 2-digit number as to whether it was less than or greater than 50, and whether odd or even (e.g., Base: "one, two" ... Driver: "less than, even"). The amount of information reduction for the C1, C2, and C3 conversation levels were 0 bits (i.e., easiest), 2.7 bits, and 4.5 bits (i.e., most difficult) respectively. The NC (no-conversation) condition was used as a control. Prior to data collection participants completed two laps without phone conversations in order to familiarise themselves with the track.

2.4. Data analysis

The dependent measures assessed for each driving task grouped by measurement type are summarised in Table 1. All raw GPS latitude and longitude data were transformed to eastings and northings using Redfearn's formula (Redfearn, 1948). GPS data were subsequently used to determine the relative position of the vehicle critical events (e.g., at accelerator release and brake depression), as well as speed of the vehicle during aspects of each driving task (e.g., approach and exit).

In addition to various kinematic and kinetic measures (Table 1), dependent measures were derived from the vehicle kinematics and included the behavioural correlate of optical tau, that is, the

Table 1
Dependent measures assessed for each driving task grouped by measurement type

Driving task	Vehicle position and speed	Vehicle acceleration	Pedal depression
Cornering	Approach speed Exit speed Distance to corner at accelerator release Distance to corner at brake initiation Tau at brake initiation	Peak acceleration	Peak accelerator depression Peak brake depression
Controlled braking	Approach speed Distance to corner at brake initiation Tau-dot	Peak acceleration Timing of peak acceleration	Peak accelerator depression Peak brake depression
Obstacle avoidance	Approach speed Swerve speed Exit speed	Peak acceleration Timing of peak acceleration	Peak accelerator depression Peak brake depression

time to contact (TTC). We will, however, also refer to this kinematically derived correlate of optical tau as "tau". We also measured the behavioural correlate of the rate of change of tau (referred to as "tau-dot") from initiation of braking (Lee, 1976; Lee & Young, 1985; Treffner et al., 2002; Yilmaz & Warren, 1995). In order to derive kinematically based correlates of optical tau and optical tau-dot we used the "tau-function". This is the time series of the instantaneous TTC computed as the ratio of current distance to current velocity, whereby distance is computed from the current position to the final position at which the goal state is reached (e.g., when the vehicle comes to rest in the controlled braking task, or the start of the corner in the cornering task). It is accepted that such kinematically derived quantities using the tau-function methodology are an accurate reflection of the values of their concomitant optical quantities (tau and tau-dot) (Lee et al., 1992; Turvey et al., 1990). We emphasise that we are not attempting to derive the precise form of the optical parameter tau, and thus are certainly not attempting to correct for non-rectilinear approach. However, we assume that our kinematically derived tau-function measures do allow testing of hypotheses related to the perceptual (tau-based) control of action, and with reasonably accuracy given the current methodological constraints.

The acceleration of the vehicle was examined by measuring the peak acceleration and timing of the peak acceleration in the mediolateral (ML) and anterior–posterior (AP) directions. The ML (side-to-side) acceleration was of particular interest in the cornering and obstacle avoidance tasks, whereas the AP acceleration was potentially of importance in controlled braking. Peak accelerator and brake depression as well as the timing of accelerator and brake depression were used as a measure of the driver's pedal control for each task. All dependent measures were computed using custom written Matlab software.

Repeated measures 1-way analysis of variance (ANOVA) and planned comparisons were used to assess the effect of conversation level (NC, C1, C2 and C3) on driving performance. Simple contrasts were used to compare the dependent measure associated with a particular conversation level against the NC condition, and Helmert contrasts were used to compare the combined mean

(C-all) from C1, C2, and C3, against the NC condition. All statistical analysis were performed with $\alpha = .05$.

3. Results and discussion

Raw data from individual trials in tasks similar to the present experiment have been presented previously and can be consulted for further detail (Treffner et al., 2002).

3.1. Cornering

During cornering, the position of the vehicle when the accelerator pedal was released was marginally closer to the corner for C-all (65.19 m) compared to NC (68.92 m), $F(1,8) = 4.01$, $p = 0.08$. The distance from the corner at which initial brake depression occurred was marginally significant (50.11, 47.02, 45.11, and 47.80 m, for NC, C1, C2, C3, respectively), $F(3,24) = 2.90$, $p = 0.06$, and was shorter for C-all (46.64 m) compared to NC (50.11 m), $F(1,8) = 8.90$, $p < 0.05$. With conversation, drivers were spatially closer to the corner when initiating control actions than when not conversing.

The instantaneous value of TTC (i.e., tau) when braking was initiated was lower for C-all (2.37 s) than for NC (2.53 s), $F(1,8) = 7.15$, $p < 0.05$ (i.e., delay = 0.16 s), and was marginally lower for C3 (2.34 s) than for NC (2.53 s), $F(1,8) = 4.94$, $p = 0.06$ (i.e., delay = 0.19 s). Thus, under conditions of speaking, brake initiation was temporally closer to the corner than when not speaking. In accord with the original "field of safe travel" concept of Gibson and Crooks (1938), drivers may have misjudged the corner's affordances (i.e., what control actions, such as appropriate speed of traversal, the corner affords the driver) and so did not anticipate the upcoming corner and initiate control actions as effectively when maintaining a conversation as when not conversing. Comparatively, non-simulator real-world driving studies have shown that emergency brake responses under phone usage ranged from 0.38 s for older females to 0.07 s for older males (Lesch & Hancock, 2004) and that in general reactions are delayed under phone use (Hancock et al., 2003). Although the cornering task included a temporally extended controlled braking event, studies of mobile phones use while driving have show an increase in braking reaction time in response to sudden events such as initiation of brake lights of a leading vehicle (Alm & Nilsson, 1995; Brookhuis, de Ward, & Mulder, 1994). Since attention has been compromised when speaking using the phone, the ability to detect the information for safe locomotion may have been compromised.

3.2. Controlled braking

During controlled braking, the distance to the boxes when the driver depressed the brake was not significantly different as a function of conversation but the effect of *type* of deceleration (deceleration style as indexed by tau-dot) was different. Deceleration for NC yielded a smaller tau-dot (0.53) compared to C-all (0.55), $F(1,8) = 5.97$, $p < 0.05$. Similarly, deceleration for NC yielded a tau-dot (0.53) less than for C3 (0.56), $F(1,8) = 5.87$, $p < 0.05$. The deceleration during conversation corresponded with the pick up and use of information specifying a "hard contact" (tau-dot > 0.5) more so than when braking without conversation (which yielded a braking style more consistent with smooth constant deceleration and tau-dot closer to 0.5) (Yilmaz & Warren, 1995). However, the vehicle did come to a stop at the target and did not pass through it as required for a truly "hard contact" with kinetic energy remaining at contact. Thus we interpret the tau-dot values as reflecting the fact that during the conversations, drivers may not have reduced their speed sufficiently early on and had to employ a higher degree of late deceleration resulting in a harsher style of braking.

3.3. Obstacle avoidance

For the obstacle avoidance task the average approach velocity to the entrance of the obstacle course was marginally significant (51.13, 49.81, 50.54, and 50.34 $\mathrm{km\,h^{-1}}$, for NC, C1, C2, C3, respectively), $F(3,24) = 2.88$, $p = 0.06$. Further, C-all (50.34 $\mathrm{km\,h^{-1}}$) was lower than NC (51.13 $\mathrm{km\,h^{-1}}$), $F(1,8) = 8.30$, $p < 0.05$. Subsequent planned comparisons indicated that when comparing C-all to NC, the average velocity was lower between entry marker and the central obstacle (47.52 vs. 49.05 $\mathrm{km\,h^{-1}}$), $F(1,8) = 5.33$, $p = 0.05$, between the obstacle and the exit marker (46.99 vs. 48.42 $\mathrm{km\,h^{-1}}$), $F(1,8) = 6.48$, $p < 0.05$, and that the average departure velocity was lower (50.43 vs. 51.48 $\mathrm{km\,h^{-1}}$, $F(1,8) = 14.17$, $p < 0.05$. The preceding results support the often-reported effect of driving slower under conversation (Haigney & Westerman, 2001).

The mediolateral (ML) accelerations (and associated "g-forces") experienced during obstacle avoidance are unavoidable and potentially detrimental to control of a vehicle. The magnitude of the first peak ML g-force associated with the initial obstacle avoidance turn was not significant, although the time of the peak occurred later for C-all compared to NC (3.21 vs. 3.14 s), $F(1,8) = 6.41$, $p < 0.05$. For the second peak ML g-force, when the driver steered around the obstacle, the planned comparison between the g-forces for NC and C-all was marginally significant (0.48 vs. 0.44 g), $F(1,8) = 4.85$, $p = 0.06$, as was the difference between the g-forces for NC and C3, (0.48 vs. 0.44 g), $F(1,8) = 4.86$, $p = 0.06$. The timing of this second peak was later for C-all compared to NC (4.82 vs. 4.68 s, respectively), $F(1,8) = 9.90$, $p < 0.05$. This continued with the timing of the third peak, which was later for C-all compared to NC (6.36 vs. 6.12 s, respectively), $F(1,8) = 7.29$, $p < 0.05$. Thus, under conversation there was a later onset of ML g-forces (which corresponds with the lower velocities observed), and suggests a delayed or slower anticipatory response under critical conditions such as obstacle avoidance.

4. General discussion

4.1. Effect on driving performance

In this experiment three hypotheses were tested regarding mobile phone use during real, not simulated, driving. The first hypothesis stated that conversing on a mobile phone, regardless of conversation type, will detract from a driver's ability to control a vehicle compared to when driving in silence. The results from the planned comparisons analysis confirmed that when the results of conversation level are combined, significant differences from the control condition with no conversation were found. Thus, may not be degree of difficulty of conversation, but conversation per se that affects driving. The second hypothesis stated that conversation level will differentially degrade a driver's ability to control a vehicle. This hypothesis was not directly supported in the current data. We did not find a clear dependence of performance on the three conversation levels chosen in this experiment (cf. Pellecchia & Turvey, 2001). However, the third hypothesis found some support in that the most difficult categorisation task was found to be significantly different from no conversation in cornering and controlled braking.

Although others have shown that complexity of conversation does matter and that simple conversations have a null or comparable effect to conversing with a passenger (Liu, 2003; Nunes & Recarte, 2002; Recarte & Nunes, 2003), our inability to reveal a linear effect of conversation type may have been because the novice drivers of the current experiment exhibited high between- and within-subject variability, or simply because the easier conversations (C1 and C2) that we used involved minimal cognitive load. Clearly, an issue for further investigation is to refine the nature of the conversations used. Quantifying the complexity of a cognitive task is non-trivial and although we employed communication theory in order to scale the difficulty of the three cognitive tasks or conversations used, the procedure is not perfect. For example, although repeating two numerals in reverse order involves zero information reduction and appears to capture the triviality of this task, repeating the English alphabet backwards clearly is difficult but still yields zero information reduction. However, it should be noted that even "natural" free conversation has been shown to produce significant degradations on driving performance (Strayer, Drews, & Johnston, 2003). Alternative procedures may involve more naturalistic, ecologically valid conversations (e.g., Nunes & Recarte, 2002) but building an acceptable and quantitatively testable theory upon such tasks (such as perceptual-motor destabilisation using a dynamical systems approach; Kelso, 1995; Treffner & Kelso, 1999) will be all the more challenging. Clearly, satisfying the dual requirements of naturalness and precise quantification of conversation will require considerable further investigation.

4.2. Information detection and affordance perception

James Gibson initiated the modern scientific study of how visual information guides locomotion in general and driving in particular. His early writing still reveals ideas that are not clearly understood today but seem to make much good sense (Gibson, 1966; Gibson & Crooks, 1938; Warren, 1998). Concepts such as the "field of safe travel" around a car and driver that effectively protects them—in a *functional* sense—from colliding with other vehicles. The field of safe travel, although originally based on intuitions related to fields in theoretical physics, is well conceived today as a perceptual (optical) field that can indicate or specify to an organism the possibilities for action and even the future consequences of current actions. The optic field is a medium consisting of a structured energy distribution that has different intensities in different directions. This is a concept at the *macroscopic* (everyday, terrestrial, ecological) scale of phenomena and is an attempt to show that macroscopic patterns of behaviour have a commensurate or corollary description in macroscopic patterns of light, in the case of visual perception (or sound in the case of audition). The ecological approach to perception and action is about showing that perception–action is a function of an organism–environment interaction based on macroscopic patterns of energy distributions (e.g., information) (Turvey et al., 1990). Most importantly, the psychological concept of meaning is explained in a Gibsonian framework by realising that information specifies or "points to" *affordances*. Affordances are the meaningful properties of the environment that potentially afford (i.e., offer) actions to the organism. Gibson had to invent a term such as affordance to capture the fact that perception is inherently meaningful in the same way that an organism necessarily defines its niche and is thus inherently a part of its environment. Such ecological notions were based strongly on Darwin's theory of natural selection (Gibson, 1966). In recent years, neo-Gibsonians (e.g., Reed, 1996) have further emphasised the deep evolutionary and indeed ecological principles behind a psychology of behaviour. As Gibson emphasised, perception is not based on sensations; sensations are a mere side effect of the process of perception. Rather, perception and action are based on *information*. Such an insight led Gibson to conduct experiments that showed that behaviour could not be reduced and explained by "parts" (e.g., in sensations and stimulation)—it was macroscopic higher-order relations and ratios within a larger macroscopic pattern of light that were thought to be crucial for controlling actions and behaviour—the perception–action cycle (Turvey et al., 1990).

With regards to the future-directed (prospective) control of driving, the current results indicate that speaking on a hands-free mobile phone while driving may significantly degrade critical components of the perception–action cycle. Specifically, degradation may occur in one's ability to detect prospective information needed for control and the timely initiation of crucial actions such as swerve and recovery (Cooper et al., 2003), cornering and braking (e.g., via tau detection; Cavallo & Laurent, 1988; Cooper & Zheng, 2000; Land & Horwood, 1995; Lee, 1976), on-line control of smooth braking (e.g., via maintaining constant deceleration by keeping tau-dot close to 0.5; Kim et al., 1993; Warren, 1998; Yilmaz & Warren, 1995), and accurate perception of heading direction (e.g., via linearlising optic flow during cornering; Kim & Turvey, 1999).

A concept that is becoming increasingly used in telematics and HCI design is that of an *affordance*—the *perceivable* possibilities for action offered by or afforded by environmental structure and events (Norman, 1988/1990). This concept has its origins in the perception–action or ecological approach to psychology (Gibson, 1979/1986; Warren, 1984). The perception–action approach primarily focuses upon the issue of what information in the ambient optic (or acoustic, haptic, or gravito-inertial) array can, via perception, *lawfully specify* upcoming events of critical importance to the organism (e.g., the affordance of a negotiable upcoming bend in the road, or the absence of an affordance for safe negotiation around an oily and slippery corner). We fully accept that tau and its derivatives may be insufficient to completely specify the affordances related to driving. Recently, a much-needed debate has emerged within the psychology community as to whether there might be a small number or even a *single* higher-order invariant or informational parameter that fully specifies the relevant affordance properties of a given situation such as various components of driving behaviour. Such a single parameter in the "global array" is considered to involve the abstract mathematical combination or confluence of various information arrays (e.g., optic, acoustic, haptic, gravito-inertial), and one's sensitivity to such an abstracted parameter could become degraded under conditions of diverted attention (Foque, Bardy, Stoffregen, & Bootsma, 1999; Stoffregen & Bardy, 2001). Clearly, with regards to the current study, the potential existence of multimodal information across multiple arrays should not be dismissed and we encourage further students of driving behaviour to explore multimodal interactions as has long been emphasised by the ecological approach (Gibson, 1966, 1979/1986). The emphasis upon a need to incorporate gravito-inertial information into future driving simulators is also encouraging (Kemeny & Panerai, 2003).

Putting aside the question of the nature of the specificational variables that are affected by simultaneous phone speech, we emphasise that the proper objects of perception (Millikan, 1999; Treffner, 1999)—the affordances of the environment—are currently best defined as a highly dynamical relation between organism and environment and cannot be defined as residing in either side alone (Chemero, 2003; Stoffregen, 2003). Thus, any capabilities of the organism—either action-related or attention-related—that are compromised will necessarily affect the kinds of the affordances that can be perceived and acted upon. Such capabilities of the organism have been referred to as the organism's ''effectivities'' (Shaw, 2003)—the direct complement of the environment's affordances. When conditions for the existence of both affordance and effectivity are satisfied, resultant behaviour becomes possible. Whether such possible behaviour becomes actualised depends on the availability of appropriate goal-directed intentions.

Speaking on a mobile phone can therefore usefully be construed as altering the effectivity structure and capabilities of the driver. Research shows that phone use while driving compromise one's attention to foveally presented visual information and manifests in the experimental paradigm known as ''change blindness'' (Rensink, Oregan, & Clark, 1997) or similarly, a form of inattentional blindness (Strayer & Johnson, 2001; Strayer et al., 2003). Thus, even though one might be looking directly at an object, one may not necessarily perceive it or act upon it (Rumar, 1990). Such results provide strong evidence for an attention-based explanation of why cognitive activity degrades driving control. The current results complement and refine the results of Strayer et al. who concluded via simulator-based braking reaction time experiments that attention is degraded towards attention-capturing, rapidly changing, sudden onset stimuli that are typical of unexpected events (e.g., a leading car that suddenly slows down). Our results show that attention is compromised towards temporally extended events that require dynamically controlled and continuously guided activity that is quite distinct from a simple reaction. The current tasks of appropriate coordination of accelerator and brake pedal when approaching a corner, when decelerating before a stationary car, or when negotiating a swerve and recovery manoeuvre to avoid an obstacle testify to the complexity underlying everyday driving skill. Our suggestion that perception of affordance properties is compromised can provide insight into why simulator-based research often reports that drivers engaged in a mobile phone conversation tend to alter speed when cornering (e.g., Charlton, 2004). Overall, our results support the thesis that concurrent mobile phone usage compromises the effectivities of the driver. Specifically, effectivities related to perceptual attention are compromised through a reduction in sensitivity to the most basic kind of perception-action information—the higher-order quantities (e.g., tau and tau-dot) that specify the affordances for safe travel available in the driving environment.

4.3. Implications for intervention and policy

Can the deleterious effect of mobile phones on attention be minimised? Recent research has investigated whether drivers can be trained to drive more effectively through guidance in techniques that focus on increasing stability of the car and, especially, the driver (Doyle, Treffner, Barrett, & White, 2000; Gardner, 1998; Treffner et al., 2002). If dynamic stability can be increased then perceptual sensitivity to the critical multimodal perceptual information available in the driving environment can be optimised. Experiments on the active stabilisation of unstable states such as during one-handed dowel balancing tasks have suggested that achieving stability involves active control of the dynamics underlying a complex system (Treffner & Kelso, 1999) and that the relevant prospective control variables include quantities such as tau (Foo, Kelso, & de Guzman, 2000). Indeed, dowel balancing studies have demonstrated that concurrent speech can directly affect and degrade the stability of the task (Kinsbourne & Hicks, 1978). Given the extent to which speech–hand interaction exists, it is perhaps of no surprise that even in a hands-free mobile phone task as in the current experiment, there was a significant effect of speech on motor coordination. Since speech and manual control are implicitly related via both neural organisation and the evolutionary context within which both linguistic competence and manual dexterity evolved, the continual increase in empirical studies showing a deleterious effect on attention and control from hands-free mobile phones should not be ignored by policy makers.

It has been said that safe driving requires keeping a vehicle balanced at all times (Gardner, 1998). If so, then the destabilising effects of active dialogue and speech might be nullified by stabilising countermeasures such as postural bracing and related techniques. Clearly, further consideration of this possibility would be prudent. Whether by using such stability-increasing techniques non-professional drivers might learn to cope with cognitive distractions as adequately as do professional drivers who use in-vehicle telecommunications regularly (e.g., taxi drivers) remains an issue to be empirically addressed (Doyle et al., 2000).

It seems likely that new telematics and information technologies will be developed that can present information that is more specific to the meaning of the conversation (e.g., via visual or haptic modalities) and so lighten the cognitive burden (Laurie, Andres, & Fisher, 1999; Patten, Kircher, Östlund, & Nilsson, 2004; Stanney, 2002; Ware, 2000). However, care must be taken that telematics technology does not result in increased stress, such as when a low-fidelity external speaker replaces an earpiece (Matthews et al., 2003), or when overall cognitive load increases (Liu, 2003). Until then, drivers would do well to continue to heed laws prohibiting simultaneous mobile phone use (e.g., McCartt, Braver, & Geary, 2003). Importantly, governments should consider increasing efforts to enforce such laws and to disseminate information detailing the effects of mobile phones. Unless continuous enforcement and publicity is maintained the public's compliance is likely to revert to pre-law statistics as was recently witnessed one year following New York's introduction of a prohibition on the use of hands-held phones while driving (McCartt & Geary, 2004). Indeed, drivers' opinions of their ability to drive and maintain a mobile phone conversation have been shown to be at odds with their demonstrable ability, and that this discrepancy between self-perception and performance is greatest for female drivers (Lesch & Hancock, 2004). The need for education programmes and enforcement therefore should remain a priority if the effect of mobile phones on accident rates is to be reduced. Together with emerging empirical evidence that supports an implicit speech–hand connection (Corballis, 2002; McNeill, 2000; Treffner & Peter, 2002), the extant studies clearly caution against attempting to maintain any kind of mobile phone conversation while driving.

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