User-Centred Car Design and the Role of Feedback in Driving.

A thesis submitted for the degree of Doctor of Philosophy

by

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To Elizabeth

In a car you're always in a compartment, and because you're used to it you don't realize that through that car window everything you see is just more TV. You're a passive observer and it is all moving by you boringly in a frame.

On a motorbike the frame is gone. You're completely in contact with it all. You're in the scene, not just watching it anymore, and the sense of presence is overwhelming. That concrete whizzing by five inches below your foot is the real thing, the same stuff you walk on, it's right there, so blurred you can't focus on it, yet you can put your foot down and touch it anytime, and the whole thing, the whole experience, is never removed from immediate consciousness.

Robert M. Pirsig
Zen, and the Art of Motorcycle Maintenance

Abstract

A survey of car manufacturers reveals an impressive list of upcoming technologies, the combined effect of which is likely to have a profound impact upon feedback to the driver. Feedback is information that the situation provides back to the driver and is specified with reference to content, source, and timing. Feedback quality is achieved when the information requirements of the task, derived from a new task analysis of driving, are matched to the sources, content, and timing of feedback provided by the environment and the vehicle.

An exploratory on-road study begins by observing that better quality feedback is implicated in increasing driver's situational awareness (even though driver's have little self awareness of this fact), and optimising mental workload. The exploratory level of analysis builds into the experimental, whereby a highly controlled simulator study replicates and builds upon these findings. Feedback is again seen to positively influence situational awareness, where changes in driver's confidence ratings as to the presence or absence of feedback information in the simulation were observed, according to the modality of feedback presented. This was achieved with a probe recall paradigm, and using psychophysical techniques as a useful extension to the Situational Awareness Global Assessment Technique (SAGAT). Similarly, an analysis of mental workload via the NASA TLX self report questionnaire demonstrates that a combination of visual, steering force feedback and auditory feedback gives rise to lower mental workload, lower driver frustration, and lower, though possibly more realistic self ratings of performance.

This knowledge can be discussed with reference to a feedback framework of driving that provides the theoretical backdrop to the key psychological variables implicated in driving task performance. Overall, the findings contribute to knowledge in terms of new and imaginative ways of designing future vehicle technologies in order to maximise safety, efficiency, and enjoyment.

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To the Trustees of the Ormsby Trust, Mrs Rosemary David, Mrs Katrina McCrossan, and Mrs Angela Chiswell, with privilege and pride I offer you this original contribution to knowledge in design and technology.

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Chapter 1

Future Vehicle Technology

1.1 INTRODUCTION

1.1.1 Overview

Driver feedback can be defined as information that the car/driver interaction provides back to the driver. A significant proportion of driver feedback is dependent upon automotive engineering and technology, and therefore can be influenced by design. The background and context for the Thesis is provided by this survey of car manufacturers. The survey examines current and future trends in automotive engineering design in terms of what it means for driver feedback.

Cars at the present level of interaction represent an excellent example of a profound technology that has woven itself into the fabric of everyday life until it is virtually indistinguishable from it (Weiser, 1991). It is also easy to forget how much computing power already exists in the modern car. A technological revolution has already begun that will eventually see computers enhancing vehicle performance, choosing routes, monitoring the driver, and even automating sections of the driving task completely. But in order to maximise safety, efficiency and enjoyment, there is a real need to properly consider the impact on the driver of these technologies.

The results of the survey are presented in a form charting the role of the computer over the short, medium and long term. It can be reasonably concluded from this survey and literature review that the increased complexity and prominence of computing in cars requires further investigation into the needs, abilities, and limitations of the driver. From the point of view of the vehicle designer, feedback is one factor of the driver vehicle interaction that they can favourably manipulate if the aims of safety, efficiency, and enjoyment, as well as greater ubiquity are to be realised. This represents the central hypothesis of this thesis.

1.1.2 Vehicle Technology

It is not uncommon for modem cars to have up to 30 computers on board, and therefore cars serve as an excellent paradigm for ubiquitous computing. Whether it is microprocessor control (for something as parochial as the windscreen wiper motor), or perhaps something approaching the more traditional notion of a computer as a centralised data processing device (the engine management), computers are found everywhere. In most cases the computing has disappeared. The engine management computer is as easily located in the engine compartment as it is under the front seats, or even the boot, and its operation is virtually transparent to the driver. Figure 1.1 below presents a typical electronic architecture for a contemporary vehicle.

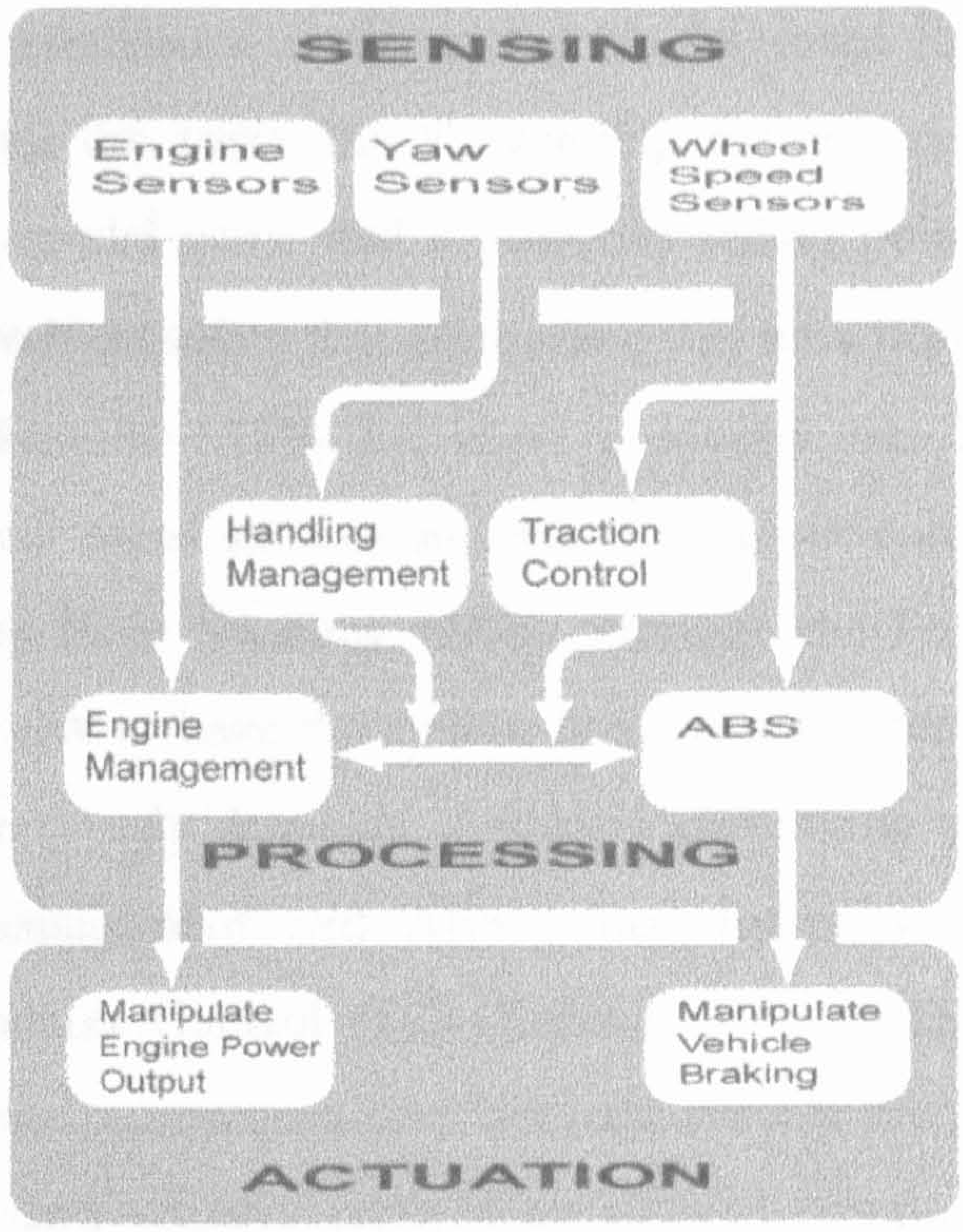


Figure 1.1 – Typical primary system architecture of a modern vehicle equipped with engine management, a handling management system, ABS, and traction control.

Ubiquitous computing within cars can trace its origins to the first meaningful introduction of solid-state electronics that occurred at the beginning of the 1970s with electronic ignition (Weathers & Hunter, 1984). Electronic ignition offered considerably improved efficiency by replacing contact breaker points, a primitive mechanical switching device, with transistorised switching and amplification. Mechanical fuel injection raised engine efficiency (and power) to new levels when it was made viable for mass produced cars with the debut of Bosch's K Jetronic system in 1973 (Robson, 1997). Computer controlled fuel injection systems were pioneered by Chrysler and Ford, as well as Lucas' EFI and Bosch's Motronic systems (Weathers & Hunter). These were among the first fuel injection systems to sense a wide range of engine parameters, and then use a computer to process the data from these sensors using a combination of closed-loop feedback and data 'look-up' tables. Fuelling and ignition could then be precisely adjusted to meet the prevailing driving circumstances. In addition, such accurate computer control enabled exhaust gases to be tightly controlled, which in combination with the introduction of lead free petrol in 1986 facilitated the introduction of catalytic converters during 1987 (in the UK and Europe) by Toyota (Robson).

Computing rapidly established itself as a powerful force for increasing vehicle efficiency, and during the 1980s the 'i', standing for 'injection', was a necessary suffix to a vehicles model name and a powerful selling point. However, it was towards enhancing vehicle safety that computing was now beginning to be applied. Antilock Braking Systems (ABS) for mass produced cars became viable with electromagnetic wheel speed sensors and microprocessor control as pioneered by Bosch and Mercedes Benz (Nunney, 1998), although the Ford Granada of 1987 was one of the first cars to have the system fitted as standard. In 1985 data began flowing between previously disparate in-vehicle computing systems for the first time, as engine management and ABS joined forces with BMW's tentative introduction of Traction Control (TC) (Robson, 1997). Throughout the 1990s greater integration and communication between vehicle systems, combined with advances in sensor and actuator technology allowed computers to take a much more active role in the mechanical operation of the vehicle. Examples of this range from variable valve timing and lift, through to semi automatic gears. Developments such as these bring vehicles to a point where nearly every area of their mechanical performance can be optimised; in other words, technology now seems to be less of a problem compared to the challenges of ensuring that this technology interacts optimally with the driver.

According to motor manufacturers, safety, efficiency, and enjoyment are the fundamental drivers behind the implementation of computing and technology in vehicles. From this perspective computing is put into the service of reducing crashes, increasing the efficiency with which drivers can use their vehicles and the road network, whilst endowing cars with qualities and features that make them enjoyable to use. Advances in microprocessor and computer control have made, and continue to make significant contributions in all these areas. But, a side effect of the increasing power of in-vehicle computing, and the types of tasks being entrusted to computer control, is that the nature of the driving task itself is changing (Stanton & Marsden, 1996).

A powerful example of this trend is Adaptive Cruise Control (ACC), the first of a new breed of advanced driver technology currently available as an option on Jaguar XK, selected Mercedes models, and increasingly on other car brands as well. ACC allows the driver to set a desired cruise speed that the car will maintain as long as the road ahead is clear. If there is a slower vehicle ahead then ACC will slow the car using the brakes, maintain a safe following distance, and only regain the set cruise speed once the road ahead is again clear. Evidently the technology currently exists to enable the vehicle to perform increasingly complex control operations previously entrusted to the driver. This point is particularly concerning where it seems apparent that user-centred issues within the design and manufacture of vehicles are not necessarily confronted in a comprehensive or systematic manner (Woodcock & Galer Flyte, 1998). Indeed, the pace of technological advancement in this domain seems to be rapidly accelerating away from research in human factors and human-computer-interaction (HCI). Taking the mantra of safety, efficiency, and enjoyment as the central issues, it is now possible to present the results of a comprehensive literature review undertaken in order to provide a synthesis of the psychological factors that are at the core of technological vehicle design.

1.2 INTRODUCTION TO PSYCHOLOGICAL FACTORS

1.2.1 Safety

Technologies aimed at addressing safety issues share a tendency towards making the driver's environment safer, thus decreasing the intrinsic risk that a driver experiences. Wilde (1988; 1994) posits that drivers have a target level of risk that they are willing to accept (or tolerate) whilst driving. If the level of intrinsic risk in the environment is lowered, driver behaviour adapts commensurate with extracting greater utility (i.e., driving faster/arriving at destinations earlier) until intrinsic risk matches the target level of risk. Wilde terms this risk compensation mechanism as 'Risk Homeostasis Theory' (RHT). Some of the principles of RHT are controversial, in particular, that determinants of an individual's target risk are situated at an aggregate population level. However, features of RHT are gaining empirical support through the recent work of Stanton and Pinto (2000), Hoyes, Stanton, and Taylor (1996), and not least Wilde's well known Munich Taxicab experiment. Taking this example, it is possible to argue the case for RHT by moving away from a macro population level determination of target risk to a micro level, behaviour compensation model couched at the level of the individual. In the Munich experiment, taxi drivers who were aware that they were using vehicles fitted with ABS tended to drive faster, brake later, and corner harder compared to those who did not have the system fitted. ABS makes the environment safer by allowing the vehicle's brakes to work to their optimum across all situations. Consequently, intrinsic risk as experienced by the driver is reduced. As a result it is argued that driver behaviour adapts in order to attain the same level of target risk, whilst at the same time allowing drivers to extract a greater level of utility in terms of, for example, arriving at destinations quicker. An important point is that the behavioural adaptation caused by ABS, or indeed any other system is not necessarily appropriate for the actual level of performance offered by the system. In the case of ABS, the fitment of the system does not mean that the vehicle will not slide or drift if using the brakes whilst cornering, or that in some circumstances a non-ABS equipped vehicle will be able to stop in identical distances.

In terms of the interaction between the vehicle and the environment, there can be little doubt that computer intervention helps to sustain the vehicle at the top of its performance envelope, thus potentially allowing the driver to fully exploit its abilities. But in contrast to the problems of RHT, the dynamic abilities of vehicles are now so high that it can be difficult for the vehicle to encourage the driver, in the name of collision avoidance, to initiate a manoeuvre that fully utilises these abilities. Lechner and Perrin (1993) show that the dynamic demands made of a vehicle in normal driving are in fact generally very low, being less than 50% of the vehicle's maximum capabilities. Encouraging the driver to bridge this large differential in vehicle performance, if demanded by a safety critical scenario, could be problematic.

Vehicles are becoming increasingly empowered with more authority to complete elements of the driving task, and this fact interacts heavily with the performance and safety of the driver/vehicle/road system. Of particular note is the issue of Allocation of Function (AoF), or what tasks should the driver be empowered with and what tasks should the computer or automation be empowered with.

Automation of parts of the driving task can make it increasingly difficult for some individual drivers to feel in control of what the vehicle is doing. Locus of control (LoC) suggests that individuals with an 'external' LoC will more readily attribute the causes of events to the technology (Parkes, 1984) and not to their own actions. Trust in automation (Lee & Moray, 1992; Muir & Moray, 1996; Muir, 1994) has only recently begun to be examined in detail, and is a factor that interacts with LoC. In terms of LoC, 'externals' can be argued as being more likely to inappropriately or 'over trust' the automation to the detriment of safety. This in turn can lead to misuse of the automation in situations that it was never designed to cope with (Parasuraman, 1997).

The main point is that vehicle technology currently requires drivers to step into the task should the situation demand it, in what Reason (1990) would term the 'catch 22' of supervisory control. The difficulty that allocation of function, locus of control, and trust issues raise are concerned with the driver intervening in the automatic process in a timely and appropriate manner (Stanton, Young, & McCaulder, 1997). This intervention is bound up in the driver's understanding of the system's state and that of the prevailing driving circumstances. If the driver has mentally handed over control to the automation it is feasible that they might be less inclined to intervene, and this problem is further compounded by the fact that intervention will become more likely if the automation is being misused, and more difficult if they do not have the necessary feedback to support a proper understanding of when intervention is required. In terms of misuse, a significant challenge for driver vehicle interaction is how to balance the conflict between encouraging drivers to make full use of the vehicle's abilities, where appropriate, whilst ensuring that in the process of doing so their behaviour does not negatively adapt.

1.2.2 Efficiency

Efficiency operates at a number of levels. It has already been seen how computing has enabled significant gains in mechanical efficiency, as well as offering solutions to increasing the efficiency with which the driver can make use of the vehicle and the overall road network. Telematics, navigation systems, devices including Head-

Up Displays (HUDs), and advanced driver technologies such as ACC all offer gains in the latter category. Navigation and telematics facilitate more rational use of the road network by offering drivers 'decision support', that in itself can be regarded as a form of feedback, connecting the driver in new ways to their environment. To some degree ACC also facilitates a more rational use of the road network. This arises as a result of smoother traffic flow due to the consistent cruising speed and headway maintenance offered by the system. But more importantly from a human factors perspective, such technology is also taking away control from the driver (Stanton & Marsden, 1996). Fundamentally the driver is being relieved of control because from an engineering perspective technology is able to offer more efficient performance than the driver; at least in relatively well defined and prescribed situations such as motorway driving. Drawing an analogy with issues in supervisory control, it can be argued that the driving task is slowly shifting from a situation of 'local manual control', whereby the vehicle merely 'mechanically extended the man' (Licklider, 1960, p. 5), to a situation of 'supervisory control' whereby the driver is monitoring a system which itself is performing some of the driving tasks (Kragt, 1992; Sheriden, 1988). Therefore the driving task is moving away from physical control tasks and becoming more heavily reliant on cognitive tasks. This raises a number of important human factors issues that have been identified by Stanton and Young (1998).

Driver mental workload is one issue that suggests extreme caution should be exercised with respect to allocation of function and the driver/technology interface (Stanton et al., 1997; Stanton & Young, 1998; Young & Stanton, 1997; Young, 2000). Mental workload is a measure of the information processing demands placed on an individual by a task versus the resources available to cope with those demands. Mental workload has its origins in aviation and dates from the 1970's (Tsang & Wilson, 1997). Mental workload is strongly related to the *difference* in the amount of attentional *resources* available within an individual, compared to those *demanded* externally by the task. Advanced driver technologies do indeed relieve the driver of parts of the driving task, but in themselves introduce new tasks. In the case of ACC for example, the driver has to monitor the system and the road environment whilst remaining outside of the control loop. In turn the driver is left with arbitrary 'left over' tasks that cannot be automated, and that tend to be ill matched to the capabilities and limitations of humans (Bainbridge, 1982). Paradoxically then, new vehicle technologies have the potential to both increase and decrease driver mental workload depending on the driving scenario. For example, low mental workload during normal system operation compared to an explosion of demand in a malignant scenario. As a result of low mental workload and poor situational awareness it becomes potentially more difficult for the driver to detect these malignant scenarios, and react to them in a timely manner (Nilson, 1995; Stanton, et al.; Stanton & Young; Young). Aside from the obvious safety issues, these factors conspire to provide an *inefficient* human machine interaction (HMI) and thus poor system performance.

Mode awareness links closely with feedback and becomes of increasing relevance as drivers interact with more complex vehicle systems and technology. Aviation represents in some measure a model for the implementation of advanced driver technology into cars (Stanton & Marsden, 1996), and mode awareness problems have been investigated within this domain. When the status of the automation effectively uncouples itself from the driver's perceived status of the automation then various automation surprises manifest themselves (Sarter & Woods, 1997). If it is assumed for a moment that feedback represents information that the environment or the vehicle provides to the driver about the current situation, and the results of driver actions, then driver's need feedback to create accurate mental models of vehicle state and its state within the environment. (A detailed definition of feedback is considered in more detail later).

Automation needs to provide appropriate feedback by ensuring that this information is presented in a manner that is appropriate to supporting the information requirements of given driving task categories. With these processes in operation the driver can accurately perceive elements occurring in their environment, or related to the automation, react to them in a more or less closed loop manner, or else comprehend them in a meaningful fashion, and use this comprehension to gauge and anticipate future states. This process is defined according to a three level taxonomy by Endsley (1995a) as Situational Awareness

(SA). Situational awareness is "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley, 1988, p. 792). For the driver, feedback creates an accurate perception of what the vehicle is doing, and what it is likely to do. In doing this, feedback can be implicated within an efficient car/driver interaction.

1.2.3 Enjoyment

Enjoyment is a major factor that increases the marketability of cars. The Ford Ka, for example, was explicitly designed with a *"fun-to-drive" character"* (Becker, Castro, Boyle, & Eichhorn, 1996, p. 36). But for all its importance within car design, driver enjoyment remains a nebulous concept lacking any systematic theoretical framework. Indeed, much is written on useability (Jordan, 1998, 1999), user acceptance, (Kantowitz, Hanowski, & Kantowitz, 1997; Michon, 1993) and driver 'well-being' (Stanton & Marsden, 1996), but little mention is made of driver enjoyment as a distinct concept. It is somewhat fortunate that a combination of brute force trial and error testing and over 100 years of motor vehicle evolution mean that very few cars are totally unacceptable in this respect (Crolla, Chen, Whitehead, & Alstead, 1998). In fact, less than 10% of recently surveyed drivers rated their new vehicles as either boring, drab, or frustrating (AA, 2000). Jordan (1998, 1999) deals with pleasure with products in a more general sense, and argues the potential for human factors research.

Feedback can be cited as a prominent factor that facilitates the driver's interaction with their vehicle (Stanton & Young, 1998). By virtue of its action-response characteristics driving often involves direct, multi modal feedback to the driver from the environment and the vehicle. Therefore, not only do drivers typically receive abundant information regarding the current situation, and the consequences of their actions, but they also receive them virtually instantaneously. With this thought in mind it is interesting to speculate on a number of human factors issues that contribute directly to the idea of feedback and driver enjoyment.

1.2.3.1 Role of the Individual

The prevailing research climate appears to view driving as an inherently dangerous, stressful, and fundamentally un-enjoyable activity, with the human component, the driver, representing the main agent responsible for errors and accidents (Stanton & Marsden, 1996; Carsten & Fowkes, 2000). There is of course some well founded justification for this line of argument, not least of which is the recent phenomenon of 'road rage'. However, this does rather ignore the fact that driving can indeed be an enjoyable experience for individuals. Evidence of this can be seen by sales of extremely expensive and uncompromising sports cars (Robson, 1997). At the individual level a number of factors come into play. Driver enjoyment of course depends on the driver's internal disposition at any one point in time, and this is influenced by a whole host of emotional and social-psychological variables such as competitiveness, thrill-seeking and time urgency (Adams-Guppy & Guppy, 1995). Though fully recognising these aspects of the individual, they do rather sit outside of the purview of this thesis. However, from a design point of view the role of the environment and particularly the vehicle become increasingly relevant.

1.2.3.2 Role of the Environment/Circumstances

The car advertising stereotype typically shows empty roads, freedom, leisure, comfort and safety. Real life driving can occasionally emulate this ideal. However, closer to the norm is that roads are crowded, and the road infrastructure frequently places much more external control on the driver, take for example speed enforcement cameras or proposed systems such as External Vehicle Speed Control (EVSC) that forcibly intervenes in the vehicle's accelerator to prevent speed limits being exceeded (Carsten & Fowkes, 2000). Furthermore, journeys are undertaken for mundane time pressured reasons such as commuting, and around 3400 people each year are killed in road crashes in the UK (RoSPA, 2000). The environmental circumstances that the driver may find themselves can vary constantly between these two extremes.

1.2.3.3 Role of the Vehicle

Even though modem cars are marketed with many additional secondary devices and gadgets, so-called 'surprise and delight' features, that are provided for the enjoyment of the driver, it is the *primary* driving/vehicle control task that remains the focus of this section. Anecdotally, any discussion about a vehicle being enjoyable to drive, or a 'driver's car' seems to invoke some mention of 'driver feedback'. Sampling more or less at random from contemporary motoring magazines reveals comments such as, "[a] *critical factor is giving the driver the sense of the car as an extension of his or her will*" (Swan, 2000, p. 79), or "*The steering is quick, direct and full of messages about what's going on below. The brakes are similarly communicative*" (Top Gear Awards, 2000, p. 83). Vehicle feedback appears to present itself as a significant factor in enjoyment and vehicles, and therefore worthy of further attention. More explicitly, it is possible to view the car as a product and to draw from Jordan's (1998; 1999) recent work on pleasure with products.

A hierarchy of user needs is presented (Jordan, 1999), whereby pleasure (level 3) stems from usability (level 2) and functionality (level 1). Cars contain abundant functionality. Functionality is a prerequisite of usability, and usability is the facet that Jordan (1998) proposes makes products easy to use. A relationship between usability and feedback emerges, and it has already been argued in the preceding section on efficiency that feedback is a significant contributory factor in increasing the effectiveness of the car/driver interaction. Clearly the quality of feedback interacts with usability, which in turn interacts with the ability of the driver to use the capabilities of the vehicle and to derive pleasure or enjoyment from doing so. However, counter to this argument regarding utility is that 'a challenge', or actually making the task more difficult rather than less difficult (for example, consider a computer game) can also enhance enjoyment. To address this contention is to state that the environment can provide most of the challenges, and the job of the driver/car partnership is to overcome them effectively. Presumably enjoyment can be derived from this effective 'team-working' between human and machine, with the machine, the car, mechanically extending the driver, giving the driver a real sense of it being an extension of their will (Licklider, 1960).

In more detail, figure 1.2 speculates on potential vehicle 'enjoyment factors', 'dissatisfaction factors', and their consequences for the driver. To provide a tentative theoretical basis for these factors, links were made towards various job attitude factors that affect motivation in another domain, the workplace (Herzberg, Mausner, & Snyderman, 1967). The consequences arising due to these enjoyment and dissatisfaction factors are derived from experimental data (Jordan, 1998).

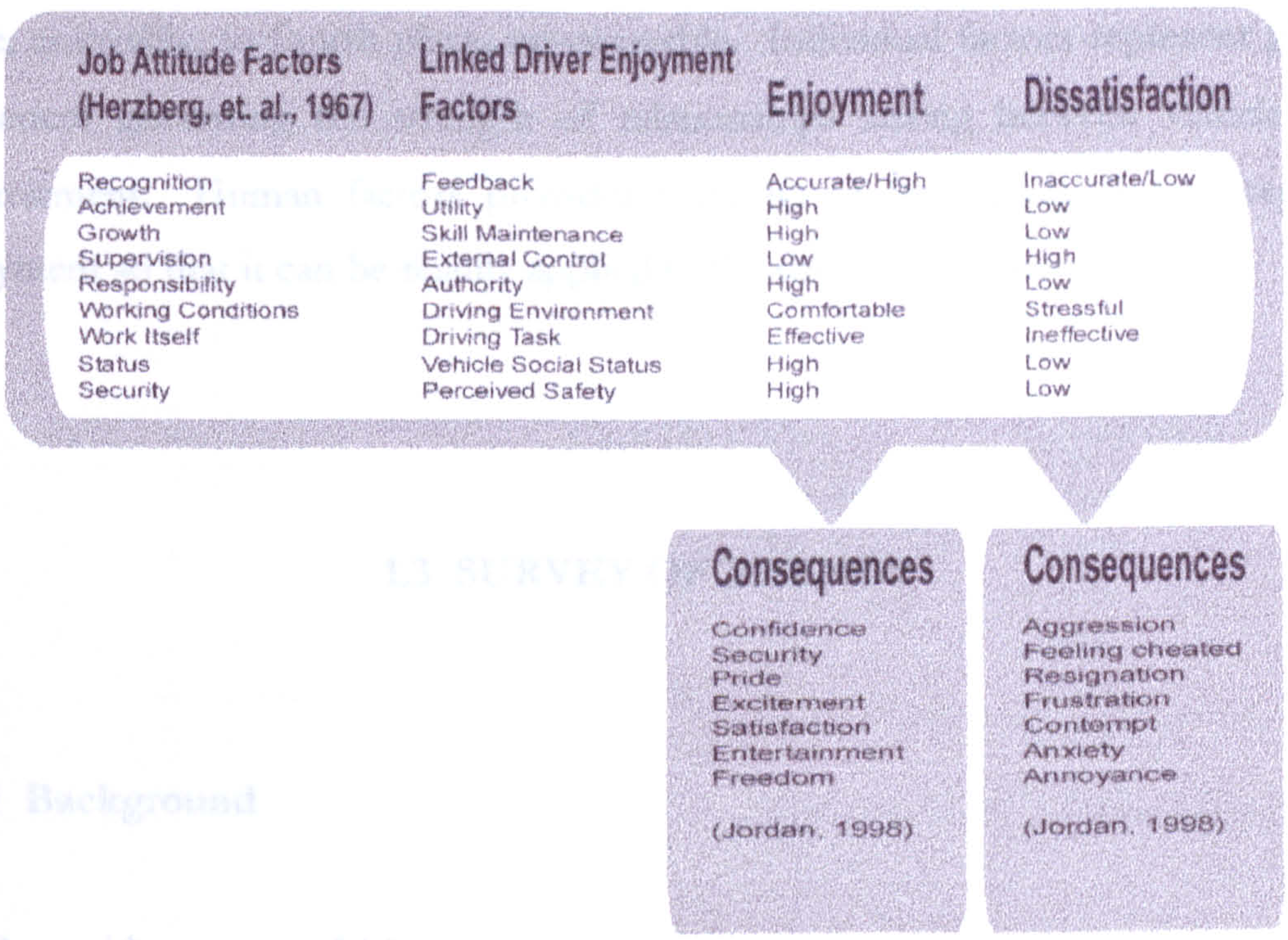


Figure 1.2 – 'Enjoyment' and 'dissatisfaction'; factors affecting the enjoyability of driving, and their consequences for the driver.

Figure 1.3 expands on the satisfying versus dissatisfying elements of the vehicle and places them within a wider context involving the individual, the vehicle, and the environment.

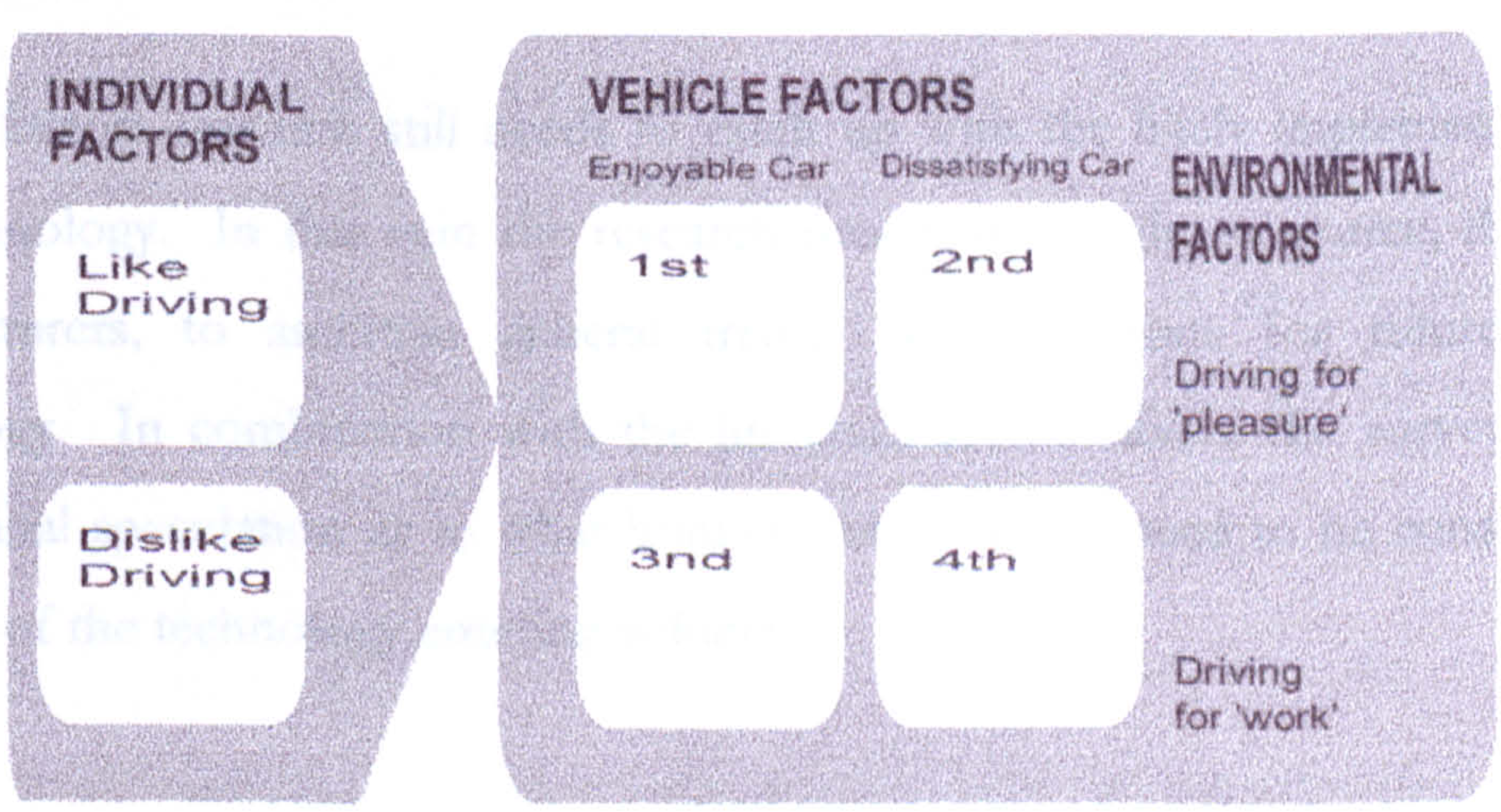


Figure 1.3 – Interaction between individual, vehicle, and environmental factors.

What the taxonomy presented in figure 1.3 illustrates, using a systems perspective, is the interrelationships between environment, vehicle, and individual. The relative level of enjoyment to be derived from particular combinations is graded from first place, enjoyable, to fourth place, un-enjoyable. Individual factors represent global influences governing the strength of relationships arising between vehicle and environment. Human factors provides a means of formalising the concept of enjoyment so that it can be readily applied to the driving context.

1.3 SURVEY OF TRENDS

1.3.1 Background

ACC provides a powerful hint at what sort of technologies are destined for cars of the future. Riding on the back of significant developments being made in sophisticated, yet inexpensive and robust computer technology ACC allows full automation of at least one part of the driving task. It does not stop there. It is not unfair to state that vehicles are poised on the brink of a technological revolution, with technology no longer merely mechanically extending the driver but relieving them more completely of elements of the driving task in the name of safety, efficiency, and enjoyment.

Human factors research still needs to catch up with the likely implementation of this technology. In this vein the research proceeds straight to source, the motor manufacturers, to ascertain general trends and directions for future vehicle technology. In combination with the literature review above the survey enables some initial speculation as to what human factors issues need to be considered in advance of the technology entering vehicles.

1.3.2 Method

1.3.2.1 Participants

Links were established with seven members of technical and research staff at five major worldwide car makers. Interviewees were drawn from Jaguar, Rover, Ford, Volvo and Daimler Chrysler.

Table 1.1 – Summary of survey respondees.

Gender	Position	Qualifications	Experience
M	Technical Specialist	MSc Ceng MIMechE	13 years
M	Chassis Engineer	PhD MSc Fellow Imech E	29 years
F	Researcher	MSc	4 years
M	Researcher	PhD	7 years
M	Researcher	BSc MSc	7 years
M	Researcher	HNC BSc	11 years
M	Research Team Leader	PhD	11 years

Table 1.1 presents the interviewees, who were highly qualified motor industry professionals comprised of six males and one female, with a mean of 11.7 years of experience in the field. To ensure a rounded synthesis of technological trends interviewees were drawn from different research backgrounds, ranging from engineers through to interface designers.

1.3.2.2 Design

The survey was comprised of a telephone interview, conducted in a focused, semi-structured format and employing a central core of open ended questions (Dillman, 1978; Groves & Kahn, 1979). To supplement the structured aspects of the interview design, the interviewer also followed up and probed for information on particularly salient or interesting trends as they arose.

1.3.2.3 Procedure

Links were established with major motor manufacturers and permission was sought via postal correspondence to speak to relevant technical or research staff. Once permission was granted, the survey was conducted via a telephone interview.

At the start of the telephone interview the purposes of the survey were stated, and it was emphasised that a personal view of significant short, medium, and long-term trends in technical developments was sought. It was further emphasised that sensitive commercial detail of forthcoming developments or products was not sought, but rather a general overview. Interviewees were also told that a finished report detailing the results of the Study would be forwarded to them upon completion.

The operators 'short', 'medium', and 'long term' were defined by the interviewer before questioning commenced; short term (0 to 5 years), medium term (5 to 15 years) and long term (15 years and beyond). The core (open ended) interview questions took the following form;

What forms of technology do you envisage entering cars in the short/medium/long term?

The interview followed this format closely, except where the interviewee encouraged further explanation on an ad-hoc basis in order to elicit the safety, efficiency and enjoyment implications of the relevant technologies being discussed.

1.3.3 Results

Interviewees were asked directly to speculate on what technologies were likely to enter road vehicles in the future. It is immediately apparent that a great deal of convergence exists between what different car makers are actively researching and seeking to implement in vehicles of the future. As a consequence, on occasions where two identical technologies/trends were cited there was complete agreement as to the likely timescale for implementation. The data derived from the interview transcripts were synthesised into the technology trajectory presented in figure 1.4. Drawing on the different research backgrounds of the interviewees enabled a larger more complete picture to emerge as all of the trends listed in figure 1.4 were not necessarily cited by all interviewees. Fundamentally, the intention within this Chapter is not to provide an *exhaustive* compendium of new technologies, but rather to present a broad cross section. This cross section permits an accurate discussion of the role of future technology in changing the nature of feedback to the driver.

2002

Examples already on the market include:
Parking aids, Night Vision, and ACC

Active Yaw Control
Already begining to be fitted to prestige and sports models from Nissan and Mercedes. Bosch ESP a contemporary system.

Navigation and Telematics
Much greater market penetration of these systems.

Information Management
Mobile phone, car audio and navigation systems integrated into a centralised dashboard unit.

Voice Recognition
For basic, non-critical in-car devices such as audio and navigation systems.

Servotronic Steering
Currently being introduced but likely to completely replace hydraulic power assisted steering with electric power assistance.

42 Volt Vehicle Electrics
Increases on electrical load from other vehicle systems requires more power. Expect 42 volt engine ancilliaries and zero RPM engine idle.

OSEK
Open Systems and their Corresponding Interfaces for Automotive Electronics. Standardised vehicle electronic architecture, with all systems communicating with each other.

Driver Monitoring
The vehicle warns the driver when a dangerous level of impairment (e.g. sleepiness) is detected.

2007

(Wet) Brake-By-Wire
Electronic servo control will operate traditional hydraulic brake master cyclinder, with the brake pedal becoming merely a transducer.

2017

Collision Avoidance and Intervention
These systems become a reality. The vehicle will sense impending collisions and help the driver to avoid them through intervention, and/or the deployment of smart safety devices.

Autonomous ACC
Vehicle will automatically assume control in cruise conditions.

Navigation Systems
These will be more or less standard fitment across model ranges.

Embedded Computing
This will enhance basic vehicle performance and contribute heavily towards brand DNA, the 'character' of the vehicle, and driver enjoyment.

In-Car-Internet
Will be commonplace.

Glass Cockpit
This becomes a reality, with the driver able to customise the appearance of their control and display interfaces.

Figure 1.4 – Technology trajectory for the implementation of future vehicle technologies in the short, medium, and long term.

In the short term it is evident that the foundations are being laid for much more embedded computing and intervention within vehicles in the form of 42volt vehicle electrics and OSEK. In the medium term, the implementation of drive by wire technologies and sophisticated driver technologies permits vehicles to become much more fully integrated, with all systems communicating with each other to accurately adapt to the prevailing driving circumstances. In the longer term it is more interesting to note what is *not* forecasted for vehicles, with levitating cars and driverless vehicles falling prey to the pragmatism of individuals who are *actually* involved in implementing new vehicle technologies. It is also perhaps reassuring to note that many of these new trends and technologies will be directed at trying to enhance the driving experience, making vehicles that are invigorating and 'fun' to drive. Nevertheless, according to this survey the driver will become progressively relieved of parts of the driving task via sophisticated advanced driver systems.

Although not exhaustive, the trends presented above seem to represent a valid cross section of the types of technologies that are realistically expected to enter vehicles in the future. They have been categorised below according to whether they are a transparent technology, an opaque technology, or an enabling technology. A transparent technology fits closely with the notion of ubiquitous computing whereby the computer has vanished into the background (Weiser, 1991). The computing silently and transparently operates in order to maximise performance in terms of extending the driver's and/or the car's performance. Opaque technologies fit a more conventional notion of computing. Here the operation of the computing is more obvious to the driver, as these technologies take over more overt parts of the driving task, and the technology has a discernable user interface between itself and the driver. Enabling technologies are classified as technologies or trends that facilitate the introduction of both transparent and opaque technologies.

1.3.4 Transparent Technologies

Drive by wire technology is concerned with the link between the vehicle's fundamental mechanical systems and the driver's controls. Such systems usually replace the mechanical link between the vehicle's control inceptors and the devices under control with an electrical link. This approach is widespread in aviation.

1.3.4.1 Steer By Wire

What the technology does: This system removes the mechanical link between the steering wheel and the road wheels. The steering wheel becomes a transducer, converting driver inputs into an electrical signal that operates electric servo devices. It is these electrical devices that actually steer the road wheels. The advantages are that vehicle steering can be integrated into a vehicle's electronic architecture to the benefit of skid control/avoidance and manoeuvrability; therefore allowing the vehicle to more accurately correspond to driver inputs. Further beneficial side effects are that steer by wire increases the viability of four wheel steer, and allows the physical location of the steering wheel to be freed from mechanical restrictions. This permits optimal positioning from the point of view of physical ergonomics, and allows left or right hand drive variants to be made at reduced cost. The trade off is that without some form of artificial control feel built into the system, steer-by-wire does not inherently provide *any* feedback sensations through the steering wheel at all.

1.3.4.2 (Wet) Brake By Wire

What the technology does: The brake pedal will no longer be directly/mechanically connected to a hydraulic brake master cylinder. Instead the brake master cylinder will be electrically powered, receiving signals from a brake pedal that is now merely a transducer. The advantages from an engineering point of view are that microprocessor control embedded within the drive by wire link could permit consistent brake pedal forces regardless of the temperature of the brakes, or whether the vehicle is fully laden or otherwise. A further engineering benefit is that the fierce modulations associated with ABS activation, and felt by the driver through the brake pedal can be avoided.

1.3.4.3 (Dry) Brake By Wire

What the technology does: This is an extension of wet brake by wire and replaces the (wet) hydraulic system with an entirely electric brake system. The brake pedal remains as a transducer, but there is no longer any form of (wet) hydraulic system. Instead the actual brake callipers/actuators are electrically powered, with the brake pedal sending electrical signals via an embedded computer directly to them. The system provides an opportunity for all manner of embedded computing to control ABS, traction control, and yaw stability with the vehicle accurately conforming to driver inputs.

1.3.4.4 What drive by wire means for the driver

In this case the computing is fully transparent to the driver and completely reduced to the background. In terms of human factors, feedback to the driver is a particularly salient issue in any discussion of the likely effects of drive by wire implementation. This is because even what could be termed insensitive drivers still exhibit very high differential sensitivity to a whole host of vehicle handling variables (Hoffman & Joubert, 1968), and drive by wire has the potential to deprive the driver completely of this feedback.

Lets take steer-by-wire as an example. Drivers receive a great deal of feedback through a vehicle's steering wheel (Joy and Hartley, 1953/4). Steering feel arises partly from disturbances involving the road surface, stored energy (or springy-ness) in the vehicles tyres, and other compliant parts of the steering system (such as rubber mountings etc). Steering feel also arises out of 'aligning torque', or the effort required by the driver to hold the steering wheel in its desired position (not to be confused with steering wheel angle). The more aligning torque, the more cornering force is developed by the vehicle's tyres (Jacobson, 1974). Put another way, the harder and more extreme the cornering manoeuvre the more aligning torque is needed to hold the steering wheel in that position, and this is an important determinant of vehicle steering control dynamics. Joy and Hartley (1953/4), in a seminal paper, describe aligning torque as giving *"a measure of the force required to steer the car, i.e. it gives a measure of the 'feel' at the steering wheel"* (pg 113). This feel arises due to a unique characteristic of pneumatic tyres termed pneumatic trail (Setright, 1999b). This refers to a systematic distortion of the tyre's contact patch with the road, and combined with the design of front suspension geometry is another contributing factor in the self centering effect of vehicle steering (Joy & Hartley). The self centering effect of vehicle steering, the shape of the aligning torque curve versus cornering speed, and the reaction of the steering wheel to disturbances from the road surface provides abundant information about the current situation and the state of the vehicle in that situation. At the most fundamental level, steering feel arises because there is a direct mechanical link between the driver and the vehicle system that they are controlling. Steer by wire does not posses such a link, and therefore does not inherently provide any of this information, though it does have the potential to do so, and even possibly to actively enhance feedback.

These same arguments centred around feedback extend, although possibly to a lesser degree towards brake by wire technology. A number of issues become important in relation to how the technology might remove some of the feedback cues made available to the driver as they operate the controls. For example, by ensuring consistent brake pedal forces regardless of the condition of the brakes or the weight of the vehicle could in fact lead to erroneous mental models of the vehicle's state within its environment. This issue can easily combine with factors concerned with risk perception. If brake pedal feel is no longer contingent on the condition/speed/weight of the vehicle, then the intrinsic risk experienced by the driver could change. Under a RHT paradigm that change would likely be to the detriment of safety. It is arguable that the sensations normally associated with ABS activation (i.e., the fierce brake pedal modulations) act as a further feedback cue to the driver that the vehicle's limits have been approached. Whether this is helpful to the driver, and indeed whether drive by wire technology offers more optimal solutions to feeding this kind of information back to the driver has yet to be fully investigated.

In terms of human factors, the key issues for transparent drive by wire technologies are related to feedback, and an uncoupling of system state from the driver's *perception* of the system state. This uncoupling process occurs through the deployment of drive by wire technology; a driver/vehicle interaction that provides the *opportunity* for optimising situational awareness and appropriate risk perception. However, it also clearly provides the *threat* of erroneous mental models, inaccurate risk perception and *poor* situational awareness.

1.3.4.5 Collision Sensing and Smart Airbags

What the technology does: Remaining with transparent technologies, smart airbags are provided with information about the nature of the occupants in the vehicle through weight sensors located in the seats. This means that airbags can be deployed in a way that maximises their safety benefits. Partial deployment for light collisions with child passengers through to full deployment for heavy collisions involving adult occupants. Collision sensing provides vital milliseconds prior to a collision in order that all safety devices (airbags included) can deploy intelligently according to the type of collision sensed. The net result of collision sensing and smart airbags is that the effects of collisions can be much more accurately mitigated.

1.3.4.6 Collision Warning and Avoidance

What the technology does: The system uses inputs from radar sensors (such as those employed within ACC) in order to detect and monitor the movements of other vehicles. Embedded computer processing will use these sensor inputs to assess the traffic scenario for likely collisions, and will signal the malignant scenario to the driver through, for example, auditory warnings. The system is also aimed at initiating collision avoidance manoeuvres by intervening in the vehicle's brakes.

1.3.4.7 Yaw Stability Control

What the technology does: Yaw stability control intervenes using selective wheel braking to maintain vehicle stability through accurate skid control in critical situations (Nunney, 1998). Ultimately these systems attempt, as far as possible, to make the car go where the driver wants it to during 'on the limit' situations. Bosch's ESP (Electronic Stability Program) is a currently available example of this technology, fitted as original equipment to a growing number of prestige and sports vehicles.

1.3.4.8 What collision sensing/warning, and active yaw control mean for the driver

These systems all operate silently in the background. But whereas collision sensing and warning offer the driver a form of decision support by reporting malignant scenarios so that the driver can respond to them, collision avoidance and yaw stability control offer active intervention. This is an important distinction, especially from the point of view of specifying the behaviour of the system. In decision support, means need to be sought for providing the driver with the necessary information or feedback in order that they can make an effective decision. Conversely, in the case of active intervention means need to be sought for an effective transition between the driver, or the automation being in control. At the present level of interaction the vehicle provides abundant implicit feedback cues as to its yaw behaviour, with driver's readily able to perceive the characteristics of under and over steer, and furthermore to provide some reaction to them (Godthelp & Kappler, 1988). How future systems may want to communicate the vehicle's state, and ensure an effective transition from automatic to manual control remains an interesting research question.

What these systems share is the potential for a negative impact in terms of RHT. Whether it is collision sensing or active yaw control, the intrinsic risk experienced by the driver is altered. In turn, under an RHT paradigm the potential for misuse of the automation grows as drivers may discover that greater utility can be achieved by leaning more heavily on automated systems to detect imminent collisions and deal with losses of vehicle control. Issues related to locus of control become highly relevant in terms of active intervention, as those disposed towards an external locus of control could be much more likely to attribute the cause of actions externally towards the vehicle, even more so if the vehicle is empowered with increased authority to take control. This poses additional problems in terms of decision support, as locus of control interacts heavily with the ability of a decision support system to *actually* support decision making by the driver.

1.3.5 Opaque Technologies

1.3.5.1 Adaptive Cruise Control (ACC)

What the technology does: The system is ostensibly a form of cruise control that allows the driver to set a desired cruise speed and headway that the vehicle will try and maintain. The heart of ACC is its radar sensor technology in conjunction with its embedded computer. The computer system processes sensor inputs according to various algorithms. This enables the system to sense other vehicles, and intervene with the vehicle's brakes and accelerator (but only up to a certain point) to maintain a constant (safe) headway. ACC's inherent limitations mean that it is offered as a comfort system, and the driver must be constantly ready to take over control (Richardson, Barber, King, Hoare, & Cooper, 1997). ACC represents one of the first commercially available forms of advanced driver technology.

1.3.5.2 Driver Monitoring

What the technology does: The vehicle monitors the driver's performance and when it detects any impairment, such as drowsiness or inattentiveness, will alert the driver. Specifically the system not only measures the driver's control inputs by interfacing directly with the vehicle's electronic architecture, but it also robustly senses the driver's visual performance by tracking their eyes as they are engaged in the driving task. Research suggests that these ocular measures are good metrics by which to measure driver attention (Victor, 2000).

1.3.5.3 Glass Dashboard/Instrument Cluster

What the technology does: A surprising number of modern cars still use a mechanical speedometer that is connected to the gearbox by a cable. The use of digital technology facilitates the introduction of the glass cockpit/dashboard, with software controlled visual displays. Sensors monitor all relevant vehicle parameters such as road speed, engine speed, temperature etc., and present this information to the driver on conventional dials using stepper motor technology, or else on software driven LCD displays. Software LCD displays could potentially allow the driver to customize the layout and appearance of their dashboard, or for the vehicle itself to alter the appearance of the displays according to the driving circumstances. This product personalization has obvious marketing benefits, but it also allows great flexibility for ergonomic means of feeding back information about relevant vehicle parameters. It is also envisaged that tactile seat displays and kinaesthetic brake pulses will offer new and additional modes of feedback for the vehicle to communicate with the driver.

1.3.5.4 Information Management

What the technology does: Navigation systems, traffic information devices, mobile communications, and in-vehicle internet (IVI) are to become widespread in vehicles. These systems will provide not only a wide range of in-car entertainment, but also real time traffic and vehicle data. These include current vehicle status, servicing requirements, 'living maps', e-mail, and even advice on parking availability or hotel reservations once the final destination is reached (Burns & Lansdown, 2000). To this end much greater product convergence is destined for vehicles, as ways are sought to manage this extra information provided for the benefit of drivers. This management includes delay and/or prioritisation of competing messages in response to the environment. For example, the system will delay secondary information if a sudden braking manoeuvre is detected. All these devices are set to merge into one system, and this brings with it the possibility of novel interface methods ranging from touch screens through to speech recognition.

1.3.5.5 Voice Activation

What the technology does: Voice activation allows the driver to literally talk to in-vehicle devices in order to control their operation. It offers, potentially, a safer means of controlling tasks secondary to the primary driving task without the driver having to remove their hands from the wheel in order to operate switches or levers. Speech recognition software will run on embedded computers, which in turn will interface with a variety of in-car devices such as navigation and audio systems.

1.3.5.6 What opaque technologies mean for the driver

Opaque technologies are more overt from the point of view of the driver, and possess a new and distinct interface for the driver to cope with. In particular, information management requires appropriate interface design in order to optimise and 'manage' the flow of feedback between the driver and the in-vehicle systems, and prevent what could be termed 'cognitive distraction' (Burns & Lansdown, 2000) or mode awareness problems. For the primary driving task it is evident that drivers can experience mode awareness problems with automation on a comparatively simple level, such as automatic gears (Schmidt, 1989), quite aside from new technology that is empowered with considerably more authority.

There exists a prominent gap between what engineers would describe as comfort and what human factors practitioners might describe as mental underload. It is seen by the engineering field that relieving the driver of tasks makes driving easier and by definition more pleasurable. However, it is apparent through recent work in this area (e.g. Young & Stanton, 1997; Stanton, et al., 1997) that relieving the driver of things to do, via these opaque technologies, can have negative consequences in terms of workload, as it appears that attentional resources tend to shrink to fit the current task demands (Young, 2000). This can present some problems related to safety. In particular, a malignant scenario can present an explosion of demand for the driver (Stanton et. al.), necessitating the driver having to take control, and thus having to make the difficult transition from low workload (i.e., mental underload) to very high workload (i.e., mental overload). It is argued that both extremes of workload are entirely inappropriate (Bainbridge, 1982; Norman, 1990), therefore expanding the case for some form of dynamic allocation of function in order that task demands maintain attentional resources at some optimum level. One of the central issues can therefore be argued as the need for these systems to communicate via appropriate feedback with the driver.

1.3.6 Enabling Technologies

Technologies falling within this category represent the backbone for the implementation of new in-vehicle technology. As such they have no direct or overt influence on the driver or the driving task. However, these technologies and architectures help to increase vehicle efficiency from a mechanical and electrical point of view.

1.3.6.1 42volt Vehicle Electrics

What the technology does: Current vehicle electrical systems are powered from 12 volts in the case of passenger cars and light vans, and 24volts in the case of large commercial vehicles. The extra power of 42 volt vehicle electrics offers a host of benefits from an engineering perspective, but fundamentally it supports the implementation of even more technology and electrical actuation in future vehicles.

1.3.6.2 Open Systems and the Corresponding Interfaces for Automotive Electronics (OSEK)

What the technology does: A recurring theme within all in-vehicle technology and computing involves its ability to be able to communicate with different systems throughout the vehicle. This is in stark contrast to the current situation whereby vehicles may have numerous isolated computing and microprocessing centres spread throughout the car. OSEK is a common electronic architecture for vehicles developed as a joint collaboration between European car manufacturers (OSEK, 2000). In a similar vein to the PC platform the proposal is to standardise the electronic architecture of cars so that all electronic and microprocessor systems/components (current and future) can integrate and communicate. This will mean, for example, that the collision avoidance system can interface directly with the engine management, airbag, and ABS systems (regardless of manufacturer) to deliver optimal vehicle performance, especially in safety critical scenarios.

1.4 SUMMARY

It can be anticipated from the data gathered in this survey that embedded computing and mechanical intervention will have reached new heights by 2017. The vehicle will become a fully integrated system with all its primary mechanical systems electronically linked, communicating with each other to accurately adapt to the driver and the road circumstances. In doing this, safety, efficiency, and enjoyment could indeed be maximised. However, all vehicle technologies have consequences not only for the interaction that the vehicle has with the road, and other vehicles, but also for the interaction between the car and driver. In particular, new vehicle technology has some profound implications for feedback to the driver. Therefore a large question mark hangs over future vehicle technologies, and the type of vehicle feedback that will be emitted (or perhaps not) from future vehicle systems.

1.5 RESEARCH HYPOTHESIS

What should be clear is that the whole issue is much more complex than merely putting yet more technology into vehicles. From the above there is clearly evidence that vehicle feedback is one significant determinant of the quality of the driver/vehicle interaction, and increased in-vehicle technology presents an opportunity as well as a threat in terms of feedback to the driver. On the one hand new technology provides an *opportunity* to fully support the driver's information needs through feedback; or on the other hand a *threat*, robbing drivers almost completely of information that is valuable and useful to them in order to help maximise safety, efficiency, and enjoyment. What is certain is that future vehicle technologies are on the way, and this fact provides a powerful new motivation for valid and imaginative means of integrating new vehicle systems with driver's. Feedback provides one dimension along which vehicle designers can help to optimise this interaction.

The central hypothesis of this work, therefore, is concerned with exploring the issue of feedback. This stems from the review of psychological factors relevant to future technologies. Here it is suggested that feedback represents one important vehicle design factor that could help to maximise safety, efficiency, and enjoyment. In order to explore the issue of feedback in vehicles the precise nature and scope of feedback has to be defined and related to all the functional elements of the driving scenario (chapter 2), the issue can then proceed into the naturalistic driving context (chapter 3) in order to provide a proper exploratory backdrop for larger scale studies performed in the Brunel University Driving Simulator (covered in chapters 4 and 5).

Chapter 2

Feedback and Driving

2.1 A FEEDBACK FRAMEWORK

2.1.1 Introduction

The driving context involves drivers, vehicles, and the road (Michon, 1993). Drivers impart actions upon their environment via their vehicles. In turn the consequences of actions and the vehicle's interaction with the road environment are fed back to the driver from or through the vehicle and the external world. A Systems Perspective captures this notion easily and very neatly. In its simplest form a system comprises an input, a transformation process, and an output (Skyttner, 1996). In the present case driving involves the output of human information processing, that is the actual physical, observable driving tasks and behaviours performed by drivers. This human output represents the input to the system. Driving involves an input from the driver, the vehicle's mechanical systems initiate some transformation process that is translated into an output in terms of vehicle speed and trajectory (figure 2.1). Interaction problems typically occur at the boundary between system elements, that in the present case would involve potential problems between the driver and the vehicle interface (between the input and the transformation process level), and also between the vehicle and the road environment (between the transformation process and output levels). These are indicated in the figure below, and as examples, problems of unintended acceleration with automatic transmissions are related to the driver/vehicle interface (Schmidt, 1989; 1993), whereas vehicle handling problems such as 'lift-off oversteer' arise as a result of problems that the vehicle has in interacting with the road.

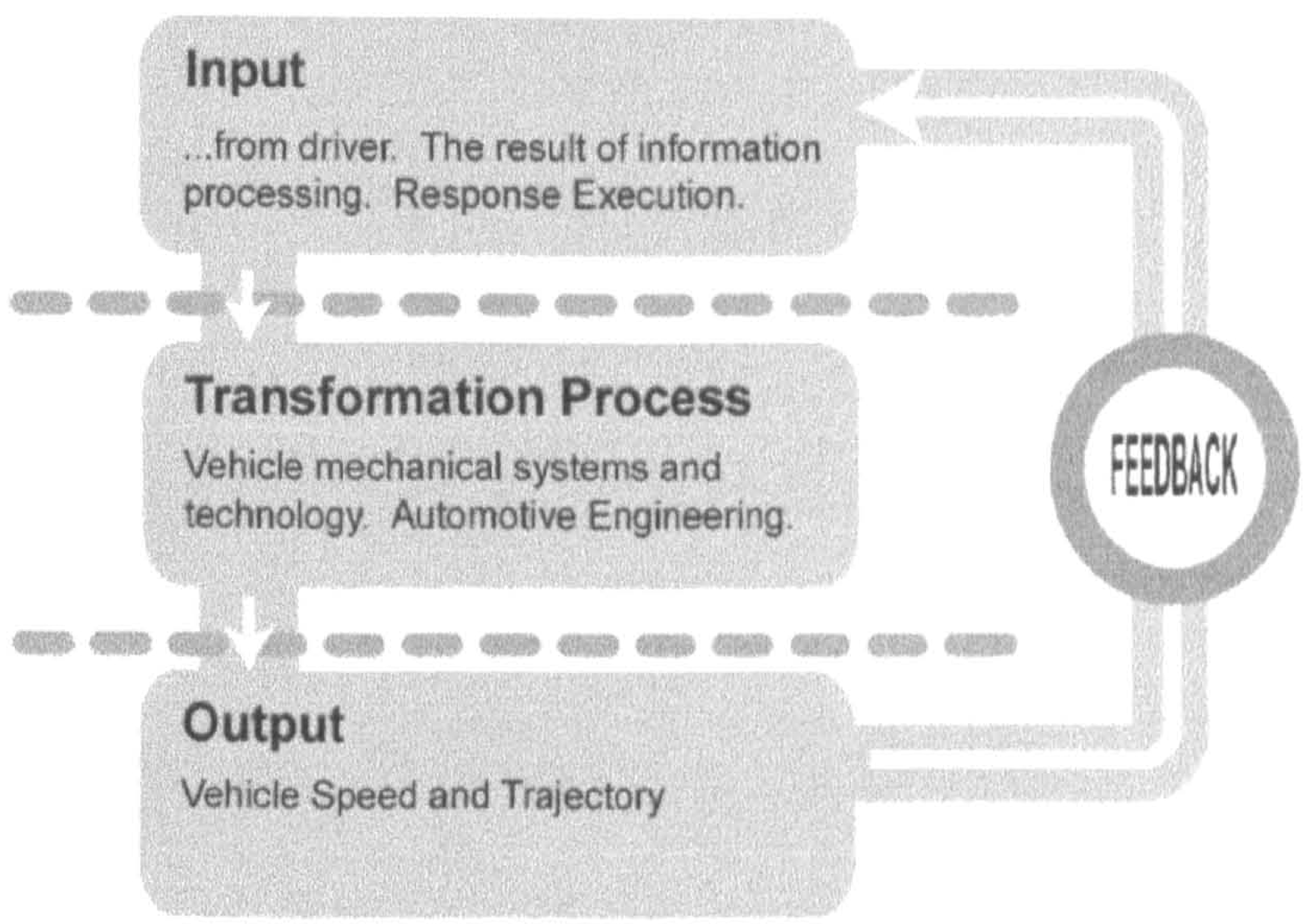


Figure 2.1 - Basic systems view of driving.

2.1.2 Synthesis of the Systems View of Driving and Feedback

The framework presented below takes the basic systems approach and reconciles it more fully with human information processing, using a systems perspective, and giving primacy to the notion of feedback. The framework is shown below in figure 2.2 and illustrates the key psychological elements of the driver, combed with driving goals and tasks, the vehicle, and its environment, all of which are linked by the common thread of feedback. Taken as a whole, the framework reconciles many of the central concepts of cognitive psychology, such as decision making, response selection and response execution, and relates them directly towards the driving context, a context that has a vehicle as an intermediate variable between the driver and the road environment. Many of the psychological concepts have already been introduced within Chapter 1. The feedback framework therefore proceeds by highlighting the key *interrelationships* between the relevant psychological variables and feedback, and their role in the wider context of driving; it presents a backdrop from which discussion and analysis of feedback in driving can proceed.

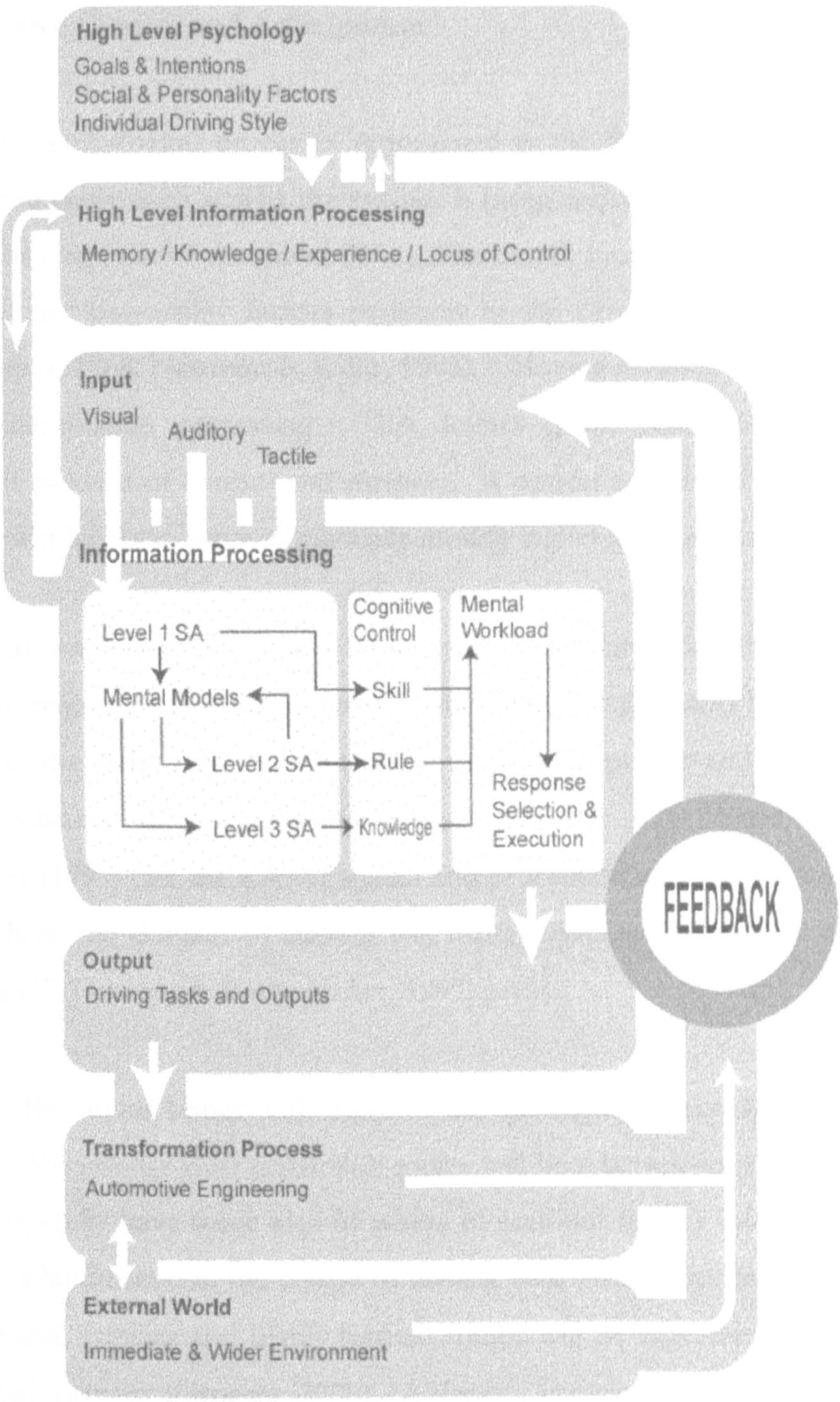


Figure 2.2 – Feedback framework of driving showing key variables of interest

2.1.3 Predictive Control and Anticipation

Higher level psychological processes represented in the framework above define the overall driving goals, such as why the journey is being undertaken in the first place, the underlying driving style of the driver (West, Elander, & French, 1992), and the various other social and personality factors pertinent to the driving scenario (for example, Doob & Gross, 1968; Newman & Willis, 1993). Moving down the feedback model is high-level information processing. This defines global resources and processing centers such as locus of control and memory. A certain amount of internal feedback from this lower level can serve to gradually modify higher level processes and goals.

Of particular interest is the role of memory. Not only does the driver process information encountered from moment to moment, but they also bring information with them to the task. Information that allows them to predict and anticipate certain events in advance of encountering them. Groeger (2000) and Groeger and Rothengatter (1997) cite the role of spatial and procedural memory in respect to this, and show how the domain of driving has made *"significant contributions to mainstream memory research"* (Groeger & Rothengatter, 1997, p. 2).

Specifically, the driver brings with them to the driving task varying degrees of route knowledge. Knowledge over unfamiliar routes will be relatively impoverished, but the driver will typically have some idea of where to seek out further information (such as road signs or landmarks) in the course of driving task enactment (Branton, 1979). On the other hand, familiar and highly learned routes will be represented in some detail within spatial memory (Groeger, 2000). A driver's knowledge of the route is cited by Branton (1979) as being *"not comprised merely of isolated snapshots of the scenery, but must consist of an ordered set of perceptual cues for active scanning and motor action"* (p. 160). Memory stores are therefore vital in anticipating when and where future information should be gathered. For example, memory enables the driver to anticipate the presence of traffic lights ahead, and this would represent a cue for seeking out further information on the particular colour that the traffic lights are showing.

Expectancy is defined by Reber (1995) simply as *"An internal state* [of an individual] *that leads it to anticipate (or 'expect') a particular event"* (p. 267). Expectancy occurs when the driver employs memory stores to anticipate not just the *presence* of upcoming informational cues, but also the actual information *content* not as yet given. Using the example above, expectancy would represent an extreme case of predictive control as not only would the driver be predicting the presence of traffic lights ahead, but memory would serve to restrict the perception of true informational states. The driver may anticipate (based on prior experience) that the lights will be showing a particular colour.

Predictive control can be discussed by citing the extreme case of 'Driving Without Attention Mode (DWAM)' (Kerr, 1991). The popular manifestation of DWAM is illustrated in a review paper by May and Gale (1998) in terms of the driver suddenly realizing their location without being able to recall how they arrived there. May and Gale state that, *"where the driving environment becomes more predictable, less feedback is required, and it is such predictability that induces DWAM"* (p. 458). Beilock, Wierenga, and Carr (2002) provide support for over-reliance on long term memory stores such as route knowledge. In situations comparable to the expert driver driving over a familiar route, it has been shown that episodic memory for specific recent events is severely limited. Under these conditions long term memory stores and route knowledge dominate driving performance. Of course this relies on the assumption that the situation is familiar and does not take an unexpected turn. If it does Wertheim (1991) would specify a more controlled mode of attention combined with active information absorption. In dynamic road situations the driver alternates between moment to moment information absorption and processing and predictive control based on memory.

2.1.4 Moment to Moment Information Processing

Cognitive processing is supplied with a steady stream of multi-modal sensory input. This lower level cognitive processing is responsible for the moment to moment processing and decision making within the driving scenario. It defines how the constant flow of information presented to the driver from the context is superimposed upon high-level driving goals; leading to the selection and output of specific combinations of driving tasks. This human output represents input to the vehicle. The vehicle's mechanical and technical systems take the driver's inputs, and transform them into changes of speed and trajectory within the external environment. The consequences of these driving tasks upon the vehicle, and the resulting behaviour of the vehicle in its environment are fed back, through the various sensory channels, to the driver. To a greater extent the nature of feedback made available to the driver, not just through the vehicle but also from the road and wider environment, is relatively well understood, or is at least measurable. Significantly less well understood is what the driver does with this constant flow of information, and exactly how they put it to use within the driving task.

Although the driving task at the higher psychological level often involves forms of open loop behaviour (with little, or sometimes no immediate feedback), input from the environment still plays a central role (Endsley, 1995a). Feedback or inputs from the environment form the basis for a drivers situational awareness (SA). Situational awareness and feedback are closely intertwined. Within the model above, the driver perceives the relevant elements of the external world (level 1 SA), which then feeds into their comprehension of the situation (level 2 SA) via their currently existing mental model of the system. A mental model forms the basis for the driver to understand, or comprehend their situation. It is a dynamic store of knowledge built from prior experience, but is updateable regarding the current situation. It also represents knowledge that can be used to try out different decisions before actually physically enacting them (Wickens, 1992). The current understanding of the situation feeds back into the mental model and these two chunks of information can be used to construct a projection of future events (level 3 SA). This projection can then be used to guide action. This is an important point, because the frame of reference in which feedback is being discussed here does not imply that driving is a totally closed loop activity. On the contrary, feedback is helpful in initiating forms of 'open loop' or feed forward behaviour, enabling certain situations to be anticipated and compensated for in advance of encountering the situation itself. Driving can be viewed as being comprised of a combination of open and closed loop behaviour, and the feedback framework is entirely compatible with this approach.

2.1.4.1 Feedback and Situational Awareness

Increasing SA is an important design objective if the aims of safety efficiency and enjoyment are to be met (Adams, Tenney, & Pew, 1995; Endsley, 1995b; Endsley, Sollenberger, & Stein, 2000). Very few studies seem to deal exclusively with *driver* situational awareness, although driving as a dynamic activity is frequently given passing mention (Endsley, et al., 2000; Endsley, 1995a; Endsley & Kiris, 1995). A notable exception, perhaps, is the study by Gugerty (1997). This analysed driver SA with reference to implicit and explicit spatial location knowledge. SA was gauged using recall measures on the spatial location of surrounding vehicles, performance measures involving a hazard detection task, and global measures of SA involving crash avoidance. The results are framed in terms of knowledge and memory, in particular, that *implicit* knowledge of surrounding vehicles made little contribution to SA. Interesting though this is, it still leaves the question relatively unanswered as to how drivers perceive, interpret, put to use information gained from the driving scenario, and how situationaly aware normal drivers actually are in a naturalistic setting.

Despite the relatively small number of studies concerned with cars and drivers, increasing SA is still a vehicle design imperative. From the outset, mechanical failure plays a very small part in overall road traffic accidents accounting for a mere 5% of causation; the label 'driver error' is often applied to cover the remaining 95% (HUK-Verband, 1990). Related to this, findings suggest that 'Misjudgement', that of course is strongly related to failures of SA accounts for up to 46% of fatal accidents (HUK-Verband). Treat et. al. (1979) also cite problems with SA, in particular level 1 SA (that includes poor observation and inattention) as being the causal agents in more road traffic accidents than decision making errors, such as speeding or inappropriate driving technique. In the aviation field many of the same problems are to do with gaining SA and thus remain centred around level 1 SA (Endsley & Bolstad, 1993). Jones and Endsley (1996) report in more detail that around 76% of errors are at level 1 SA, this finding being defined by limitations in working memory and attention. It would seem reasonable, based on the available evidence, to suggest that the same is broadly true for road travel also.

There is no shortage of justification for examining the role of driver feedback and SA, although very few studies seem to address the issue explicitly. According to the Feedback Framework of Driving feedback is directly involved in level 1 SA. Thus feedback presents itself as a useful adjunct to potentially increasing SA at precisely the level where most problems seem to occur. This of course should benefit decision making performance in driving.

2.1.4.2 Cognitive Control

The level of cognitive control (in a Rasmussen et al. sense) has been indicated in the model. Actions relating to level 1 SA can be associated with skill based processing, level 2 SA can be related to rule based processing, and knowledge based processing relates to level 3 SA. This is an important distinction, as it shows that greater cognitive effort (which itself is reflected in mental workload) is associated with different levels of SA. In more detail, the construction of a projection of future events (level 3 SA) is commensurate with knowledge based, conscious real time processing, compared to the simple perception (level 1 SA) and rapid, unconscious highly skilled response to elements in the environment. These short cuts between different levels of cognitive control are implied in Rasmussen et al.'s skill rule knowledge taxonomy.

Coming from the opposite direction, a Contextual Control Model of cognitive control (Hollnagel, 1993) would suggest that operation under different conditions of mental workload will itself lead to different modes of control. For example, high workload conditions might be expected to lead to opportunistic control (Hollnagel), and this can be argued as being directly related to the enactment of skill based behaviours. In comparison, strategic control (Hollnagel) would be similarly related to the enactment of knowledge based behaviours. A key issue here is the contention that the relationship between mental workload and cognitive control is being influenced from two directions, consistent with prevailing theories (Hollnagel; Rasmussen et. al.). So not only can different levels of SA be related to different modes of cognitive control (Rasmussen et. al.), but the mental workload implied at different levels of SA can also exert an effect on information processing strategies (Hollnagel). This is difficult to represent pictorially in the model above, but clearly there would appear to be optimum *converging* levels of mental workload and SA.

2.1.4.3 Mental Workload and Driving

Kahneman (1973) infers that attentional resources are fixed, representing an undifferentiated resource pool that can be devoted in its entirety towards the completion of a task. Wickens (1992) argues that various research findings in regard to human performance on dual tasks indicates to the contrary. That, in fact, attention is comprised of multiple resource pools, each with their own unique properties and resource characteristics (Wickens). Young (2000), and Young and Stanton (2001) go even further by suggesting that attentional resources are not even fixed in size, and that the demands of the task to some extent mediate the supply of attentional resources towards it. The demands or requirements of the task are specified by task difficulty, the task context, the performance standards to be met, and the time needed for completion of the task. Under Young's Malleable Attentional Resources Theory (MART) these task characteristics also represent an element of internal feedback within the model of driving, in as much as task demands can help to determine what quantity of attentional resources need to be supplied (in underload conditions at least). Therefore, the latest thoughts on mental workload view attentional resources as malleable, comprised of multiple resources (and therefore multiple characteristics), and that mental workload is an expression of any imbalance between these resources and the requirements of the task.

As is the case for situational awareness, optimum mental workload is also an important design goal. The major design implications of workload, as Sanders & McCormick (1993) outline are concerned with the allocation of function between automation and humans, comparing workload between different designs or paradigms, adaptive task demands contingent upon the workload experienced by the operator, and finally, analysing individual differences in mental workload. Mental workload has major implications for the design and operation of complex systems, including cars. For one thing, it might be assumed that relieving drivers of tasks and activities would decrease their mental workload. There is certainly evidence for this within the domain of driving.

Zeier (1979) performed a study of manual versus automatic transmissions and did indeed detect lower mental workload with the automatic gearbox. Clearly automatic gears, in the scope of normal driving, relieve the driver of certain driving tasks and this is reflected in mental workload. In the seminal article Ironies of Automation, Lisanne Bainbridge (1982) agrees that in many cases mental workload is likely to decrease with increasing automation. However, she also hints at the phenomena of mental underload, where for example humans in some task scenarios such as industrial process control, or commercial aviation have been marginalized by automation. This is due to efficiency and human error reasons; basically the automation performs the task better than the human. Yet paradoxically, these same individuals are still required to jump back into the control/feedback loop in the case of emergencies (Reason, 1990). The problem (or irony) of this approach is twofold. Firstly, the automation means that operators are less likely to be able to practise precisely the skills that justify their marginalized existence within the system, and secondly, the new task for the human is one of vigilance, one for which humans are notoriously poor (Davies & Parasuraman, 1982). These problems are exacerbated by mental underload, as Stanton et. al. (1997) can explain with reference to the driving domain.

In studies concerned with Adaptive Cruise Control (ACC) it was found that the lowered task demands cause attentional resources to shrink, as predicted by MART, and in the case of automation failure drivers could not assume control quickly enough to avoid a crash. Stanton et. al. discovered that in this automation scenario demand went from underload to explosive. Of course, both of these extreme levels are entirely inappropriate for optimum performance. Unfortunately, as Norman (1990) outlines, this problem of demand versus resources crops up frequently. The reasons for this are often concerned with inappropriate interaction and feedback (Norman), or otherwise known as Out Of The Loop performance problems (OOTL) (Endsley & Kiris, 1995). Under this situation individuals have poor or non-existent SA regarding the current or future system state. This is usually because they are no longer responsible for the moment to moment running of the task, and are therefore out of the control/feedback loop entirely. As a result of this operators not only have poor SA, but they are frequently mentally underloaded as well. Emergency situations therefore more easily exceed the reduced attentional resources available, thus severely handicapping effective decision making. This process is shown below in figure 2.3 where task demands are low, and over time attentional resources decrease. A sudden increase in task demands, that under normal conditions would not exceed available attentional resources will now do so, causing a time lag until resources are back to their normal level. Whilst task demands outstrip available attentional resources demands and resources are unbalanced, and performance is poor; as illustrated below.

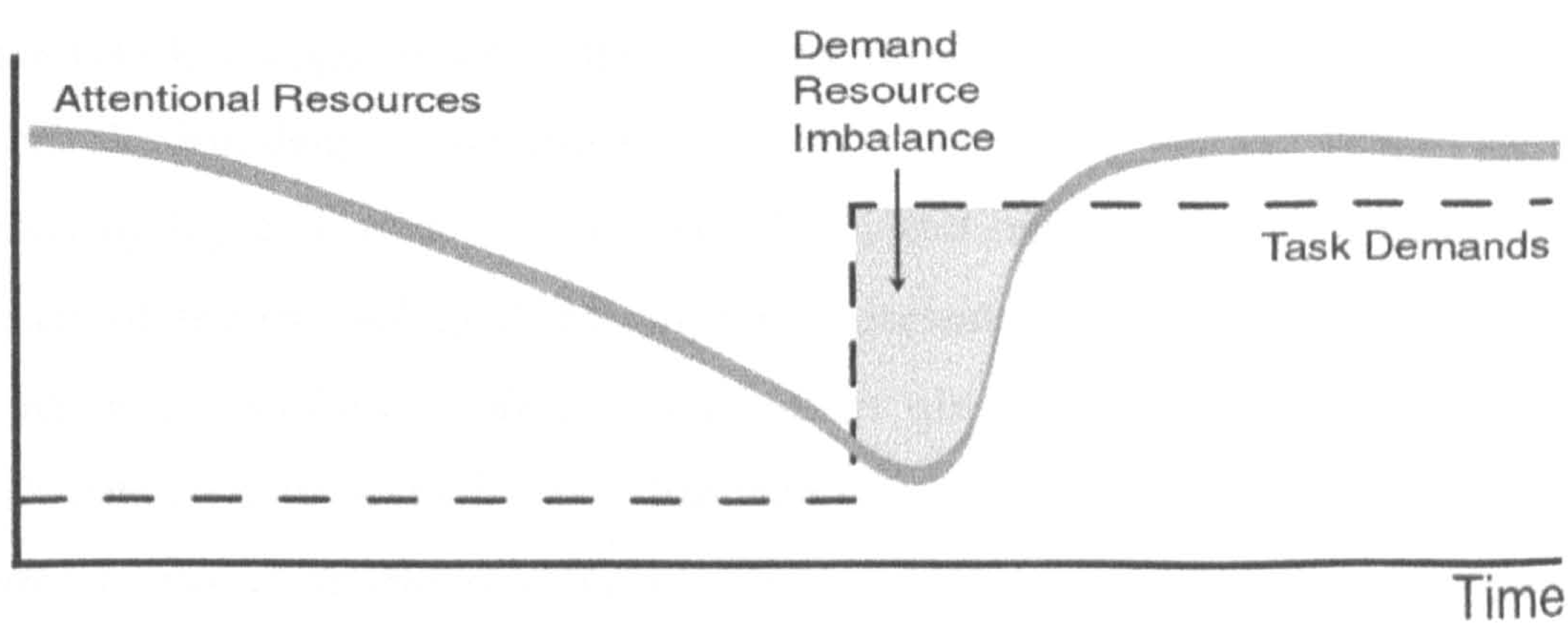


Figure 2.3 - Example of mental underload and changing task demands.

2.1.5 The Vehicle as an Intervening Variable

The vehicle's mechanical systems are constantly in opposition with the vehicle's moving mass and the driver's desired trajectory and speed. The driver controls these mechanical systems and is therefore constantly working against these forces, and a little of the stress that these mechanical systems are sustaining is fed back to the driver through the vehicle's controls and its response to control inputs; control and system dynamics respectively (Wickens, 1992).

In representing an intervening variable in the driver-road interaction, the manner in which the vehicle communicates its status and that of its environment to the driver, in the form of vehicle feedback, should not be underestimated (Hoffman & Joubert, 1968; Stanton & Young, 1998). Drivers are remarkably sensitive to feedback, in particular feedback derived from their vehicle. Joy and Hartley (1953/4) studied the ability of drivers to detect (very slight) differences in certain vehicle handling characteristics. In the experimenter's own words, the detection threshold roughly corresponds to "*...the difference in feel of a medium-size saloon car with and without a fairly heavy passenger in the rear seat*" (Joy & Hartley, p. 119). Consider that a typical British saloon car of that era might weigh around one tonne, and that a fairly heavy passenger weighs in the region of 90kgs (0.09 of a tonne). In other words, it takes the addition of 0.09 of the vehicle's weight to bring about a perceivable difference for drivers in terms of the vehicles handling characteristics. This level of sensitivity towards vehicle feedback is cited by Joy & Hartley as being very high, and reflects upon the sensitivity and primacy of the psychological information processing modules employed within the driving task. Similarly, Hoffman and Joubert obtained Just Noticeable Difference (JND) data on a number of vehicle handling variables, and they too found, "*a very high differential sensitivity to changes of* [vehicle] *response time, and reasonably good ability to detect changes of steering ratio and stability factor*" (p. 263). As such, let there be no doubt about the abilities of normal drivers not only to perceive, but to interpret, and put vehicle feedback to use within the driving task, often with little or no conscious awareness and little cognitive effort.

Anecdotal evidence exists in abundance for the favourable role of vehicle feedback. A brief survey of any motoring publication will yield quotes as follows, "*The Jaguar's steering...* [is] *neither too light nor too heavy, yet really alive and informative.*" (Frazer, Aug. 1998, p.81), or "*...there's a significant surge of power at 2000rpm, followed by a muffled growl at 3500rpm and then another noticeable step up at 4000rpm.*" (Overland, Aug. 1998, p.75). Car makers themselves are certainly not unaware of this aspect of vehicle design. A contemporary BMW advertising campaign (that happens to coincide with the closing stages of this Thesis) is entitled 'Feel Connected', and seems to be attempting to bring vehicle feedback into driver's consciousness, and in doing so offers a means of adding value and increasing sales (BMW, 2002). In this particular manufacturer's case, ways to describe their maxim of the 'ultimate driving machine' invoke statements such as, "*no other car puts such a degree of feeling* [in the steering system] *where it matters most: in the palm of your hands*", or "*BMW's acoustic engineering strategy is to make sure any noise you hear provides either information or pleasure*", or even, "*BMW suspension is finely tuned (....) It offers instant feedback to the driver about how the car is reacting to changes on the road, helping you drive with a greater degree of precision*". (BMW). All of this is related strongly to the quality of vehicle feedback (if not, then the quality of marketing hyperbole).

2.1.6 Feedback Framework Summary

Although closed-loop conceptions of driving are not new in themselves (e.g. Bellet & Tattegrain-Veste, 1999; McRuer, Allen, Weir, & Klein, 1977; Milliken & Dell'Amico, 1968; Verwey, 1993), each new model expresses its own particular research emphasis. In the present case, the emphasis, firstly, is on an inclusive contemporary grounding in all of the functional aspects of driving. These functional aspects are high-level psychology, high-level information processing, sensory inputs, further lower level information processing, driving tasks, the car, the context/environment, and feedback (back) into driver information processing. The arrows linking these functional aspects are at this stage inferential. But the key point remains that the functional elements embody not only driver psychology, but its relationship towards driving tasks, automotive engineering, and vehicle dynamics; a relationship that the disparate worlds of engineering and psychology have yet to fully reconcile. Secondly, the emphasis is also focused on feedback to the driver, and this is the common thread running through the framework. So far, the discussion has presented a review of the literature, and a synthesis of the relevant psychological processes implicated in successful driving task enactment. This level of discussion has implied a number of defining characteristics of feedback, setting the stage for the notion of feedback to be properly defined for the purposes of further analysis.

2.2 A DEFINITION OF DRIVER FEEDBACK

2.2.1 Background

Thus far it has been possible to understand driver feedback as providing information back to the driver about the state of the current situation and interaction. This level of explanation has been sufficient for the discussion so far, but it is clear that there is much else implied under the term driver feedback.

Feedback is an important psychological concept that Donald Norman refers to as, *"...sending back to the user information about what action has actually been done, what result has been accomplished..."* (Norman, 1998, pg 27), or knowledge of results (Annett & Kay, 1957). Noyes and Baber (1999) show how this conventional definition of feedback can be difficult to apply to a task such as driving. Generally speaking driving is a continuous task, and there is rarely any natural termination of a driving action. Consider for example the continuously variable scope of adjustments that have to be made when steering a vehicle. This is why driver feedback has so far been viewed in relation to a *continuous interaction* rather than a discreet task. As a result of this, the type of 'outcome' feedback that Norman (1998) talks of above becomes more difficult to define.

On the other hand Welford (1968) is interested in the timing of feedback, where it is argued that minimal delay between action and feedback is most effective for performance and learning. So by virtue of its continuous action-response characteristics, drivers typically receive an abundant stream of knowledge of results regarding the consequences of their actions, and they also receive them virtually instantaneously.

Baber (1997) discusses the notion of feedback levels; an argument that helps to define the purpose that feedback serves within an interaction. The argument is presented in relation to HCI research and the enactment of a discreet task (a key press on a computer). The levels of feedback start off with primary feedback concerning the operation of the control itself, in this case the movement and sound that the computer key makes. It progresses through to outcome feedback concerning the resulting output that the control action gives rise to, such as the appearance of a character on the computer screen, or some other change in system status. The feedback therefore progresses from the physiological level (understanding that the key press has been performed correctly) to the cognitive level (understanding the output of the action in relation to wider user goals).

Levels of feedback can be related to driver feedback in terms of Wickens' (1992) definitions of control and system dynamics. Control dynamics would be concerned with the reaction of the control (i.e. the steering wheel) to the driver's inputs, and is therefore couched at a generally physiological, primary feedback level. System dynamics are related to the resulting vehicle output such as a change in trajectory, couched at a generally more cognitive, outcome feedback level. However, unlike a computer keyboard, many of the vehicle's controls provide primary *and* outcome feedback.

Clearly there are further questions implied in the concept of driver feedback. Where does the feedback come from, through which sensory modalities does it proceed through, and what information should the feedback convey? Feedback is therefore defined for the purposes of this thesis as embodying three dimensions; the source of feedback, the timing of feedback, and the content of the feedback.

2.2.2 Source of Feedback

Feedback can be perceived *directly* from the environment, particularly in the form of visual stimuli. Feedback can also be perceived *indirectly* through the vehicle, for example, as in the case of steering force feedback. Feedback can be *reactive,* arising as a direct consequence of driver actions, or it can be *passive,* arising through the vehicle's natural behaviour as it constantly interacts with the road environment. In other words, feedback can supply knowledge of results, or it can provide updates on the vehicle's ongoing status. Feedback can also be *explicit,* in the form of overt feedback interfaces such as vehicle instruments or warnings, and it can be *implicit* in the form of subtle changes in control feel or response. Explicit feedback involves devices or displays that are purposefully designed to present the driver with information that they need. Implicit feedback is rather more subtle, and tends to rely on the driver correctly perceiving the meaning of stimuli such as changing steering feel or vehicle response that are not overtly designed as such, but arise as a natural consequence of the vehicle's behaviour in a given situation. Related to the originating source of feedback is the *sensory modality* through which the feedback information proceeds. For example, the driver can perceive vehicle speed explicitly, via vision, by looking at a speedometer, or else they can perceive the feedback information implicitly through wind noise (auditory modality) and/or vibration from the road surface (tactile modality). So in terms of the sources of feedback, the central thrust is that feedback can be reactive to inputs from the driver, or simply passive as it interacts constantly with the situation; feedback can emanate directly or indirectly from the situation, can be implicit or explicit, and a complex interplay between these factors largely determines through which sensory modality (or modalities) the feedback information is communicated.

2.2.3 Content of Feedback

Feedback is, quite simply, a chunk or stream of information. The content of the information is defined according to whether it is providing a *rich* source of information compared to an *impoverished* source. In other words the feedback information can provide abundant cues as to the state of the current situation, or else it may only provide tenuous information. Similarly, the content of feedback can be defined according to the *quantity* of information as well as the nature of its content. Related to this, the content of feedback can be defined according to whether it is an *accurate* representation of a given situation or whether it is an *inaccurate* representation.

2.2.4 Timing of Feedback

Feedback information can be communicated along a time scale, ranging from *instantaneous* at one end through to what ever time lag is required at the other end of the scale, up to and including *infinity* in the case of pure open loop behaviour. The timing of feedback information is dependent upon the *response of the vehicle* to inputs from the driver, as well as inputs from the environment. Timing also speaks towards the *sequence* of feedback, where the situation might present different types of feedback in a particular order contingent upon the nature of the situation being encountered, or task being performed. This relates back to Baber's (1997) earlier argument regarding levels of feedback. Here a sequence of different feedback levels is implied.

Timing is related strongly to the sources of feedback, as different sources imply different temporal properties, for example, the tactile sense possesses faster stimuli response times than vision. Therefore an example might be that implicit vehicle stimuli may communicate its information quicker than, say, voice synthesis.

2.2.5 Feedback Dynamics

Good feedback can be regarded as supporting the information requirements of safe, efficient and enjoyable driving. Feedback is specified according to a three level framework of sources of feedback, content of feedback, and timing of feedback. The source of feedback to some extent dictates what the feedback information can physically contain. Similarly, the source of feedback also, to some degree, determines the temporal properties of feedback. Therefore, as figure 2.4 shows below, in terms of the dynamics of feedback, information content and timing stem from the source of feedback.

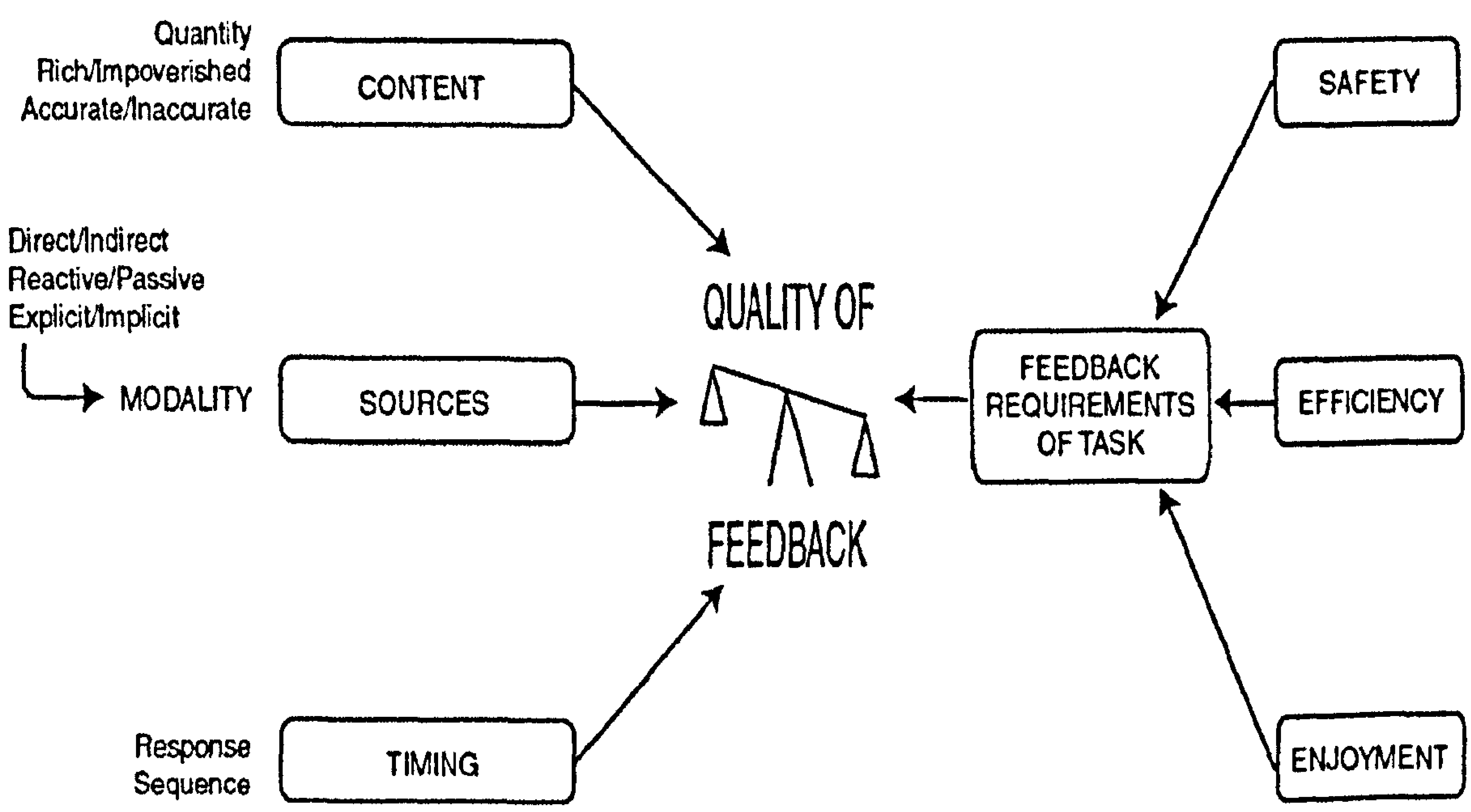


Figure 2.4 - Dynamics of feedback according to a three level taxonomy

If source, content, and timing of feedback describe the *process* of feedback, then feedback quality represents the *product*, or end state. This is arrived at through a match between the sources, content, and timing of feedback, and the specific information requirements (along these dimensions) of the given driving situation. Quality of feedback represents the ultimate design goal, whereas source, content, and timing represent how feedback can be manipulated by the vehicle designer. An analysis of the information needs of drivers shows in what direction feedback properties should be manipulated. In order to ascertain the information requirements of drivers, some means of systematically and exhaustively analyzing the driving task and situation has to be performed.

2.3 STUDY 1: HIERARCHICAL TASK ANALYSIS OF DRIVING

2.3.1 Background

The driving situation is an interesting case when compared to other transport systems. Notwithstanding certain constraints imposed by the triad of driver, vehicle, and road, the human role in driving is still unusually large. Godthelp, Farber, Groeger, and Labiale (1993), and Fuller (1984) rightly point out that journeys are initiated at self chosen times, with self chosen vehicles, along self chosen roads, and that the task of driving is essentially a self paced activity. Compare this to air or rail travel. Within these domains the range of permissible manoeuvres is restricted by infrastructure such as railway tracks, and external supervision such as air traffic control (Michon, 1993). Driving therefore represents a domain with considerable autonomy, providing the driver with unprecedented control over their interactions between the vehicle and road.

Considerable research effort has been expended on driving, so what exactly is it? Although there is a sizeable body of knowledge concerned with driver behaviour (and the psychology underpinning that behaviour (e.g., Shinar, Meir, & Ben-Shoham, 1998)) there is comparatively little knowledge related to precisely what drivers are *actually doing* as they drive. An exhaustive task analysis is presented below that helps to answer this more specific question in some detail.

2.3.2 Psychomotor Control

The vehicle's fundamental systems are controlled by the driver via various control inceptors. Vehicle steering (fundamental system) is controlled by the steering wheel (inceptor), engine speed and power output is controlled by the accelerator pedal and vehicle brakes by the brake pedal. These inputs to the vehicle require the driver to enact various forms of psychomotor behaviour.

Driving is a manual control task. Manual control can be defined with reference to the manual output of human information processing, such as the movement of limbs and hands to operate system controls and inceptors. Tracking refers to when this output has to be continuous in order to keep the system within certain parameters. Traditionally this might be understood as keeping a nuclear power station, chemical plant, or some other form of process system within acceptable boundaries of performance and safety. Acceptable boundaries of performance in car driving are defined by a host of variables that need not be rehearsed in detail here. They include auditory feedback from the engine, through to factors such as 'time to collision' for steering and braking. Unfortunately, Sanders and McCormick (1993) state that humans are not generally regarded as being particularly good at tracking tasks.

What vehicle controls have in common, broadly speaking, is that the *position of the control* is more or less directly related to the *rate of output* (Milliken & Dell'Amico, 1968). In the scope of normal driving this linear and therefore predictable relationship holds true. For example, steering wheel angle is directly proportional to the rate of turning in a similar way that accelerator position is proportional to the rate of engine power delivery, and brake pedal position is proportional to braking force. Milliken and Dell'Amico (1968) point out that 'rate' control is intuitive to drivers.

In combination with 'rate' control a number of strategies can be employed to aid human performance in tracking tasks. Whether by design or otherwise, vehicle feedback provides some of these aids. For example, the design of front suspension geometry endows vehicle steering with an inherent self centering effect, and this characteristic is an aid to accurate tracking performance (Sanders & McCormick, 1993). Vehicle design factors play a significant role in explaining how an ostensibly complex mechanical system such as a car can be controlled so easily by such a diverse population of drivers. In fact, it has been suggested that riding a bicycle presents equal if not more control difficulties (Milliken & Dell'Amico).

The manner in which humans inherently control motor actions is another significant factor in making car driving a relatively straightforward task. Verwey (1996) suggests that driving tasks can be broken down into 'motor chunks'. These are a predetermined sequence of motor actions, such as those needed to change gear, perform a hill start using the handbrake, or pull up to a stop. A motor chunk is triggered by a variety of feedback information that relies on attention-demanding response selection. However, as Shinar, Meir, and Ben-Shoham (1998) state, the motor chunk itself requires little such attention from the driver. It requires little attention because it is highly learned, practiced often, and largely automatic.

It can be argued that much of the psychomotor control exhibited by the driver can be captured by various motor chunks (Verwey, 1996). This efficiency in motor control enables many driving (and for that matter non-driving) tasks to be performed in parallel with little if any decrement in performance. However, Shinar et al. point out that many driving tasks take a large amount of task exposure (perhaps a number of years) until this level of automaticity arises.

At the most basic level driving a car is characterized by goal directed motor action. Regan (1997) states that *"an individuals motor reaction time is fastest when the individual knows in advance what information will be presented and what response should be made (simple reaction time).* [...] *Motor reaction time is longer when a decision is required (choice reaction time)"* (p. 204). Exposure and experience not only help appropriate motor chunks to be constructed, but they can help to speed up decision making time underpinning psychomotor behaviour. Rasmussen's (1994) skill and rule based levels of cognitive control capture this process to a great extent. Skilled behaviour relies on stored procedures that are called into action pre-cognitively, as opposed to non-skilled behaviour (such as novice performance) that has to be cognitively processed in advance of psychomotor output.

2.3.3 Driver Feedback, Transfer Functions, and the Tracking Loop

The driver is involved in a tracking loop comprised of a command input, given the notation ic(t). This command input is represented by the enactment of driving tasks, and is issued in response to some form of error that needs to be neutralized (such as cues from the environment telling the driver that a collision will occur unless some action is taken), and is given the notation of e(t). The force applied to the relevant control (such as the steering wheel) is expressed as f(t), and the movement of the control in relation to the force f(t) is expressed as u(t). The relationship between f(t) and u(t) is termed control dynamics (Wickens, 1992). Control dynamics is specified in terms of the relationship between the force applied and the movement of the control, or the reaction of the control to an input from the driver (Wickens). Obviously this relationship will be influenced by feedback through the control from the environment, and this can be notated as id(t). For example, the driver applies a rotational torque to the steering wheel that causes it to turn. This action overcomes any resistance within the vehicles steering and front suspension system, and works against any feedback from the road. The response of the car to the control input (f(t)) is termed o(t), and this is termed system dynamics (Wickens). System dynamics is the relationship between control position, and the output of the system. In the present example this output relates the position of the steering wheel to the lateral acceleration of the vehicle within the external world. The relationship between system and control dynamics can be mapped onto a number of transfer functions. The transfer function presents the mathematical relationship between the input from the driver, and the output provided by the car. In doing so they can effectively map the *physical* driver vehicle interaction.

2.3.4 Goals and Tasks

In terms of the *psychological* driver vehicle interaction, it is goals and environmental inputs that feed into psychological processes, these processes lead to observable manual control task activities, activities that are performed on the car and the environment; activities that represent the driving task. A task is defined as an "*ordered sequence of control operations that leads towards some goal*" (Farber, 1999, p.14). "*A goal is some system end state sought by the driver*" (Farber, 1999, p. 18). One of the ultimate if albeit simplistic goals of driving is to reach a destination. This goal is comprised of many other associated goals, such as reaching a destination quickly, comfortably, even enjoyably, and in such a manner as to avoid crashes. In order to fulfill the high-level goals of driving a vast array of individual tasks have to be performed more or less competently by the driver. It is interesting to note that the only attempt at a systematic and exhaustive task analysis of driving quoted in contemporary literature (for example, Michon, 1993) remains the work of McKnight and Adams (1970). McKnight and Adams' work was prepared for the U.S. Department of Transportation in order to "*identify a set of driver performances that might be employed as terminal objectives in the development of driver education courses*" (McKnight & Adams, p. vii). Although the study was initiated mainly from the point of view of driver tuition, it nonetheless provides some useful insights into the range of activities that a driver has to perform. This range is clearly extensive, with 43 primary tasks comprised of 1700 sub tasks.

Despite providing these extremely useful insights into the range and quantity of tasks enacted by drivers, the stated purpose of McKnight and Adams' (1970) study severely limits its research applicability; neither is the report widely available. A reasonable corpus of knowledge exists about what vehicles are doing in response to driver inputs (for example Lechner & Perrin, 1993; Tijerina, et al., 1998) but thus far very little is actually known about what *drivers are doing*, or the specific nature and structure of the driving task itself. Despite this it is interesting to note the wide range of assumptions currently made about the driving task, especially given the fact that none of these assumptions appear to be based on any kind of systematic task analysis. In particular, a recurring contention made in the literature is one originally made by McRuer, Allen, Weir, and Klein (1977), whereby driving is stated as being comprised of a three level hierarchy; navigation, manoeuvring, and control. There can be no doubt that navigation, manoeuvring and control are important aspects of the driving task, but their specific role and interrelationships can surely be better examined using structured methods, of which task analysis is one.

2.3.5 Construction of the Hierarchical Task Analysis of Driving

To address this shortfall, a comprehensive task analysis of driving has been designed and constructed, and appears in full within Appendix A. The task analysis follows the rubric of Hierarchical Task Analysis (HTA) as pioneered by Annett and Duncan (1967). The basis of HTA is the axiom that a task is specified by its objectives or end products, and that plans are needed in order to achieve the desired goal (Annett, Duncan, Stammers, & Gray, 1971). Under this taxonomy the overall task goal, such as "drive a car" is broken down into constituent goals. Goals are the unobservable task goals held by the driver (Stanton & Young, 1999). On the other hand tasks or operations are *observable* physical activities (such as "depress brake pedal") that are performed by the driver in pursuit of the unobservable goals. Plans are also *unobservable*, and they specify the sequence of task enactment needed, often contingent upon necessary conditions being met, in order to achieve the desired goal state. The necessary conditions that have to be met mean that feedback is an important concept within task analysis. The Test Operate Test Execute (TOTE) sequence describes the relationship between task enactment and feedback in terms of pursuing a particular goal state (Miller, Gallanter, & Pribram, 1960). Under this TOTE sequence the individual tests or checks for a criterion state, performs an operation to affect that change, checks again (and returns to the operate stage until the criterion is met), when the criterion is met, the task or action is executed. The practical manifestation of the TOTE sequence within the current HTA is that the plans contain logical operators such as IF THEN OR AND ELSE and WHILE. A probability/cost heuristic is also applied to define the limits of the HTA, as clearly the analysis can proceed to the microscopic level with no further increases in design utility. If the probability of failure at a particular level of task enactment is small, and the consequences of that failure are similarly small then the analysis can cease.

HTA has a lineage in training (Annett & Duncan, 1967), as does the analysis conducted by McKnight and Adams (1970), though this is not a Hierarchical Task Analysis of the form espoused by Annett and Duncan. Contemporary approaches view HTA as a tool that is valid within a much wider context. This context includes overcoming performance problems, developing hypotheses, deriving detailed situational awareness requirements, refining performance criteria, and understanding skill requirements, or task contexts, to name but a few (Shephard, 1998). In the present case the interest is in determining the structure of the driving task, to gain a measure of the range of tasks performed by drivers, and in conjunction with future studies, to attempt to determine driver's information and feedback needs at each stage of task enactment.

The HTA of Driving (HTAoD) begins by defining the driving activity (drive a car), setting the conditions in which this activity will take place (a modern, average sized, front wheel drive vehicle, equipped with a fuel injected engine, being used on a British public road), and the performance criteria to be met (drive in compliance with The Highway Code (1993), and the Police Driver's System of Car Control (Coyne, 1994)). This exercise is extremely important in constraining what is already a large and complex analysis within reasonable boundaries. Furthermore, this tight specification of the performance standards to be met emphasizes the point that the HTA represents a normative description of driving task enactment, a *specification* for good driving.

This highest level task goal is completely specified by seven first level sub goals, which altogether are completely specified by 1600 further individual operations and tasks occurring at lower task levels. All of these are bound together by 400 plans of a logical form. These plans define how task enactment should proceed, often contingent upon specific conditions being met or criterions being present. The top level of the HTAoD hierarchy is shown in figure 2.5 below as a summary.

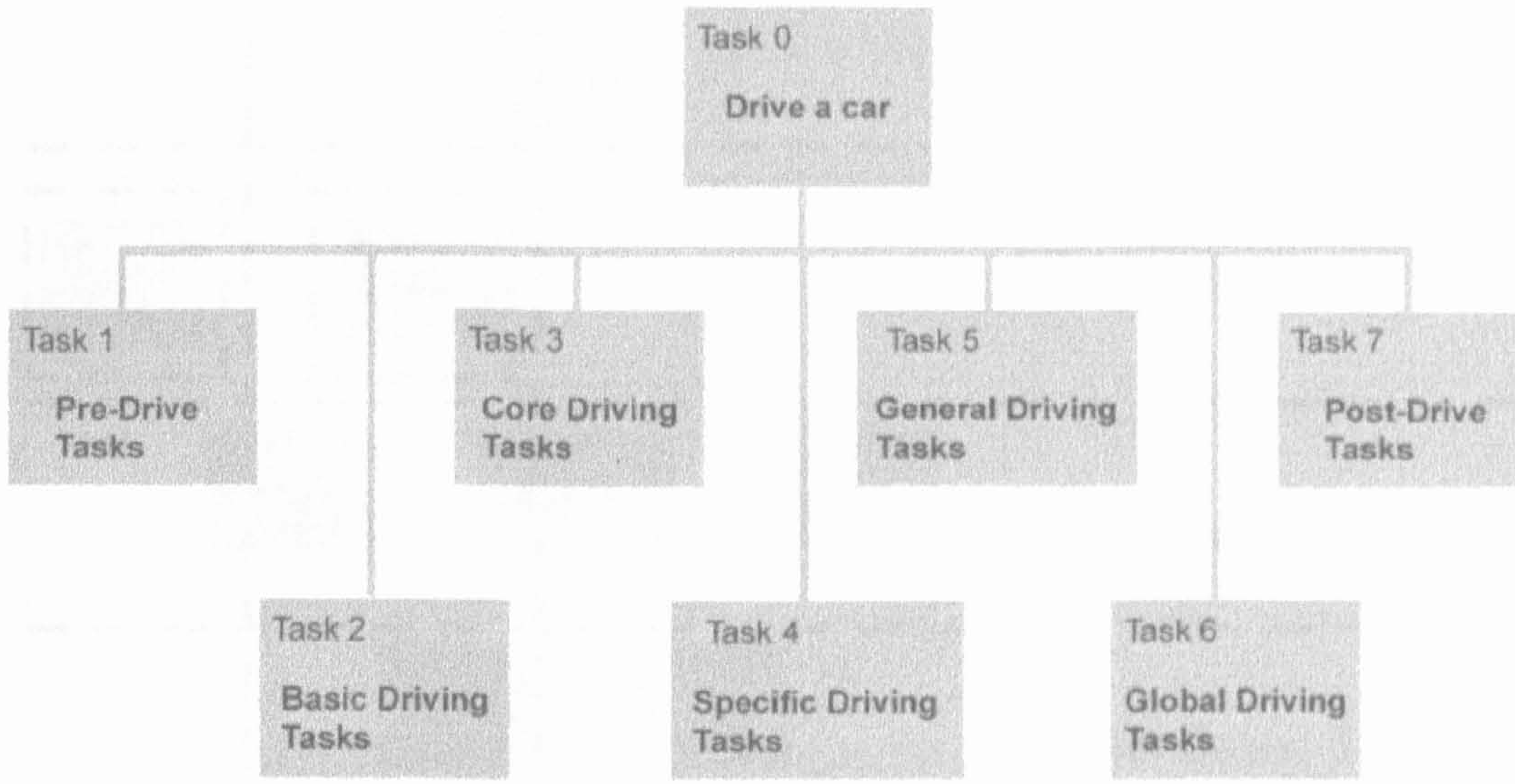


Figure 2.5 - Top level of the HTAoD.

2.3.6 Hierarchical Task Analysis of Driving Behaviour Categories

On the basis of the current HTAoD it can be argued that driving (apart from pre and post drive tasks) is made up of five behaviour *categories*. To avoid confusion with terminology, HTA *levels* define the vertical structure of the HTA, working downwards through goal and sub goal levels right down to the bottom task and operational level. On the other hand, the behaviour *categories* are an expression of the *horizontal* structure of the HTAoD. This horizontally based taxonomy is comprised of Pre-Drive Tasks, Basic Driving Tasks, Core Driving Tasks, Specific Driving Tasks, General Driving Tasks, Global Driving Tasks, and Post-Drive Tasks. *Separating out* Pre and Post-Drive tasks leaves the driving behaviour categories responsible for the primary driving tasks enacted whilst on the move. Figure 2.6 below shows these behaviour categories, and their relationship towards HTAoD levels.

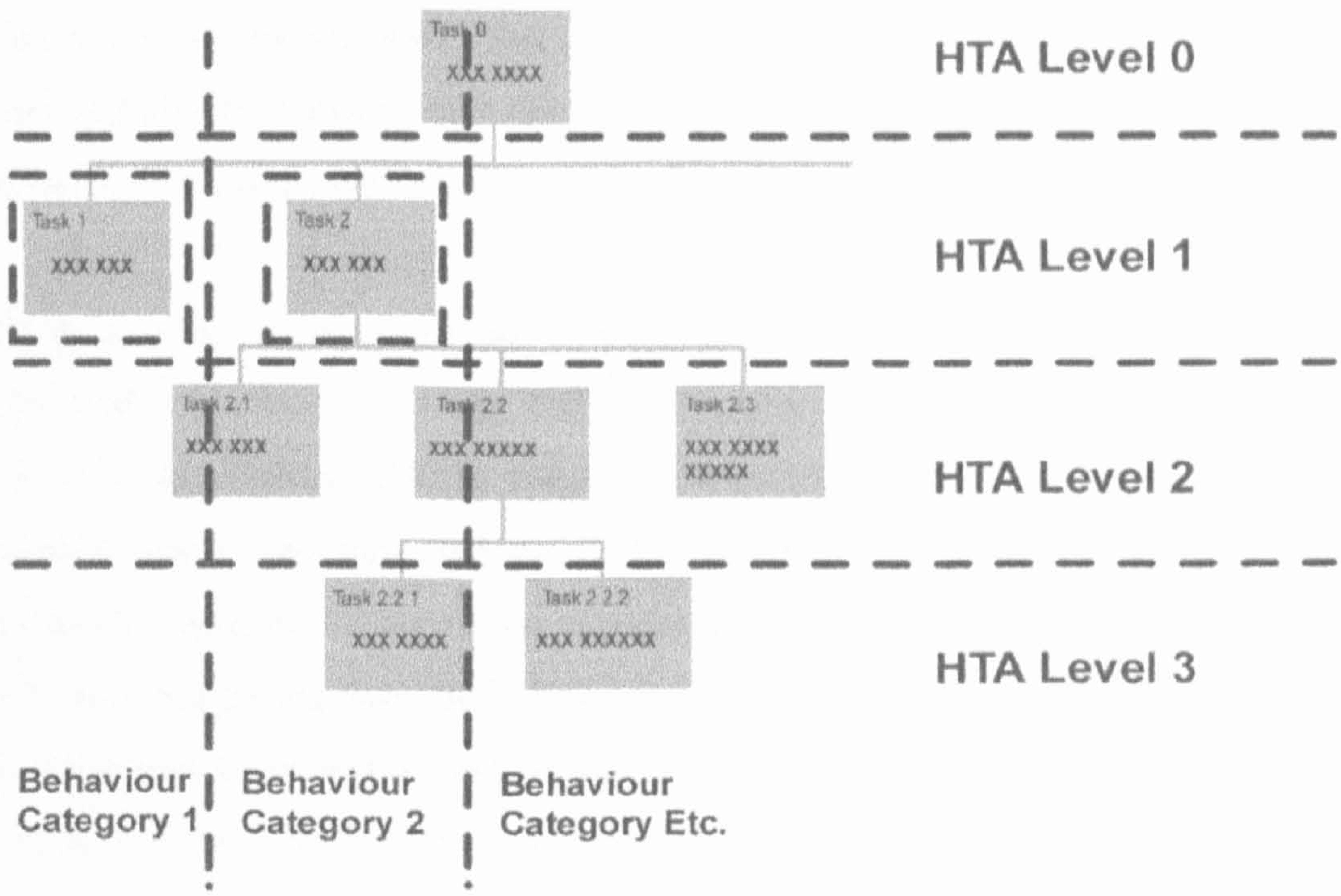


Figure 2.6 - Driving task behaviour categories and task levels

Behavior Category 1: Basic Driving Tasks are concerned with fundamental physical vehicle control tasks performed by the driver.

Behavior Category 2: Core Driving Tasks are still basic physical operations applied within a basic contextual setting of controlling vehicle speed and trajectory.

Behavior Category 3: Specific Driving Tasks cover strategies and operations for coping with specific road environment situations, such as junctions or crossings.

Behavior Category 4: General Driving Tasks represent increasingly goal orientated, overarching strategies for adapting to different road types, or general procedures for dealing with other traffic.

Behavior Category 5: Global Driving Tasks are concerned with goal orientated operations related to high-level driving strategy, such as rule compliance or navigation.

As expressed in the top level Plan zero (shown later below in table 2.1) the external world and driving context, in a dynamic manner, demands the enactment of all five behaviour levels from the driver, concurrently and interchangeably.

HTA possesses a certain craft skill element, contingent upon the skills and impartiality of the analyst (Stanton & Young, 1999). Therefore, although the prior task analysis of McKnight and Adams (1970) was referenced extensively, it was *not* used as the structural basis of this new analysis. Still, reassuringly, the current HTAoD fell readily into similar categories of behaviour as those presented in McKnight and Adams' earlier work, thus suggesting that the behaviour categories cited above are reasonably valid. These categories can replace the old three level hierarchy espoused by McRuer, Allen, Weir, and Klein (1977) with a new five level hierarchy that is actually based on a systematic analysis of the driving task.

2.3.7 Hierarchical Task Analysis of Driving Sub-Goals

Moving down the HTAoD one more level helps to illustrate in greater resolution the nature of the sub-goals pursuant of the five behaviour categories. These sub-goals become increasingly contextually grounded, and a truncated form of the HTAoD is presented in tabular format below (table 2.1).

Table 2.1 - HTAoD sub-goals.

0 TASK STATEMENT

Drive a modern, average sized, front wheel drive vehicle equipped with a fuel injected engine, on a British public road, in compliance with the Highway Code, and using the Police Driver's System of Car Control.

Plan 0 – do 1, THEN 2 AND 3 AND 4 AND 5 WHILE 6 THEN 7

1 PRE DRIVE TASKS

Plan 1 – do in order

1.1 pre operative procedures

1.2 starting

2 BASIC DRIVING TASKS

Plan 2 – do 2.1 AND 2.2 THEN 2.3 THEN 2.4 [contingent upon events specified in 2.4]

2.1 pulling away from standstill

2.2 steering

2.3 speed control

2.4 decrease speed

3 CORE DRIVING TASKS

Plan 3 – do 3.1 AND 3.2 AND 3.3 [contingent upon events specified in 3.3]. do 2.4 THEN 3.4 [as required]

3.1 directional control

3.2 negotiating bends

3.3 negotiating gradients

3.4 reversing

4 SPECIFIC DRIVING TASKS

Plan 4 – do 4.1 to 4.7 [contingent upon events specified in 4.1 to 4.7]

4.1 emerging into traffic from side road

4.2 following other vehicles

4.3 overtaking

4.4 approach junctions

4.5 deal with junctions

4.6 deal with crossings

4.7 leave junction (crossing)

5 GENERAL DRIVING TASKS

Plan 5 - do 5.1 to 5.4 [contingent upon events specified in 5.1 to 5.4]

5.1 deal with different road types/classifications

5.2 deal with roadway related hazards

5.3 general tasks for reacting to traffic

5.4 emergency manoeuvres

6 GLOBAL DRIVING TASKS

Plan 6 - do 6.1 to 6.4 [contingent upon events specified in 6.1 to 6.4]

6.1 surveillance

6.2 navigation

6.3 rule compliance

6.4 tasks related to the environment

6.5 IAM system of car control

6.6 vehicle/mechanical sympathy

6.7 driver attitude/deportment

7 POST DRIVE TASKS

Plan 7 - do in order

7.1 parking

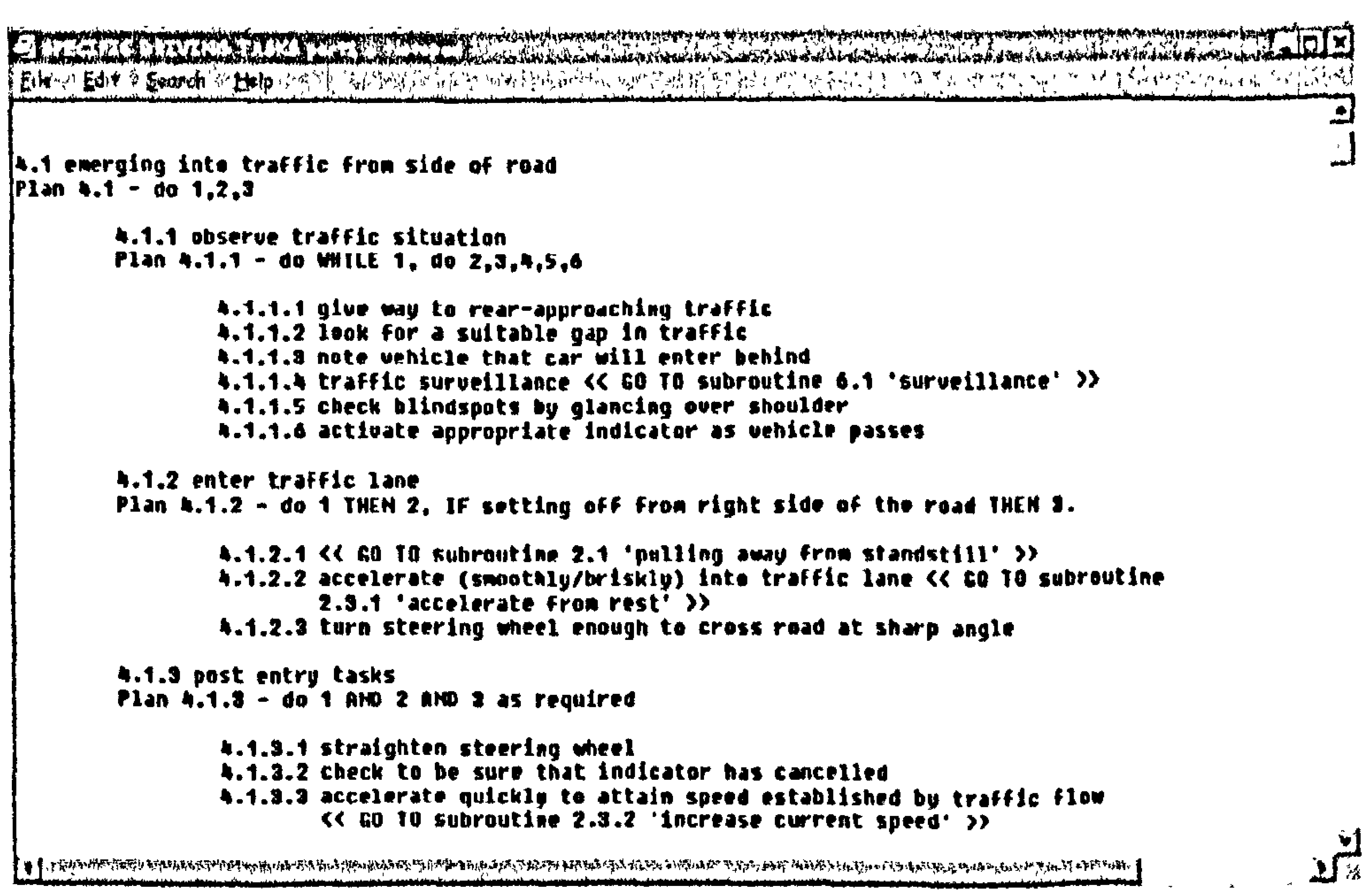
7.2 making the vehicle safe

7.3 leaving the vehicle

At this level the practical applied value of the HTAoD becomes even more evident, as a goal directed analysis such as this can be employed to determine in some detail the precise information needs of drivers. An important feature of this HTA is that other sub goals and tasks are repeatedly called into action when the situation demands. A significant rationalization of the analysis is realized through using this procedure, as sub goals and tasks do not have to be repeated unnecessarily. For example, the specific driving goal of 'approach junction' involves decreasing speed which calls in the enactment of sub goal 2.4 from the basic driving task level. To use a computer programming metaphor, in effect this calls in the enactment of sub routines, given the notation in some computer programming languages and this task analysis of GO TO (or 'go to' a given sub routine).

2.3.8 Hierarchical Task Analysis of Driving Bottom Level Operations

One thousand six hundred individual tasks and operations contribute towards making up the total driving task. In essence, small clusters of these individual tasks go towards achieving the desired super-ordinate goal states. At this bottom level of analysis the operation of the TOTE sequence is much in evidence, as shown in the plans featured in the example below in figure 2.7. The reader is again referred to Appendix A for the complete version of the HTAoD.



File Edit Search Help

4.1 emerging into traffic from side of road
Plan 4.1 - do 1,2,3

4.1.1 observe traffic situation
Plan 4.1.1 - do WHILE 1, do 2,3,4,5,6

4.1.1.1 give way to rear-approaching traffic
4.1.1.2 look for a suitable gap in traffic
4.1.1.3 note vehicle that car will enter behind
4.1.1.4 traffic surveillance << GO TO subroutine 6.1 'surveillance' >>
4.1.1.5 check blindspots by glancing over shoulder
4.1.1.6 activate appropriate indicator as vehicle passes

4.1.2 enter traffic lane
Plan 4.1.2 - do 1 THEN 2, IF setting off from right side of the road THEN 3.

4.1.2.1 << GO TO subroutine 2.1 'pulling away from standstill' >>
4.1.2.2 accelerate (smoothly/briskly) into traffic lane << GO TO subroutine 2.3.1 'accelerate from rest' >>
4.1.2.3 turn steering wheel enough to cross road at sharp angle

4.1.3 post entry tasks
Plan 4.1.3 - do 1 AND 2 AND 3 as required

4.1.3.1 straighten steering wheel
4.1.3.2 check to be sure that indicator has cancelled
4.1.3.3 accelerate quickly to attain speed established by traffic flow << GO TO subroutine 2.3.2 'increase current speed' >>

Figure 2.7 – Example of bottom level HTAoD tasks and operations.

Overall, the feedback requirements of the driving task are represented within no less than 400 plans, and 1600 tasks. Cognitive and perceptual elements of the driving task have to be necessarily inferred from this, and studies conducted later in this Thesis systematically elicit driver's information needs from the HTAoD for further analysis.

2.3.9 The Hierarchical Task Analysis of Driving and the Feedback Framework

Fundamentally the HTAoD is an event driven model. It is interesting to speculate that in theory a computer or some form of expert system could indeed be programmed with this HTAoD, along with every possible combination of contingent driving event such that it would then be able to drive as well as a human driver. Although potentially of some use in a practical domain, this brute force, rule based 'IF-THEN' approach is unlikely to represent the way that human drivers process information as they drive. The HTAoD is offered as a tool for research, and thus the intention is to employ it as a means of uncovering and understanding in more detail the nature and structure of cognitive processing enacted by drivers. As such, the HTAoD can now be synthesized alongside sensory perception within the feedback model of driving shown below in figure 2.8.

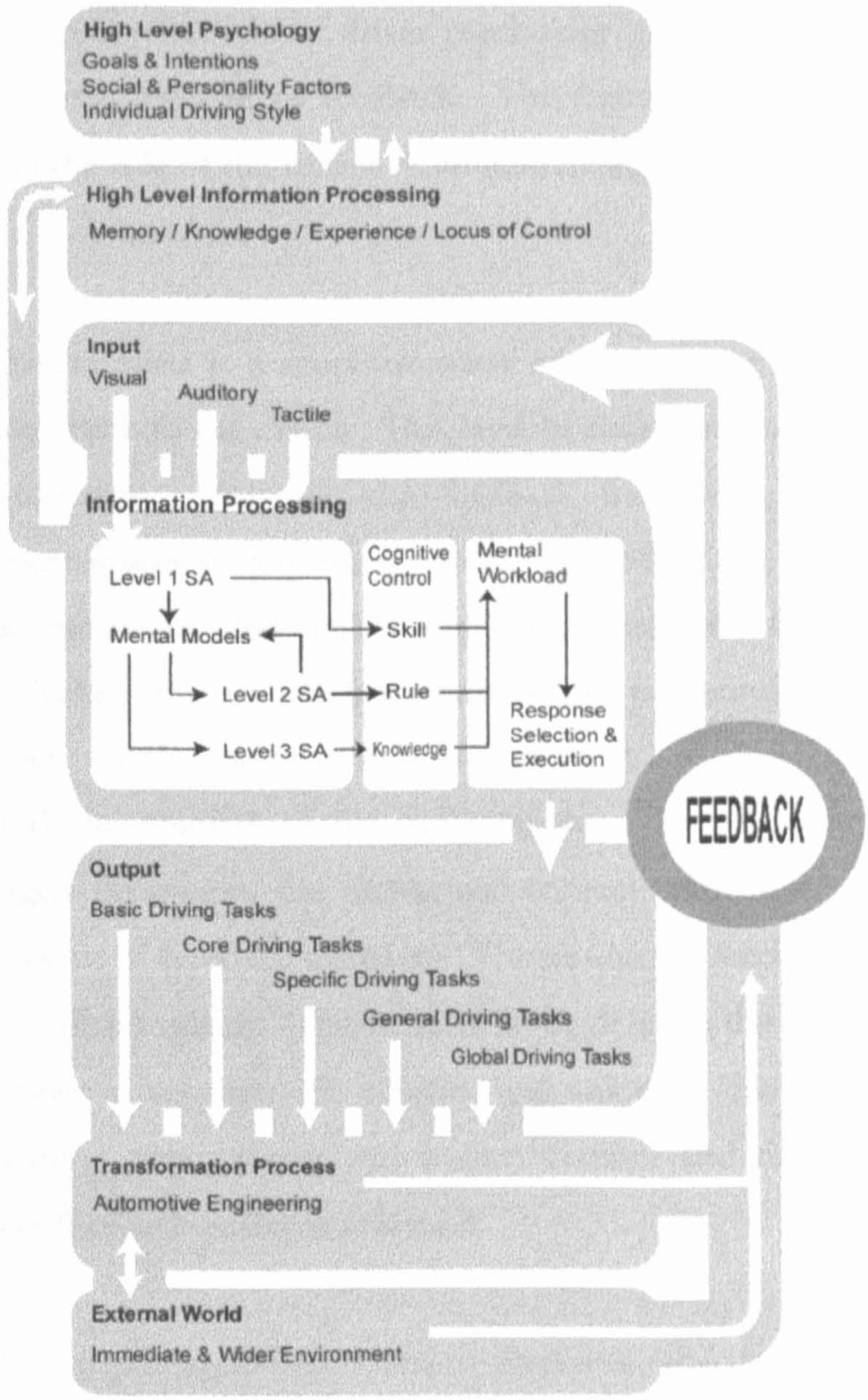


Figure 2.8 - Feedback model of driving with the addition of the HTAoD.

2.4 SUMMARY

The psychological effect of future vehicle technologies provides justification for examining in more detail the interrelationships between cognitive processes and feedback within this chapter. In order to facilitate a proper scientific exploration of the role of feedback, this chapter takes the psychological mechanisms highlighted earlier and synthesizes them within a feedback framework of driving. This provides a necessary backdrop for the role of driver psychology, the vehicle, the environment, and most importantly the role of feedback. The framework gives an emphasis on feedback, and on the role of the vehicle as an intervening variable in the driver vehicle interaction.

Feedback can be regarded in a simplistic sense as representing information that the situation provides back to the driver. This level of definition has, in earlier sections, been largely sufficient. However, the feedback framework, the review of the psychological mechanisms underpinning driving task behaviour, and the role of the vehicle in this behaviour, has rather implied a number of different feedback characteristics. Taking this knowledge, feedback can be defined according to three dimensions. These are the source of information about a situation, the timing of that information, and the content of the information. The source of the feedback information largely determines the timing and content, and these three dimensions represent the process of feedback dynamics. The product of feedback, the desired end state is termed feedback quality. This is achieved by defining the information required by driver's in order to support safe, efficient and enjoyable driving. When a match between information requirements and source, content and timing of feedback is gained, then high feedback quality is achieved.

The discussion of psychological mechanisms illustrates what feedback can do to the manner in which driver's process information. The definition of feedback shows the dimensions along which the designer can manipulate the characteristics of the vehicle, in turn the HTAoD provides a specification for the information requirements of safe, efficient, and enjoyable driving. This represents a tool that the domain of driving research has until now been largely lacking. It illustrates the range and complexity of the goals and tasks performed by drivers, and feedback provides one means of supporting this behaviour. In the following chapter the issue of feedback is explored in a naturalistic on-road context. This provides the kind of initial insights needed to more accurately guide the design and use of the HTAoD in highly controlled driving simulator experiments.

Chapter 3

On-Road Investigations of Vehicle Feedback

3.1 INTRODUCTION

3.1.1 Background

Naturalistic driving is defined for the purposes of this Study as normal driving occurring in its everyday context. Literature within applied cognitive psychology often uses naturalistic driving as an interesting case study (e.g. Barber, 1988), and indeed, much of the weight of cognitive psychology and human factors research is brought to bear upon the domain of driving. Nevertheless, surprisingly few studies seem to directly analyse driving within the environment and situation in which it normally takes place. There are of course many valid reasons for this. The naturalistic driving scenario is very difficult to experimentally control, with factors such as weather and traffic conditions virtually impossible to precisely repeat between trials, and individual differences between and within drivers are typically very large (Lechner & Perrin, 1993). Furthermore, the processes of measuring driving can to some extent alter the phenomenon under measurement, the Hawthorne Effect, as individual driving style and behaviour could be influenced by such simple factors as having a passenger present in the vehicle. But these arguments often remain just as powerful for simulator based research as well. In terms of driving simulation, experimental control is in direct conflict with ecological validity (Jackson & Blackman, 1994). In mitigation thought, the 'reduced world' view of simulation would suggest that it is sufficient merely to preserve the *functional relationships* encountered in real life driving as specified by the research questions of interest (Ehret, Gray & Kirschenbaum, 2000). Despite this debate, there can be no dispute that simulator studies still have the potential disadvantages of an environment that is simply not as realistic as the real world, with the drive being completed in a vehicle not owned or normally driven by the driver. Therefore, combining naturalistic and simulator research would appear to be a valid approach, especially if the ecological validity of real world driving provides evidence for the sorts of questions to be answered in a more controlled simulator environment. This is the essence of the present Chapter.

3.1.2 Review of Naturalistic Driving Studies

Human factors work on vehicles and drivers, at least such work that exists within the public domain appears to have begun in earnest during the 1960s. In fact, a lack of available technology to enable realistic driving simulation left few other options but to conduct studies in real cars either on public roads or the test track. It is interesting to review what these studies set out to achieve, and the methods that were used, even though directly analysing driver cognition does not seem to feature prominently. Representative of this now largely forgotten type of study is Segel (1964). This study involved a variable steering vehicle whereby steering force gradient and steering system torque were manipulated for two cornering tasks. Conclusions were based upon a transcript of driver verbalisations and ratings of subjective driver judgments and opinions. The experiment was conducted with five drivers, an experimenter on board for the duration of the trial, and a flat off-road test site was employed. Useful data on the relationship between the vehicle's steering dynamics was gained as it related to subjective driver ratings. Similarly, Ritchie, McCoy, and Welde (1968) studied the relationship between longitudinal velocity and lateral acceleration in curves. Fifty participants drove an instrumented vehicle with the experimenter present, over a 110 mile test route containing over

200 identifiable curves. Predictably, the faster that drivers travelled in the longitudinal plane the less lateral forces (G) they were willing to accept in corners. Considering that the domain of psychology was, at that point in time, situated firmly within the behaviourist tradition it is hardly surprising that the interest was equally firmly couched in objective, measurable driver/vehicle behaviours.

It has already been seen earlier on in Chapter Two how objective behaviours have been thoroughly described and analysed by McKnight & Adams (1970). This analysis is descriptive in nature, and although offering the potential for starting to infer underlying cognitive processes in driving this was never its primary objective. Moving away from the descriptive approach are Godthelp and Käppler (1988). This study involved an experimental vehicle with an experimenter present during the trials, and was concerned with vehicle handling characteristics and how this factor influences driving strategy. This study begins to answer some of the 'why' questions, but from the point of view of perception rather than underlying cognitive processing.

By the 1990's significant advances in technology made increasingly accurate driving simulation viable. These same advances also enabled much more sophisticated vehicle telemetry to be employed as a tool for research, and thus some renewed interest in descriptive on-road driving studies is evident during this time. Lechner & Perrin (1993) performed a methodologically interesting study in attempting to answer the simple (and surprisingly unanswered) question of exactly how much of a vehicle's dynamic performance normal drivers actually used. An experimental vehicle was employed, but it was unobtrusively instrumented. Also, no experimenter was present as drivers drove over the experimental route and proceeded to use only 50% (at most) of the vehicles total dynamic abilities. In a similar vein, Tijerina et al. (1998) unobtrusively instrumented participant's ***own cars***, and proceeded to measure normal daily driving, again with no experimenter present. Vehicle telemetry data was employed within this particular study for the development of a drowsy driver monitoring algorithm. In addition, the US National Highway Traffic Safety Administration (NHTSA) performed a comprehensive descriptive evaluation of an intelligent cruise control system (Koziol et al., 1999). Employing fully instrumented vehicles enabled almost every conceivable aspect of driving performance to be measured, and comparisons based upon different cruise control conditions were carried out. The remit of all these recent studies was, however, not to begin inferring underlying cognitive processes in driving, and therefore unsurprisingly they do not make any attempts in that direction.

A cross section of the literature demonstrates that the naturalistic on-road study paradigm is not generally employed as a starting point to begin analysing the cognitive processing underpinning normal driving. But the methodological approaches nonetheless remain interesting. These vary from carrying out the study on private test tracks, in an experimental vehicle, and with an experimenter present, through to sending out normal drivers in their own vehicles, on their normal journeys, with full vehicle telemetry.

3.1.3 Motorcycles

Motorcycles, of course, provide an interesting alternative driving task with distinct feedback properties. For the sake of interest, there is no reason not to consider these distinct properties experimentally with cars. Unfortunately, compared even to cars the literature on the human factors of motorcycle riding is particularly sparse. Such literature as there is mainly focuses on rider skill (e.g. Rice, 1978), machine dynamics (e.g. McKibben, 1978 and Hartman, 1978), and safety (e.g. Hurt & DuPont, 1977). On the whole the comparative lack of human factors work on motorcycling is particularly concerning given the possible safety insights that research of this nature could yield.

Motorcycle riding, though distinct from car driving in certain key respects, is still a comparable alternative type of driving task. Evidence of this can be gained from McKnight and Heywood (1974), this being a comprehensive task analysis of motorcycle riding following in the vein of the earlier task analysis of car driving performed by McKnight and Adams (1970). From this it can be seen that the two tasks are broadly comparable, both of them falling into "basic control tasks, tasks related to roadway characteristics, tasks related to traffic conditions, and tasks related to the environment" (McKnight & Heywood, 1974, p. vi-ix). Under the McKnight and Adams' analysis, car drivers had a total of approximately 1700 tasks to complete. For motorcyclists this increases to nearer 3500, although the nature of the motorcycle task analysis involves many more spurious tasks related to carrying pillion passengers and securing cargo (McKnight & Heywood). Within the *central* activity of motorcycle riding there are still quite a number of manifest differences, including tasks such as, *"maintaining balance"*, *"maintaining stable angle of lean"*, and worryingly tasks related towards, *"if a fall becomes inevitable"* (McKnight & Heywood, p. v-ix). It is clear that motorcyclists have more to do in order to control the machine. Not only do motorcyclists have more to do, but they are exposed to large differences in the sources, content, and timing of feedback.

From the point of view of vehicle feedback, compared to a car driver the motorcyclist is in more or less direct contact with the environment. Not only are they exposed to noise, wind, and weather, but by virtue of their overall mechanical simplicity motorcycles also offer *abundant* feedback in terms of information derived from or through the machine. Not least of which is that when compared to their light weight (less than a quarter of the weight of most cars) the power output endows even the humblest motorcycle with prodigious acceleration. Thus control and system dynamics in the lateral accelerative plane are exceptionally responsive, with minimal time lag. In fact, motorcycles are probably the only road vehicle that are capable of generating roughly equal levels of accelerative and decelerative force. An admittedly very high performance, but nonetheless contemporary super-bike, the Suzuki GSX-R 1000 provides an illustration of this in taking a mere 5.75 seconds to accelerate from 0 – 100 mph, and 4.6 seconds to brake from 100 – 0 mph (Hargreaves, 2001). However, due to the power and performance on offer, the gain and feedback of the system is in some cases ferocious, perhaps even excessive? This may conspire to make the situation seem riskier than it actually is when it is considered that motorcycles are fundamentally stable once in motion.

In comparison to longitudinal performance parameters it is often much more difficult for the rider to initiate lateral manoeuvres or cornering on a motorcycle, and this is often where a significant portion of crashes occur (Coyne, 1996). RoSPA (2001) define 13% of accidents as *"going ahead on a bend"* (p. 8), and the heavier and more powerful the bike, the more likely this type of crash becomes. For car drivers, by comparison, going ahead on a bend accounts for only 8% of crashes (RoSPA, 2001). The gyroscopic effects of the two wheels and the spinning engine components (the same effects that help keep the motorbike stable and upright) can often make turning and steering a motorcycle rather more difficult than its mechanical simplicity would lend it to appear, and rather more difficult than that encountered in a car. This difficulty is reflected in the differences in the sources and content of feedback that are required by the motorcycle riding task. These differences help to easily separate motorcycles from car drivers in terms of feedback. Therefore in any study concerned with examining the on-road effects of vehicle feedback on cognition, motorcycling offers a unique experimental manipulation and an opportunity not to be missed.

3.1.4 Verbal Protocol Analysis

Drivers and riders in these Studies were required to provide a verbal commentary whilst they drove, and this was analysed using a Verbal Protocol Analysis paradigm. The purpose of Verbal Protocol Analysis is to make 'valid inferences' from the content of discourse (Weber, 1990). In the present case this discourse is a written transcript gained from driver's thinking aloud as they drive around a predetermined course on public roads. The valid content of this written transcript is then examined using an analysis based on themes (the *meanings* encapsulated within sentences and phrases). The analysis proceeds by extracting the valid content based on themes and categorising it according to a defined categorisation scheme. Thus, Verbal Protocol Analysis is a means of data reduction, keeping the content derived from transcripts of thinking aloud manageable in size, and theoretically valid. This approach enables relevant concepts or interrelationships to be analysed and inferred. In human factors settings Verbal Protocol Analysis has been shown to be a good exploratory method, and careful experimental design can help to optimise reliability and validity. Providing that verbalisations are concerned with the content or outcomes of thinking (and thinking aloud can provide this information) then psychological processes can be inferred even if individuals are not generally self aware of them. Within the context of exploring hypotheses and conducting studies in naturalistic settings, Verbal Protocol Analysis can be extremely useful, and has much to offer.

3.1.5 Summary

Set against this background, the present Study sets out to directly analyse the underlying human information processing used by normal drivers in a naturalistic setting. The purpose of this is to gain a measure of the effect of all the dimensions of feedback as they apply to car driving, and to interpret these findings in relation to the feedback framework. The issue of vehicle feedback and its relation to driver cognition can therefore proceed from the level of predictions based on survey findings and literature and on into the *exploratory* level of analysis. This is the central purpose of the present Chapter.

3.2 METHOD

3.2.1 Design

This was an exploratory study comprised of three experimental groups defined as high feedback cars, low feedback cars, and motorcyclists (with their respective drivers/riders). The independent or predictor measure was the experimentally defined feedback status of the vehicle (high or low feedback car or motorcycle), and dependent variables were the results of the content analysis performed on the driver's concurrent verbal protocol, combined with questionnaire measures of situational awareness and mental workload. The between subjects nature of the experimental paradigm was bolstered by controlling factors that were represented in the Study by measures of driving style, locus of control, and driver demographic characteristics. These factors are provided to help ensure that the systematic effects of vehicle feedback are being measured. Within the naturalistic context of the Study, experimental control was exercised (as far as practicable) over weather and traffic conditions, whilst employing a standardised experimental protocol and test route for all trials. Under this data driven analysis it is tentatively expected that the changes in the source, content, and temporal aspects of feedback inherent within the defined vehicle feedback groups will be reflected within the analysis of driver's verbalisations and post run questionnaire measures.

3.2.2 Participants

Eighteen male drivers took part in the study, six per feedback group. Males were used for two reasons. Firstly, within the context of this small sample size gender differences could provide an unwanted confounding variable. Secondly, males were also chosen due to time and availability factors, given that motorcycle ownership is by far the highest amongst males (RoSPA, 2001). Overall age ranged from 17-20 through to 50+ categories, although no participants fell within the 41-50 category. The overall modal age category was 21-25, with the modal category for the high and low feedback groups being 50+ and 21-25 respectively. This artefact was not systematic, as older drivers of low feedback cars were still represented, as were younger drivers of high feedback cars. Also, with a sample of this size only 2/6 participants fell within the modal age category compared to 1/6 for each of the other age categories. The distribution of ages for motorcyclists was in fact bi-modal, between 26-30 and 31-35 year old age categories. This actually conforms well to population level motorcycle ownership versus age data (RoSPA, 2001). Overall mean driving experience was 13.5 years and ranged from 3 to 44 years. Mean driving experience for motorcyclists, high, and low feedback groups was 8.3, 19.2, and 7.8 years respectively, although anything above six years can for the purposes of this Study be considered 'experienced'. By this reasoning even the least 'experienced' driver in the Study has been exposed to many thousands of hours of driving. All drivers held a full UK driving licence with no recent major endorsements, and reported that they drove approximately average mileages per year of 10 to 12 thousand miles (or around seven thousand miles for motorcyclists). Participants were comprised of members of the public, student, and staff members of Brunel University.

3.2.3 Materials/Apparatus

3.2.3.1 Experimental Apparatus for High and Low Feedback Cars

A miniature PCB video camera was affixed to the driver's-side door window of the participant's vehicle. The camera was powered, via a voltage regulator, from the vehicle's cigarette lighter socket. The video signal from the camera was passed to a Gateway 9300 LX laptop computer, equipped with a video capture card, and ATi multimedia video capture software. The typical forward scene afforded by the video setup is shown below in figure 3.1, and Figure 3.2 shows how the video apparatus looked as installed in a participating vehicle.

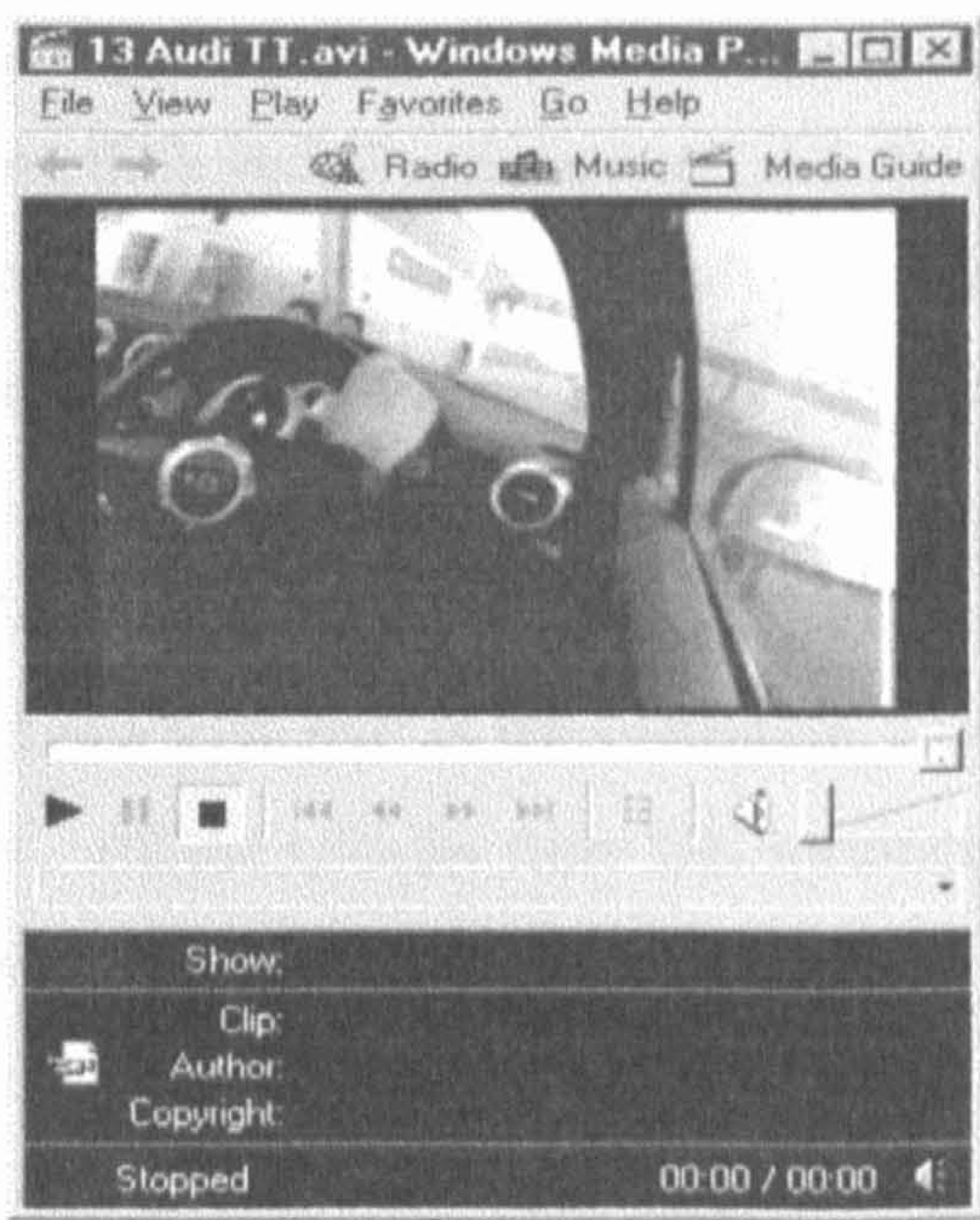


Figure 3.1 - Forward view from video apparatus

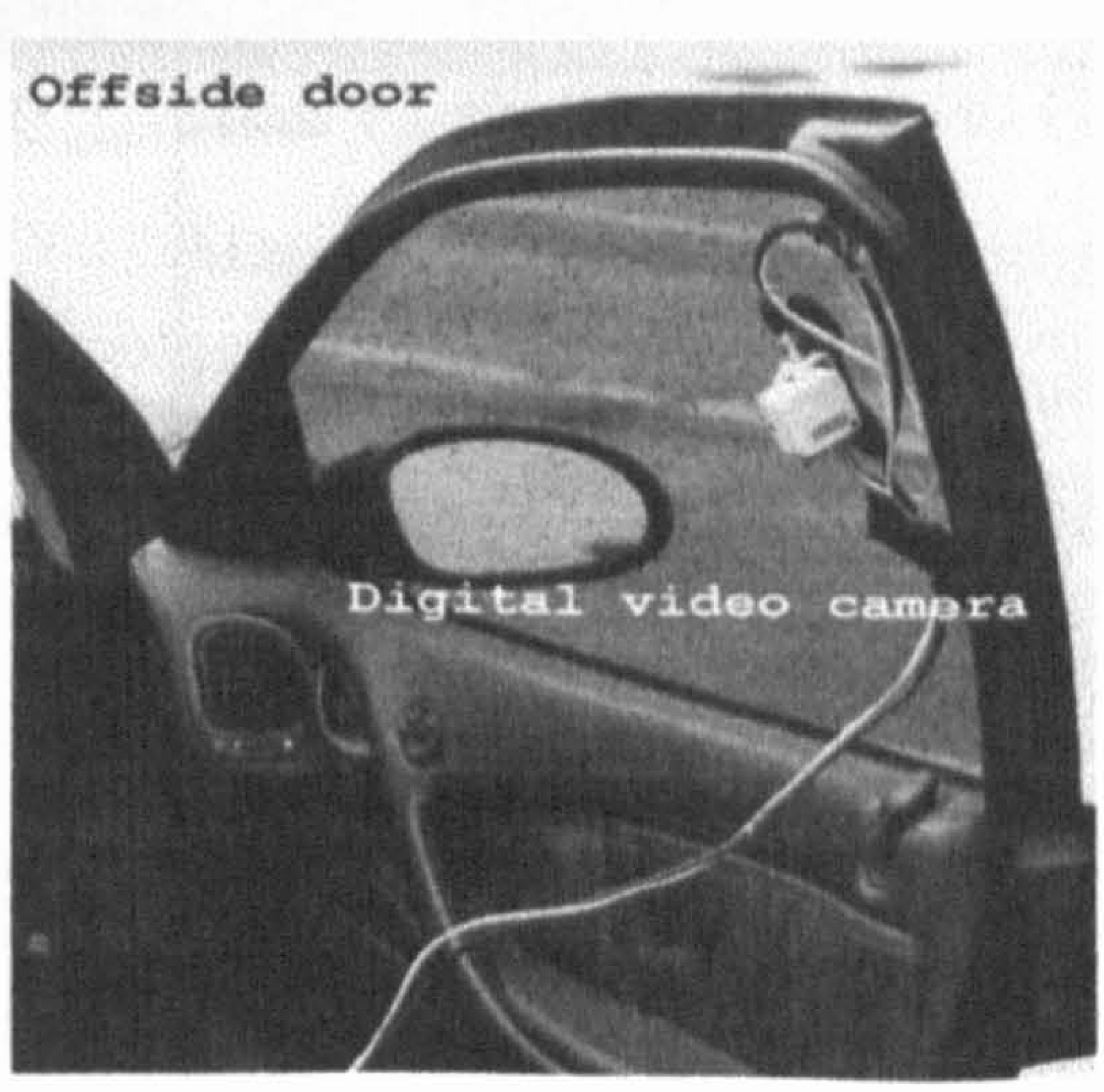


Figure 3.2 - Video apparatus installed in participant vehicle

A miniature omni-directional lapel type microphone was attached via its own clip to the driver's seat belt, and this in turn was connected to the computer's microphone input. The computer's built in condenser microphone was also employed on occasions where it gave superior performance over the lapel microphone.

3.2.3.2 Motorcycle Experimental Apparatus

For the analysis on motorcyclists the video facility was not used. Instead a purpose built microphone device (designed to ameliorate the effects of very high background noise) was installed in the participating rider's crash helmet. The rider also carried a mini disc ™ player. This player was time synchronised with identical apparatus carried by the experimenter. The recordings were started simultaneously, the participant providing their verbal commentary, and the experimenter providing details of when the participant had passed the relevant marker points around the course, and providing information on mitigating circumstances.

3.2.3.3 The Vehicles

Six motorcycles and 12 cars took part in the evaluation, all were owned and driven by their normal drivers*. All the vehicles were UK specification, and the cars were right hand drive models. The vehicles that took part in the study are listed in table 3.1 below.

Table 3.1 - Participating cars and motorcycles

Motorcycles	High F/B Cars	Low F/B Cars
Triumph Daytona 900	Audi TT Quattro	VW Golf TDi
Suzuki TL1000R	Masarati 3200GT	Toyota Tercel
BMW R1100GS	Holden HSV GTS	Mitsubishi Space Runner
Laverda 750 Formula S	Morgan 4/4	Renault 18 GTL Estate
Suzuki GSX400F	BMW 325i Sport	VW Golf CL
	Toyota MR2	Peugeot 309 GLD

* This vehicle owned by Talacrest AD Ltd and driven by the company's test driver.

The motorcycles were all standard UK road models ranging from a touring/trail bike design (e.g. BMW R1100GS), through commuting, touring, and sports touring models (e.g. Honda CBX, Suzuki GSX, and Triumph), and further super-sports models (Laverda and Suzuki TL1000R). Thus a range of road going models, and the types of riders who own and use them were sampled. Compared to car drivers, motorcycles represent an easily distinct group in terms of feedback. However, the operational characteristics of the two groups of cars needs further elaboration. High feedback vehicles, in an informal sense would be classed as 'driver's cars', whereas low feedback cars would be similarly classed as 'average cars'. Strictly speaking the designation 'high' and 'low' feedback is nominal, though it does refer to the quality of feedback provided to the driver from or through the vehicle. High and low feedback involves changes in the sources, content and timing of feedback. High feedback vehicles generally possess a richer and greater quantity of feedback content, faster timing of feedback, and changes in the sources of feedback and the information conveyed by the various sense modalities. This characterisation based on feedback quality can be defined with reference to a host of objective automotive engineering features that are extensively examined for the participating vehicles, and summarised below.

Table 3.2 presents the car group divided into high and low feedback categories according to certain objective vehicle features defined fully here. BHP/Tonne is the power to weight ratio of the vehicle and is an expression of how responsive the vehicle is in the longitudinal plane. Clearly, the more power per unit weight the more energetic the performance, and the more instantaneous the response or timing of feedback is for a given accelerator input. Once again drivers are (sometimes unwittingly) sensitive to this aspect of feedback (Evans & Herman, 1976; Horswill & Coster, 2002). The vehicle with the lowest power to weight ratio was the Peugeot 309 GLD at 69.1 BHP per tonne, the highest was the Maserati 3200 GT with 236.4 BHP per tonne (although this is low compared to the most powerful participating motorcycle. This is the Suzuki TL1000R, clearly not designed for the faint hearted, featuring 685.3 BHP per tonne).

Drive refers to the driven wheels of the vehicle, and obviously motorcycles are all rear wheel drive. High feedback cars are either rear wheel drive or four wheel drive. This factor is a good metric for handling and roadholding characteristics as it directly effects such factors as vehicle weight distribution and suspension design. Evidence of this is that sports orientated vehicles are one of the few remaining classes of vehicles employing any drive system that is not front wheel drive (Robson, 1997). Related to this is Dynamics, and refers to vehicle dynamics, which is an expression of the vehicles underlying handling, or directional control traits (Jacobson, 1974). Depending upon the driving circumstances vehicles can sometimes exhibit a number of handling traits interchangeably, therefore the dominant handling trait is presented in table 3.2 below. Understeer (US) is the only form of vehicle handling found in low feedback cars, and this is a relatively stable albeit uninvolving trait (Nunney, 1998). In broad terms, as the vehicle's limits of road holding are approached, an understeering vehicle will gradually lose grip from the front. This has the effect of naturally scrubbing off vehicle speed, and causing the front of the vehicle to progressively run wide (Joy & Hartley, 1953). This effects the source of feedback (originating from the front of the vehicle), which in turn effects the content and timing of feedback. Due to engineering compromises involving the design of front suspension geometry on front wheel drive cars, the content and richness of the information supplied to the driver through steering feel and vehicle response can be relatively dulled, and involve greater time lag (e.g. Hall, 1981; Gillespie & Segel, 1983; Pitts & Wildig, 1978).

In comparison, vehicle dynamic characteristics such as oversteer (OS) mean that as the vehicle's limits are approached the rear of the car will lose grip first. Thus causing the rear of the car to slide outwards, and inviting the driver to apply controlled amounts of opposite lock on the steering (Godthelp & Käppler, 1988). OS is not a particularly stable trait, but in more normal driving, generally speaking an oversteering vehicle tends to have a more sensitive steering system from the point of view of feedback. In normal driving, generally speaking, an oversteering vehicle tends to be more sensitive to lateral control inputs with minimal response time lag and richer feedback content. The net effect in the case of oversteer tends to be finer more delicate handling traits, with greater, richer feedback content, and faster feedback timing.

In the same vein, four wheel drive vehicles tend to be more or less neutral (N) in terms of handling characteristics, with neither pronounced under or oversteer. Four wheel drive represents a form of automotive engineering ideal (Nunney, 1998) with respect to endowing a vehicle with handling characteristics that most accurately follow driver's control inputs, as well as providing high levels of driver feedback and controllability through the steering and throttle. The key point is that rear and four wheel drive, as distinct from front wheel drive, offer different sources of feedback, and the potential for better feedback content and timing (and by implication subtle changes in the sort of information carried by the various sense modalities).

In table 3.2, instrumentation refers to the dashboard instrumentation, and the amount of feedback supplied explicitly to the driver about various vehicle parameters. Low feedback vehicles present the crucial information to drivers such as speed and fuel, but in most cases little else (Standard/Basic). High feedback vehicles have a more comprehensive range of instrumentation, offering the driver information on a wider range of additional vehicle parameters such as engine revs and oil temperature, (Full).

Table 3.2 - Operationalisation of vehicles according to objective features, high feedback vehicles are the top group, low feedback vehicles the bottom group.

	BHP/Tonne	Drive	Dynamics	Instrumentation
Morgan 4/4	127	Rear	OS	Full
BMW 325i	162.6	Rear	OS	Full
Holden HSV GTS	222.5	Rear	OS	Full
Toyota MR2	115.8	Rear	OS	Full
Audi TT 1.8T Quattro	161.3	Four	N	Full
Maserati 3200 Coupe	236.4	Rear	OS	Full
Peugeot 309GLD	69.1	Front	US	Standard/Basic
VW Golf CL	73.8	Front	US	Standard/Basic
Toyota Tercel	71.8	Front	US	Standard/Basic
Mitsubishi Space Runner	101.9	Front	US	Standard/Basic
Renault 18GLT Estate	81.7	Front	US	Standard/Basic
VW Golf TDi	88.2	Front	US	Full

In summary, the objective features that define high feedback cars within the present Study are as follows:

1. Higher levels of vehicle responsiveness (feedback timing).
2. More involving road holding and handling characteristics due to more sophisticated and less compromised drive train and chassis configurations (sources and content of feedback).
3. Richer levels of instrumentation (source of feedback).

Low feedback cars are average cars, and can be defined with respect to the following objective features.

1. Lower levels of vehicle responsiveness.
2. Less involving road holding and handling characteristics due to more compromised drive train and chassis configurations. These configurations are orientated more towards vehicle packaging and comfort rather than driver involvement and feedback.
3. Basic levels of vehicle instrumentation.

3.2.3.4 Questionnaire Measures

Four questionnaire measures were administered to all participants. Driving style was assessed via the Transport Research Laboratory's (TRL) Driving Style Questionnaire (DSQ) (West, Elander, & French, 1992), Locus of control was measured via the MDIE questionnaire (Montag & Comrey, 1987), situational awareness was assessed via the Situational Awareness Rating Technique, or SART questionnaire (Taylor, Selcon, & Swinden, 1993), and finally, mental workload was assessed via the NASA TLX rating sheet (Hart & Staveland, 1988). Questionnaire measures were selected as being the quickest and most practical means of measuring the relevant constructs. Particular importance was placed on not interfering with the naturalistic nature of the Study, and questionnaires provide a means to achieve this whilst still providing the initial insights required for an exploration of the relevant issues. These questionnaires appear in full within Appendix B.

3.2.3.5 Content Analysis Encoding Instructions

Highly defined written instructions for the desired form and content of the verbal protocol were provided for the participating driver or rider to read through. Written instructions were also devised for the protocol analysis encoding scheme, for use by the analyst during the analysis phase. This is a good exercise in terms of tightly setting the encoding criteria that the verbal protocol will fall into. Given the length of time it can take to encode data of this sort these instructions are constantly referred to, and this in turn helps to ensure intra-rater reliability (within raters). Of course, these same instructions will be used for when inter-rater reliability (between raters) has to be established later using multiple raters. These instructions appear in full within Appendix C.

3.2.3.6 The Test Route

A highly defined 14 mile test route was devised for the Study incorporating six different road types. The route commenced three miles from Brunel University's Runnymede Campus, and this initial stretch represented a warm up section for participants. The route finished one mile from the University campus. Specifically, the route was comprised of one motorway section, four stretches of A or B classification roads, one stretch of C classification 'country' roads, three stretches of urban roads, one residential road section, and ten junctions. The route occurred within the West London area of Surrey and Berkshire, and a map is provided in Appendix D for reference.

To offer some control over traffic conditions, runs took place at 10:30 in the morning and 2:30 in the afternoon (Monday-Thursday) and 10:30 on Friday, or any daylight time during weekends. These times avoided peak traffic hours for the area, and all runs were completed in dry weather.

3.2.4 Procedure

3.2.4.1 Pre-Run Phase

Formal ethical consent was obtained from all participants before the study commenced. Consent forms were read and signed by the participant, with particular emphasis on their ethical rights as experimental participants, and the fact that the control of the vehicle and the safety of other road users remained their responsibility at all times. Participants then completed the pre run questionnaire measures of driving style, the DSQ, and the MDIE for locus of control. During this time the experimenter installed the video equipment into the vehicle, or into the crash helmets of the motorcyclists.

Once the equipment was installed in the vehicle/on the rider and the pre run questionnaires were completed, a run sheet was filled in which contained information on driver demographics and their particular vehicle (Appendix E). The participant was then comprehensively briefed over what the study required of them. An instruction sheet (Appendix F) on how to perform a concurrent verbal protocol was read by them, and the experimenter provided examples of the form and content of the desired verbalization. It was emphasised to participants that the interest was in what they were thinking about (rather than what they were actually doing), and on what feedback they were putting to use within the driving task. After any questions were dealt with the participant was instructed to drive off when they were ready.

In the case of the motorcyclists, they were further instructed that the experimenter would follow them in an offset road position. They were instructed to watch in their mirrors for directional indications from the experimenter, and to act upon them. This procedure is standard IAM practice. The mini disc players were started simultaneously, and the recording levels finally checked before setting off.

3.2.4.2 Experimental Phase

Participants were instructed to begin the concurrent verbal protocol as they left the university campus. On the three mile approach to the start of test route the car driving participant was 'warmed up' on how to perform a suitable concurrent verbal protocol. During this phase the experimenter offered guidance from the passenger seat, encouraging the participant to follow the encoding instructions and helping them to do so when required. As the beginning of the experimental route neared the participant was informed that the experimenter would now remain silent except to offer route guidance, and they were reminded finally to report what they were thinking about, and to keep talking.

The motorcyclists were also warmed up prior to starting the run. Motorcyclists performed an imaginary verbal report, and were advised accordingly. Also, over the part of the route leading up to the start of the experimental course proper, the experimenter took the opportunity to pull over safely and check the recording of the verbal data for correctness, and to finally advise and check with the participating rider that all was well. Furthermore, they were reminded to watch out for the following riders indications, and to keep talking.

For the cars, during the data collection phase over the experimental route, the experimenter remained silent aside from offering route guidance and monitoring the video capture process on the computer. The experimenter also made notes in the run sheet where mitigating events presented themselves (such as traffic jams, or level crossings closed etc.) that would impact upon subsequent data analysis.

Similarly, for the motorcyclists the experimenter followed at a safe distance, remaining in the lead rider's rear view mirrors at all times, and using their own indicators to guide the participant around the route. The experimenter provided a brief commentary that described road, traffic, environmental, and mitigating circumstances. Most importantly, the experimenter reported when the lead rider entered onto different road types, as defined by pre arranged marker points around the course.

3.2.4.3 Post Run Phase

When returned to the campus, participants were asked to complete the SART and NASA TLX questionnaire measures, whilst the experimenter disassembled the video equipment from the vehicle, or the microphone recording equipment from the crash helmet. Once any questions were dealt with the experimental procedure was completed.

3.3 RESULTS AND DISCUSSION

3.3.1 Analysis of Pre-Run Questionnaire Measures

The Driving Style Questionnaire consists of question items probing six dimensions; these being speed, calmness, planning, focus, social resistance, and deviance. No statistically significant differences were detected between motorcyclists, high, or low feedback car groups for any of the DSQ dimensions, *apart from* the deviance scale, as shown in figure 3.3 below. Here it was found that motorcyclists measure significantly higher than both groups of car drivers on this scale (Chi-Square = 5.69, df = 2, $p < 0.05$). That said, outright levels of driving deviance still remain very low, with motorcyclists scoring a mean of 2.5 out of a possible maximum score of 12.

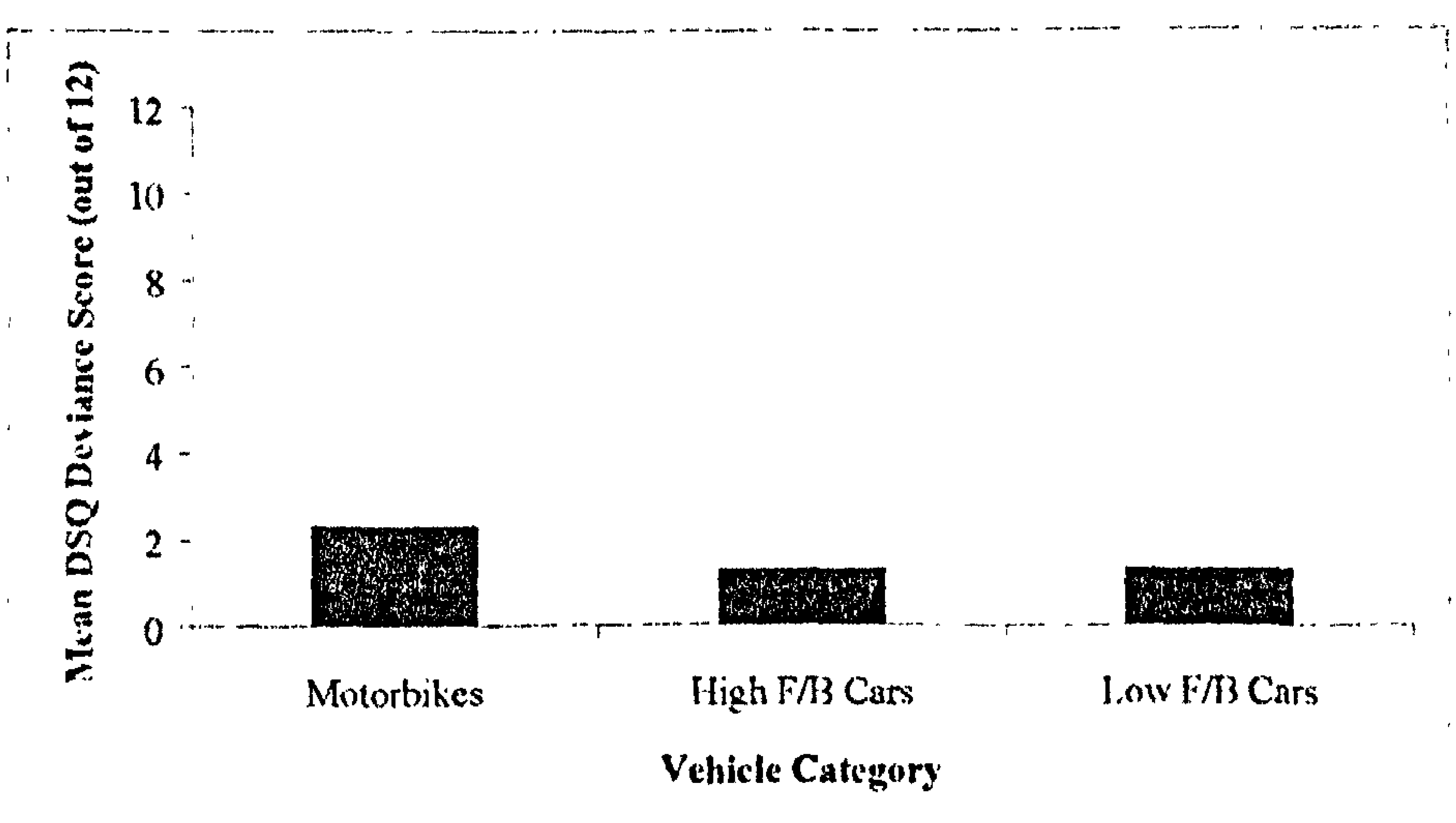


Figure 3.3 – Driving style questionnaire mean deviance sub scale scores for motorcyclists and car drivers.

This finding nevertheless suggests that motorcyclists enact significantly more 'deviant' driving behaviours *relative* to their car driving counterparts. This is clearly more reflective of differing driving styles adopted by motorcyclists, although caution should be exercised over the fact that behaviours such as passing on hatched areas, and filtering between lanes of queing traffic *are* legal, and readily enacted by motorcyclists (The Highway Code, 1993). This could be a limitation of the DSQ in this case. Deviance aside, these findings can still be taken to offer at least some reassurance that effects due to the feedback status of the vehicle are being measured, and not complex, global artefacts of individual driving style.

In terms of Locus of Control (LoC), as measured by the MDIE questionnaire, significant differences were detected for the internality dimension, $F(224.67, 54.21)=4.14$; $P<0.05$. Bonferroni post hoc tests show that motorcyclists rate significantly higher than high feedback car drivers (but not low feedback car drivers) on this dimension. This suggests that motorcyclists see the source of their own behaviour as residing within them more than certain groups of car drivers. This effect is shown in figure 3.4 below.

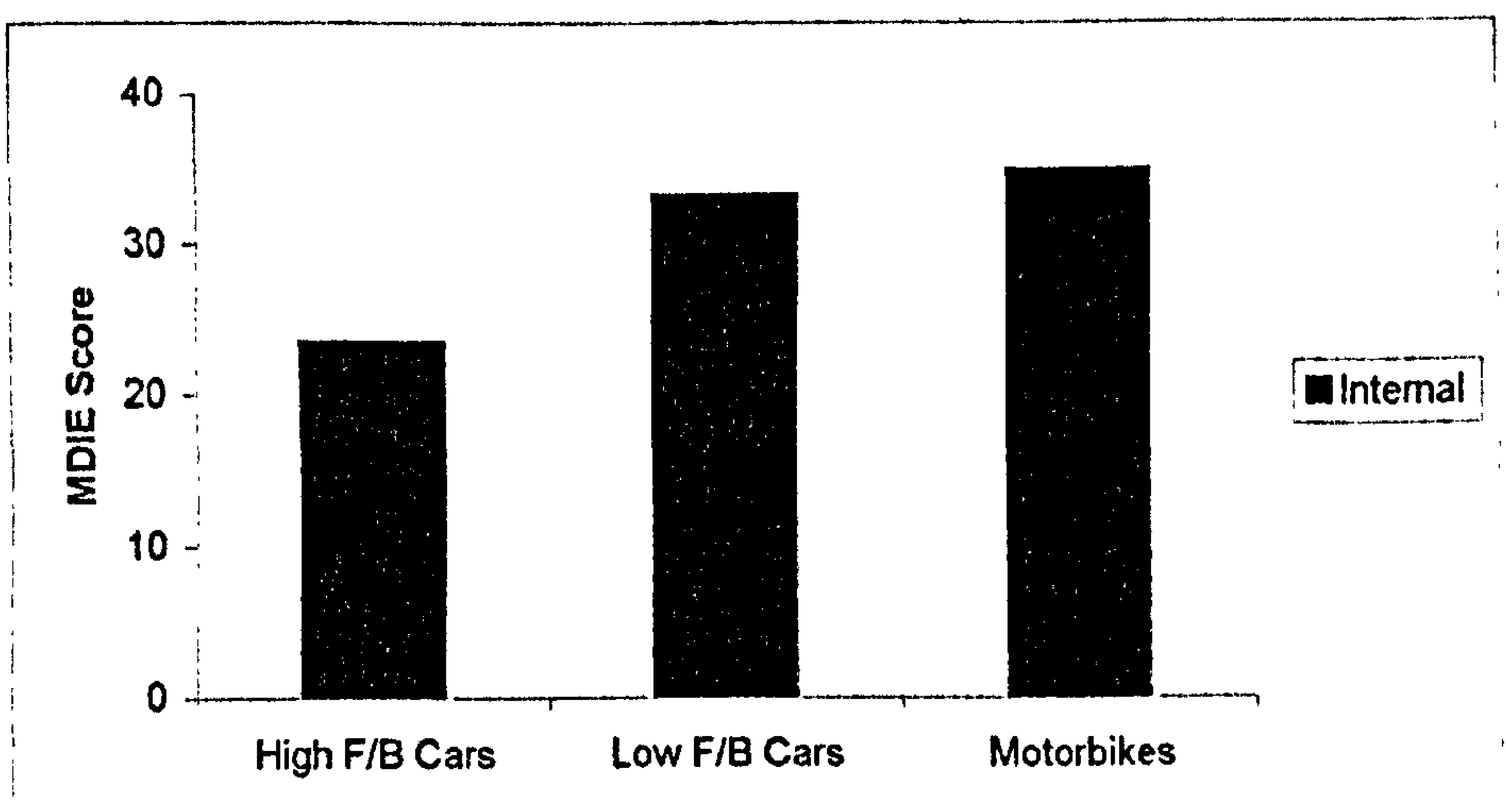


Figure 3.4 – Bar chart of locus of control dimensions versus feedback.

Whether these LoC artefacts are a cause of the type of vehicle purchased, or an effect of the vehicle driven is unclear. Studies hint that LoC tends to be a relatively stable, global personality trait (Stanton & Young, 1998), though perhaps the vehicle can still act as a mediating variable over time, and furthermore that feedback can influence the perceived source of one's behaviour. In either case the results from the content analysis below do not show any particular evidence of bias due to LoC, as verbalisations concerning 'own behaviour', and thus related to internality, are not significantly different between groups.

3.3.2 Data Reduction; Content Analysis of Verbal Protocol

The first step in the data reduction phase of the verbal protocol analysis is to transcribe, verbatim, the verbalisations provided by the participating drivers. The verbal commentary was completed against a two second incremental time stamp. This is shown in figure 4.4. The decision to base the analysis of the driver's verbalisations on themes was taken a-priori. A theme based analysis centres around the encoding of the *meaning* of phrases and sentences into shorter thematic units or segments (Weber, 1990). For example 'the engine's at 3000rpm, nice and smooth'. The thematic segments might be as follows. Here the driver is referring to the *behaviour of* their *car*, that is being *perceived* and *comprehended* by the driver, and the *information* is being *gained from vehicle instruments.* A protocol analysis based on themes provides the richest and most flexible source of data. A further advantage of a verbal protocol couched at this lower level of driving task enactment is that feelings and opinions about the status and performance of a car make no difference. The driver can talk positively or negatively about a vehicle, but the encoding will be the same.

The next step is to establish a conceptual framework for the encoding scheme (Walker, [In Press]). In the present case this involves grounding the encoding scheme within the feedback model of driving. The feedback model's basic elements are built upon theoretical foundations, and this in turn helps to ensure some degree of construct validity. In this case the conceptual framework enabled the verbalisations to be fitted into three overall encoding groups, behaviour, cognitive processes, and feedback.

The behaviour category (BEHAV.) enabled the verbalisations to be coded according to whether the driver was referring to their own behaviour (OB), the behaviour of the vehicle (BC), the behaviour of the environment (RE), or the behaviour of other traffic (OT).

The second encoding group is 'cognition' (COG.), comprised of four sub categories. This enabled the verbalisations to be categorised according to whether the verbalisation represented 'perception' (PC) of some element in the environment, 'comprehension' (CM) or understanding of the current situation, 'projection' (PR) of this understanding onto future states, or some form of 'action' execution (AC). PC is analogous to level 1 situational awareness, CM to level 2, and PR to level 3 (Endsley, 1988); this step is deliberate.

Finally, the third category is 'feedback' (FB). The interest here is to gauge the source of vehicle feedback. To achieve this, verbalisations that fell within the PC or 'perception' category (and where this perception arose from the vehicle), could be categorised into three further encoding categories. These are as follows. Does PC (or feedback) that has arisen due to the vehicle originate from the vehicle's 'system dynamics' (SD) or 'control dynamics' (CD) (Wickens, 1992), or else from the vehicle's 'instruments' (IN).

These encoding categories are derived, and refer exclusively towards the feedback framework of driving. This can be shown graphically by overlaying the encoding categories on top of the relevant parts of the feedback model of driving shown in figure 3.5 below.

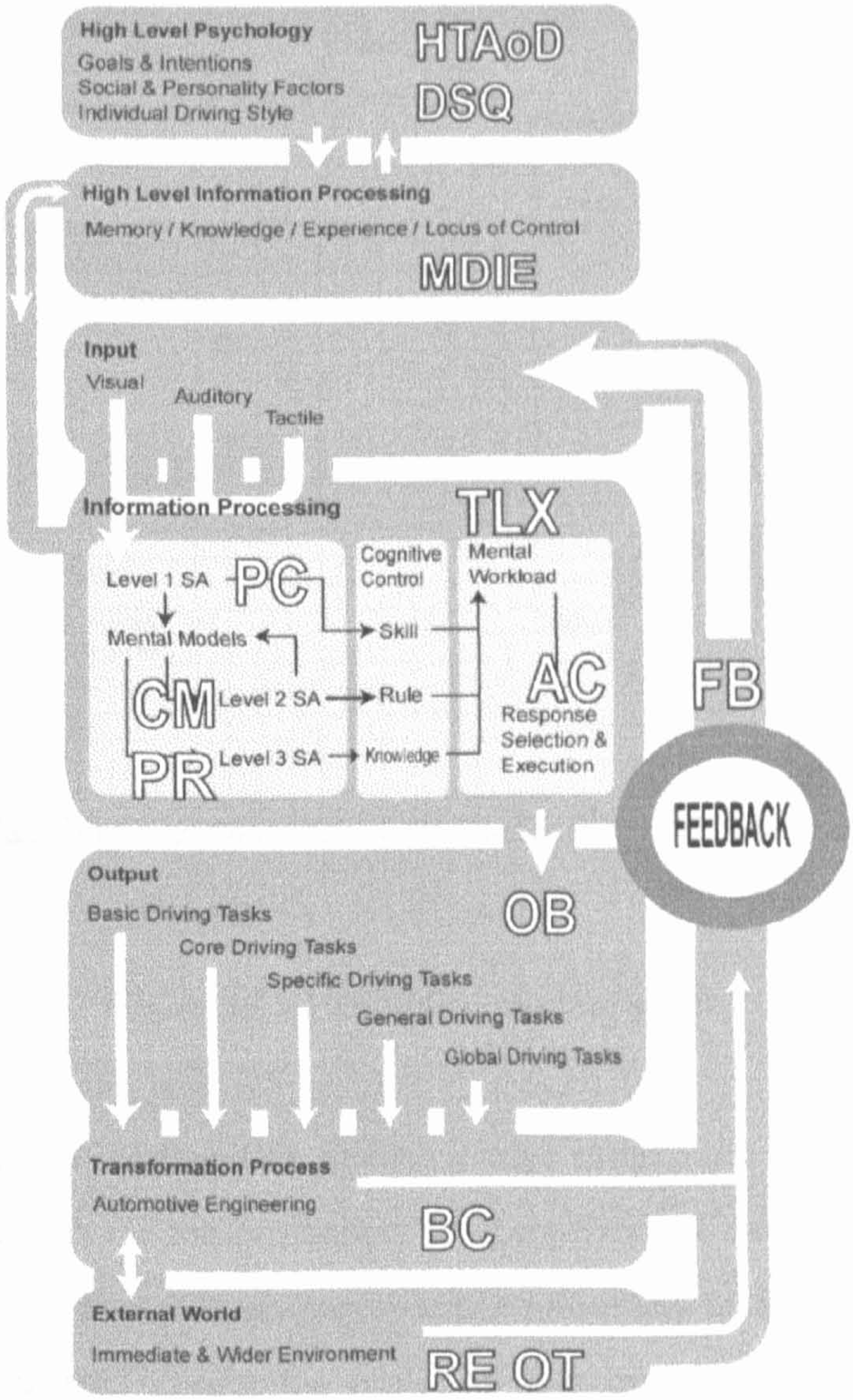


Figure 3.5 - Feedback framework of driving overlain with the experimental variables, showing what components of the model were measured during the study.

Driver's verbalisations were categorised into this encoding scheme, and an example of an encoding worksheet is shown in figure 3.6. Another decision was taken at this point to determine whether the encoding categories should be mutually exclusive, or exhaustive. Typically, for an analysis based on themes mutual exclusivity need not be applied, and the theme can fit into as many encoding categories as valid and defined from the written encoding instructions. Under this scheme the encoding is 'exhaustive'. As such, whenever a theme meets the definitions described in the encoding instructions, a number one is entered in the relevant encoding box.

TIME	VERBALIZATIONS	ENCODING BEHAV OB	BC	RE	OT COG PC	CM	PR	AC F/B SD	CD	IN	EVENTS	PROTOCOL STRUCTURE
mm: ss													
01:34	70mph, 5th gear		1			1					1	1	Glances at gear lever	
01:36	2800 rpm		1			1						1		
01:38	that's quite smooth		1				1							
01:40	he's slowing down				1	1							Other car crossing from lane 3 over	
01:42	don't know what's wrong with him	1			1		1						to hard shoulder in front of driver	
01:44														
01:46														
01:48														
01:50														
01:52														
01:54														
01:56														
01:58														
02:00														
02:02														
02:04	it's all clear ahead				1	1								
02:06														
02:08	chap behind has eased off a bit luckily				1	1	1							
02:10														
02:12	make my intention clear that I'm going right	1		·					1				Indicating right	
02:14	so I'll stick to the right side of this slip lane	1		1			1							
02:16														
02:18														
02:20	bit worried about overtaking him	1			1		1						Passing other vehicle	
02:22														
02:24														
02:26														
	Section Frequency Counts	4	3	1	5	5	5	0	1	0	1	2		
02:28														
02:30														

Figure 3.6 - Example encoding sheet.

After transcribing the verbal data against a time index, and having encoded the themes, the final part of the worksheet is comprised of other data columns as shown in figure 3.6. This was an opportunity to note any mitigating circumstances that may have occurred during the trial, and that may have effected the verbal report. The structure of encoding could also be analysed with reference to the type of road that the driver was driving upon, thus providing the potential for future work, perhaps with a larger sample, to analyse the effects of road type as well as vehicle feedback. Currently the variety of road types present on the course *control* for road type, rather than representing an independent variable.

Having reached this point the protocol analysis procedure was put to the test within the context of a small pilot study, or pilot run. This indicated that the verbal data collected was useful, that the encoding system worked, and that inter and intra-rater reliability were satisfactory. Nevertheless, this opportunity was taken to refine the procedure further before conducting the final complete Study.

After completing the encoding process for all participants, the reliability of the encoding scheme was then established. For inter-rater reliability (between different independent raters) this is especially important when using themes. Themes rely on shared meaning, and an analysis of reliability will indicate how well this meaning is in fact shared. Intra-rater reliability (within raters) will help to measure any potential drifting in encoding performance over time. In Protocol Analysis reliability is established through reproducibility. In other words, an independent rater or raters need to encode previously encoded analyses (or a sub set of previously encoded analyses). They do this in a blind condition, unaware of the previous rater's encoding results. The independent raters make use of the same categorisation instructions that the original rater employed before beginning their own categorisation (Appendix C). Two independent raters encoded an experimental run from the high and low feedback groups respectively. Across the eleven individual encoding categories inter-rater reliability (IRR) was established at Rho=0.7 for IRR 1 and Rho=0.9 for IRR 2, both these values being significantly correlated ($p>0.05$ for IRR 1 and $p>0.01$ for IRR 2, $n=11$). Intra-rater reliability was also examined to check for any drifting in encoding performance over time. This analysis posited a correlation of Rho=0.95; $n=11$; $p<0.01$, suggesting that encoding performance over time is remaining very stable. At this exploratory level of analysis the reliability of the encoding scheme was demonstrated.

Having conceptually grounded the encoding scheme by relying on the feedback model of driving, having established intra-rater reliability through the use of encoding instructions, and inter-rater reliability by employing independent encoders, the results can now be analysed.

3.3.3 Content Analysis Results for High vs. Low Feedback Cars

Experimental runs took an overall mean of 27 minutes to complete, at a mean speed of 31.11mph (SD=2.97 mph) over 14 miles. A grand total of 15506 encoding points were derived from the content analysis of riders and drivers verbalisations. A One-Way ANOVA did not reveal significant main effects of total encodings versus vehicle type. Neither were their significant differences in the amount of time it took the respective groups of vehicles to complete the circuit, despite the very great differences in performance potential. The balanced nature of the experimental course (in terms of road types) is borne out here, as the route did not favour any particular vehicle, or expose any group to systematically longer route completion times and therefore influence the quantity of verbalisations supplied.

3.3.4 Content Analysis Results for Motorcycles versus Cars

According to the content analysis, the three vehicle groups appear to be talking about qualitatively different things. In other words the structure of verbalisations would seem, by visual inspection of figure 3.7 below, to be different in certain key respects to that of car drivers. Of particular note is that perception, system, and control dynamics are especially well represented. The general pattern of results lends support to the notion that drivers have little difficulty in verbalising their own behaviour and actions, in comparison to inner psychological processes.

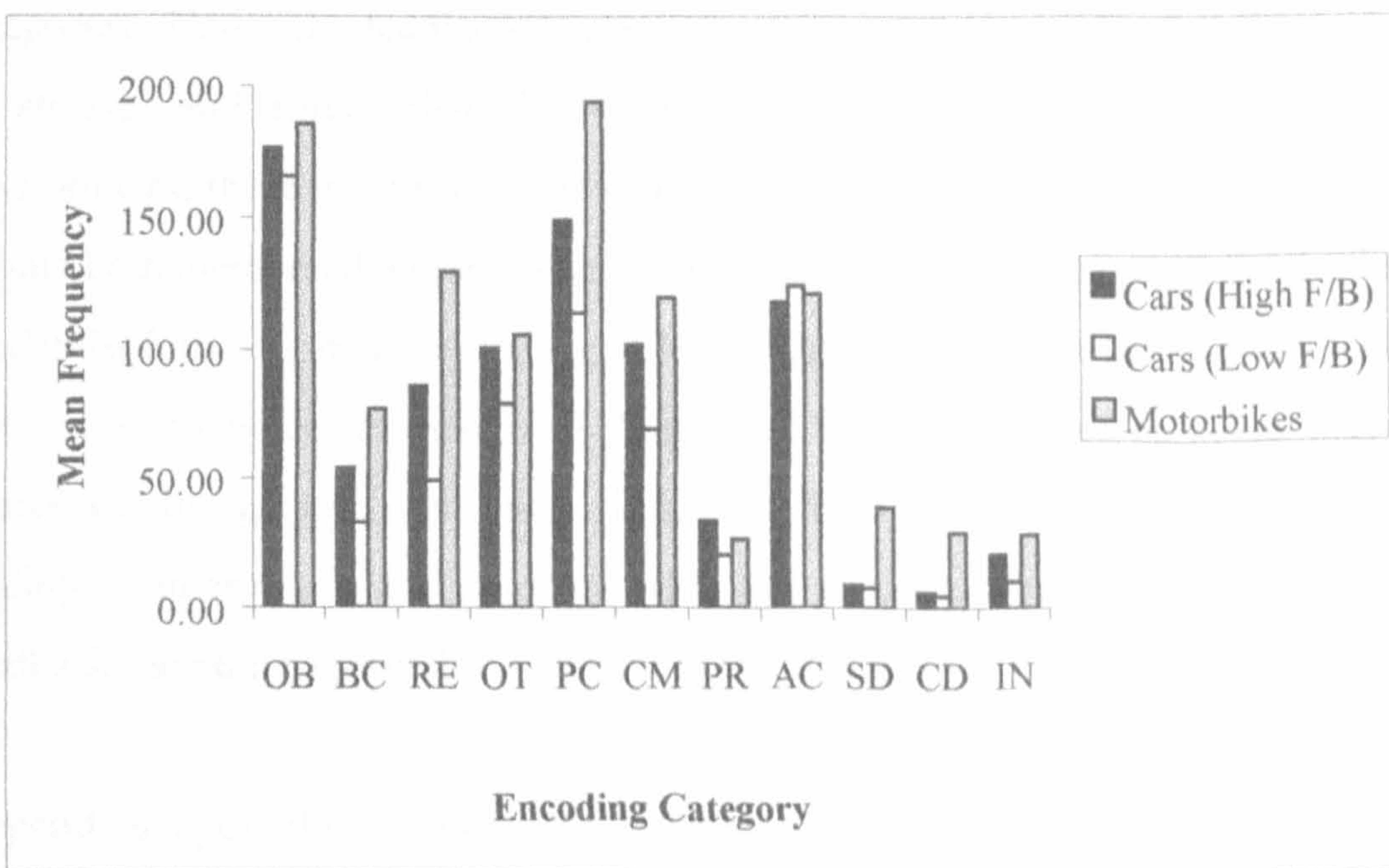


Figure 3.7 - Mean frequency of encodings per content analysis category.

By visual inspection alone of figure 3.7, verbal reports about the driving task mostly refer to the driver's (or rider's) own behaviour, perception, and actions. This is in comparison to relatively few reports concerning the behaviour of the vehicle and psychological processes. In terms of situational awareness driver's report most about perception and least about projection. Feedback from the vehicle seems to be mostly gained from the vehicle's instruments and system dynamics, though overall, instruments, system and control dynamics are not talked about to a great degree by drivers. In general, drivers/riders seem especially good at verbally reporting events at the beginning and end of the information processing cycle. These operations might reflect the level of consciousness involved at these stages. Comprehension and projection (levels 2 and 3 SA) might be couched at an implicit knowledge level, and thus not readily accessible by self report methods (Taylor & Selcon, 1991).

Ignoring the motorcycle data just for a moment, and focusing the attention on the results gained from the operationally closer high and low feedback car categories reveals several interesting results. Significant differences were detected between high and low feedback cars in two encoding categories; verbalisations concerning the road environment ($t=2.93$, $df=10$, $p<0.05$), and perception ($t=2.27$, $df=10$, $p<0.05$). Drivers of high feedback vehicles report significantly more within both categories. Under the feedback framework, greater vehicle feedback will be related to stresses and forces that the vehicle is sustaining in relation to the road environment, these in turn provide more for the driver to perceive. Perception, it should be remembered within the feedback framework, is the gateway for the sense modalities into cognitive processing. Clearly high feedback cars are providing more for drivers to perceive, increasing their level 1 SA, and it would seem that the source of this greater perception is derived from the road environment. This finding is interesting, and concurs with the feedback framework in terms of feedback seeming to provide a basis for better driver SA.

Depending upon the variance and normality of the data under consideration, a One-Way ANOVA or Kruskall Wallis procedure was used to test for significant differences in encoding between the three groups of motorists, motorcycles included. As it transpired, motorcyclists made more verbalisations concerned with the road environment, $F(9661.17, 1160.41) = 8.33$, $p<0.01$, comprehension, $F(3885.06, 918.82) = 4.23$, $p<0.05$, system dynamics (Chi-square = 10.79; $df = 2$; $p<0.01$) and control dynamics (Chi-square = 9.38; $df = 2$; $p<0.01$) compared to car drivers. Motorcyclists stand alone by reporting significantly more than *both* groups of car drivers in terms of system and control dynamics. But, post hoc tests (Bonferronni for the ANOVA and Dunn's test for the Kruskall Wallis) show that the remaining differences lie between motorcyclists and low feedback cars *only*.

In summary, this analysis would tentatively suggest that motorcyclists are more aware of the road environment, and that equal levels of perception, or level 1 SA are implicated in terms of greater comprehension/level 2 SA (or at least greater verbalisations thereof) when compared to low feedback car drivers. Furthermore, motorcyclists report more about the feel and interaction of their machine when compared to both groups of car drivers.

3.3.5 Analysis of Post-Run Questionnaire Measures

In terms of self reported SA (measured through the SART questionnaire), no significant differences were detected between the three vehicle groups on the dimensions of demand on cognitive resources, supply of cognitive resources, understanding of the situation, and overall SA. From this it would seem that gross differences in the source, content, and timing of vehicle feedback (as operationalised within this study) led to significant changes in the structure of verbal protocol data; but self perception of SA is insensitive and operates independently. Figure 3.8 below illustrates this poor self awareness of SA even more clearly. Looking at the absolute values of self perceived SA, these hover around a self confident 75%, therefore it would seem that drivers have poor awareness of any *lack* of SA as well. This is perhaps hardly surprising as Endsley (1988) states that ignorance is often bliss in regard to self perception of SA, as drivers cannot be expected to be aware of SA that they are not gaining.

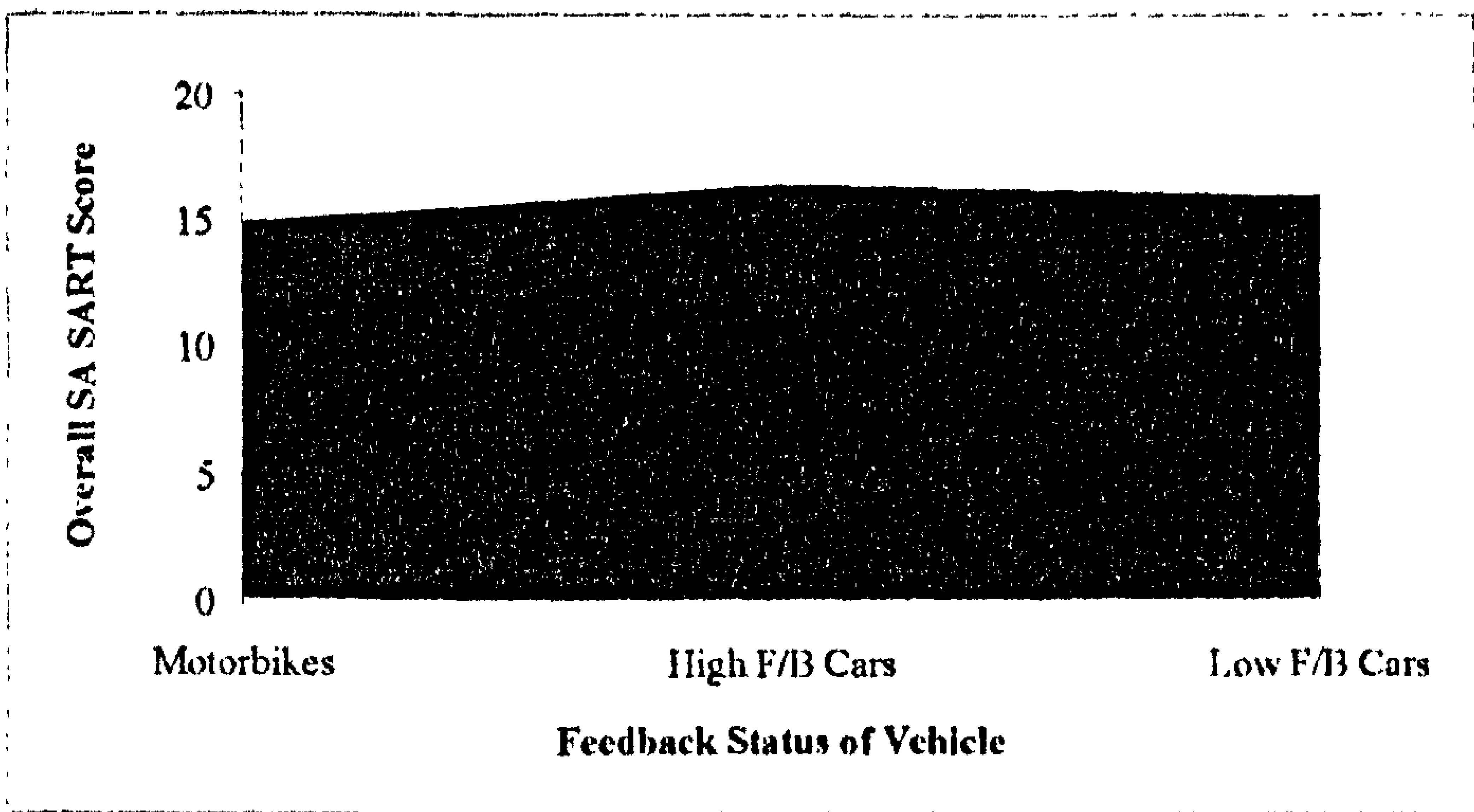


Figure 3.8 - Self awareness of situational awareness as rated through the SART questionnaire.

Due to concern over essential differences in the physical nature of the driving/riding task, the analysis of MWL scores proceeds in two phases. The first phase analyses just the car data, followed by the second phase which then builds in the motorcycle data. High feedback car drivers achieved a mean Overall mental workload score of 6.44 (SD=1.35), low feedback car drivers a score of 8.58 (SD=1.82). Based on only the car results, significant differences were detected for overall mental workload ($t=-2.312$, $df=10$, $p<0.05$). Higher feedback cars report significantly lower mental workload than low f/b car drivers. These results for Overall mental workload are derived from the average of the six component sub-scales of the TLX, and are shown below in figure 3.9.

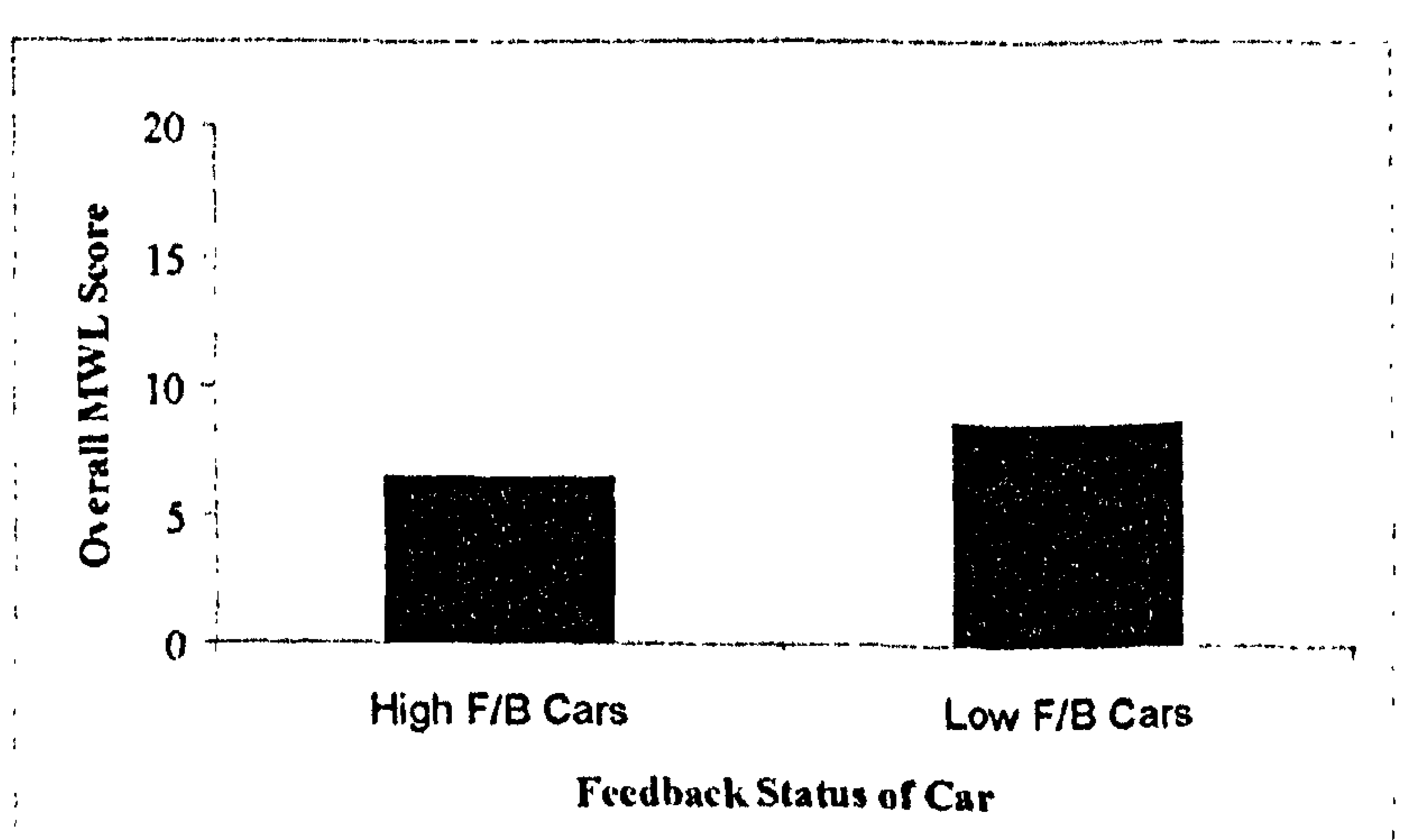


Figure 3.9 - Overall mental workload scores for high and low feedback cars.

A more fine grained analysis examines the individual TLX subscales of mental demand, physical demand, temporal demand, performance, effort, and frustration separately. Here it was found that significant differences were apparent in the temporal demand ($Z=-2.59$, $p<0.01$), and frustration scales ($t=-2.41$, $df=10$, $p<0.05$). A non parametric test (the Mann Whitney U) was employed for the analysis of the temporal demand scale due to heterogeneity of variance. High feedback cars are implicated in lower driver frustration (read greater driver satisfaction perhaps), and drivers of low feedback cars rate higher in terms of temporal, or time pressure. These results could, amongst other factors, be a reflection of the relative lack of vehicle performance embodied by low feedback cars.

Adding the results gained for motorcyclists into the analysis reveals that motorcyclists experience the *highest* overall mental workload (mean score of 10.7), compared to high feedback car drivers (mean score 6.4) scoring the lowest. Figure 3.10 seems to indicate that high feedback cars might be achieving optimal workload, compared to low f/b cars and motorbikes.

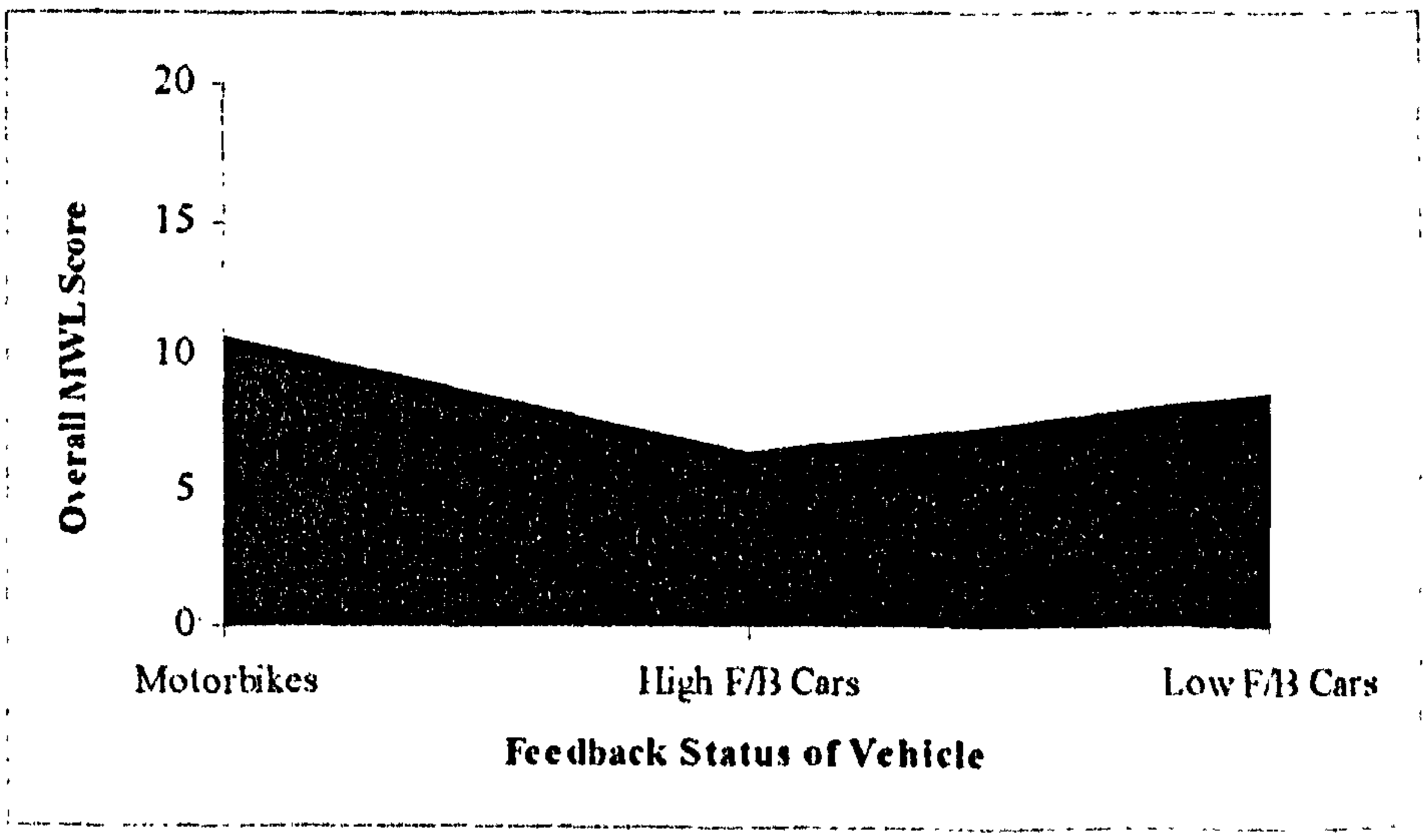


Figure 3.10 - Bar chart illustrating the relationship between vehicle feedback and mental workload.

Overall MWL differs significantly between groups (F(27.8,4.14)=6.72; p<0.01). Bonferroni post hoc tests demonstrate that motorcyclists measure significantly higher than high feedback cars, though not significantly higher than low feedback cars. Similarly, low f/b cars seem not to differ significantly from high feedback cars, though a significant difference *was* observed without the contribution of the motorcycle data. This could well be a problem with the relatively small sample size.

Retaining the motorcycle data, and deepening the analysis into the TLX sub scales, a one way ANOVA detected differences between the three groups in terms of physical demand F(80.67,14.61)=5.52; p<0.05 and temporal demand F(81.5,8.1)=10.06; p<0.01, but not frustration as with the car only data. Bonferonni post hoc tests revealed that motorcyclists measured significantly higher than both groups of car drivers on these sub scales, and it to these that the findings in respect of overall mental workload are likely to derive. As it stands motorcycle riding seems to be implicated in more physical demand. This is unsurprising considering the extra driving tasks involved, not to mention physical effort. Motorcyclists also rate higher in terms of temporal demand or time pressure, just like low f/b car drivers when they were compared to high f/b cars only. Unlike the car drivers, lack of vehicle performance is unlikely to be an explanatory factor, instead the result could be reflected in the greater complexity of motorcycle riding, and the need perform additional complex tasks such as balancing the machine in dynamic traffic environments.

3.4 CONCLUSIONS

3.4.1 Overview

The key exploratory findings can be summarised as follows:

1. In terms of locus of control, motorcyclists rate highly on internality, seeing the source of their behaviour as arising internally compared to both groups of car drivers who do not differ on this measure.

2. The driving style questionnaire showed no significant difference between any of the groups of riders or drivers, except in the deviance sub scale, where motorcyclists scored significantly higher than car drivers. This could well be a limitation of the DSQ. Therefore there is still a fair degree of reassurance that during the content analysis strong artefacts of individual driving style are not being measured, in comparison, the vehicle feedback manipulation is the most pronounced and *systematic* experimental variable.

3. High feedback cars compared to low feedback cars are implicated in better level 1 SA, or perception of elements in the environment. Motorcyclists seem to possess significantly better levels 1 *and* 2 SA compared to low feedback cars. Motorcyclists are also characterised by greater reporting of the road environment, system, and control dynamics. Clearly the operationalised vehicle feedback manipulation is exerting an effect on driver's verbal reports.

4. Motorcyclists measure the highest for Overall mental workload, followed closely by low feedback car drivers, with high feedback car drivers seeming to be operating at a lower, arguably more optimal level.

5. SART scores show no significant difference between vehicle groups in terms of self reported SA compared to significant differences detected in the content analysis. In terms of SA ignorance does indeed appear to be bliss (Endsley, 1995b;1988). Self awareness of SA, or any shortfall in perceived SA is poor.

Despite the exploratory nature of the current experimental paradigm, vehicle feedback can be argued as being the key explanatory factor for the results obtained. Even though a between subjects paradigm was used, which in this exploratory context is not unreasonable considering the cost and time constraints of doing otherwise, vehicle feedback remains the most systematic experimental manipulation. Psychological and driving style/individual factors were measured a-priori, a standardised route and protocol were employed, and other variations in driver characteristics are heavily blurred compared to the clearer feedback demarkation. This offers reassurance that the more systematic effect due to vehicle feedback is the strongest experimental manipulation influencing the data.

3.4.2 Feedback Framework of Driving

Taking a systems perspective, the quality of vehicle feedback occurs at the boundary between the car and the driver; the transformation process level and the driver's *perception* of the vehicle's state in its environment. In other words, it is at this system boundary that the vehicle has an opportunity to translate and communicate it's current dynamic status and that of its environment back to the driver via feedback. The manner in which the vehicle communicates this status is completely specified by the vehicle's automotive engineering and technology. The feedback manipulation employed within the present Study occurs at this boundary, a boundary between the objective state of the world and how the vehicle responds to this objective state. The present findings, although exploratory in nature do offer evidence if favour of the feedback framework's validity.

It will be recalled that within the feedback framework of driving information flows around the various systems; and feedback interacts more or less directly with level 1 SA. Motorcycle riders and drivers of high feedback cars report more about situational awareness, *particularly* level 1 SA. The implication here is that level 1 SA, perception of elements in the environment, is being enhanced through greater feedback on the dimensions of content, sources, and timing of feedback information. In contrast, it would appear that there is a relative failure on the part of low feedback car drivers to adequately perceive relevant elements in the environment. In passing, this relative failure of level 1 SA is cited as being the most common SA error, certainly within the domain of aviation (Jones & Endsley, 1996). It would appear to be so for driving as well.

Findings in respect of SA provide evidence of greater engagement in the driving task by driver's of high feedback cars and motorbikes (Endsley & Kris, 1995). In terms of engagement, it could be tentatively suggested that more verbal reports concerning the road environment are reflective of the fact that greater situational awareness is leading to different driving strategies in terms of anticipating and dealing with different road conditions and layouts. In terms of disengagement, with fewer implicit and multi modal feedback cues being provided by the low feedback vehicle (Loasby, 1995), the driver may be relatively out of the loop. There is evidence to suggest that as drivers become increasingly removed from the driving task, through, for example, increasing automation or even 'refinement' then SA will suffer (Gugerty, 1997; Jentsch, et. al., 1999). According to the feedback model differing levels of SA, leading to operation on differing levels of cognitive control, are likely to have effects on MWL.

At this exploratory level of analysis the feedback framework of driving would suggest that low feedback car drivers, compared to high feedback car drivers may have to employ more effortful cognitive strategies couched at the rule or knowledge based levels of cognitive control (Rasmussen, Pejtersen, & Goodstein, 1994). These strategies would be employed in order for low feedback car drivers to determine information and gain SA not achieved through more implicit vehicle feedback. This accords with the suggestion within the feedback model that greater cognitive effort is associated with different modes of cognitive control and levels of situational awareness. If mental workload is taken as an approximate metric for information processing speed and efficiency, then operating at the skill based level of cognitive control, aided by level 1 SA appears to be very favourable. This can be shown with reference to the feedback framework presented in figure 3.11 below.

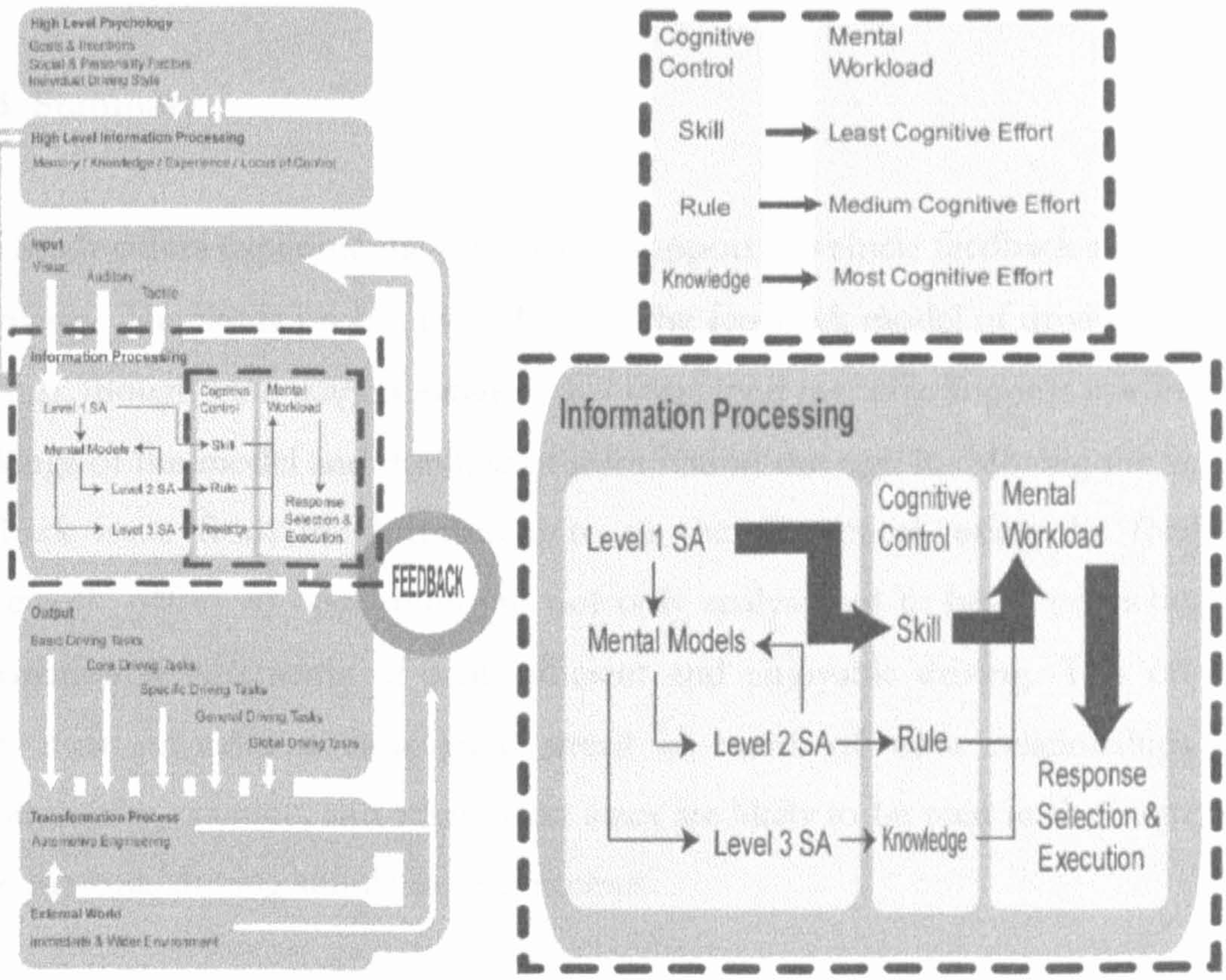


Figure 3.11 - Illustration of cognitive information processing efficiency gains through skill based processing and lower mental workload.

The favourable relationship between cognitive control and level 1 SA can assumed to be in action for *high* feedback car drivers, who despite experiencing relatively high levels of feedback experience the *lowest* mental workload. This could be because much of this feedback is couched in terms of level 1 SA, itself implicated in efficient and relatively effortless skill based processing. However, it would seem that as feedback levels are increased, as is the case for motorbikes, then the channel emboldened in figure 4.12 above starts to become more heavily loaded, and mental workload begins to rise again. Although mental workload is rising there is no suggestion within this Study that performance is decreasing, though this will likely be the case beyond certain upper limits. A final interesting point concerns the findings in respect to the frustration scale of the NASA TLX. Low feedback car drivers rate higher on this dimension, and it is not inconceivable that mental isolation, as Zuboff (1988) puts it, or loss of SA, as Endsley states, could be the reason for this. In either case, a tentative relationship between feedback and driver enjoyment has been observed.

3.4.3 Summary

This Study offers experimental evidence in support of vehicle feedback and it's role in driving. The Study probes every level of the feedback model of driving, and the findings, though *exploratory in nature* at this stage lend tentative support towards the workings of the model and the flow of information through it. Moving the vehicle feedback issue from the literature into to the theoretical, using the feedback framework, offers an opportunity to not only analyse but to begin predicting the information requirements of safe, efficient and enjoyable driving. This on-road study now provides a clear view ahead in terms of what relationships and hypotheses to examine, and what effect sizes are likely to be seen in the context of more rigorous driving simulator experiments.

Chapter 4

Design and Construction of the Brunel University Driving Simulator

4.1 INTRODUCTION

This Chapter deals with the design and construction of the Brunel University Driving Simulator. The simulator provides the capability to take the issue of feedback onwards from the exploratory to the experimental level. So far Chapter One has dealt with the issues of safety, efficiency, and enjoyment and how feedback could help to maximise these design goals with regard to future vehicle technologies. Chapter Two presents a definition of feedback and a structured analysis of the driving task in order to determine the feedback needs of drivers, as well as presenting the comprehensive feedback framework. Chapter Three explores the feedback framework in the context of an exploratory on-road study, and prepares the ground for experiments to be conducted within the highly controlled Brunel University Driving Simulator environment.

In this and the following Chapter the experimentation now turns to the driving simulator laboratory, an environment that allows tools such as the HTAoD to be fully utilised and experimental control not obtainable in earlier on-road studies to be answered. The Brunel University Driving Simulator was designed and built by the author specifically for this purpose.

4.2 THE BRUNEL UNIVERSITY DRIVING SIMULATOR

4.2.1 General Features

The experiments both made use of the Brunel University driving simulator. This is a fixed base simulator designed and constructed by the author employing a Series One Ford Mondeo Ghia as the donor car. The general layout of the simulation lab is shown in figure 4.1 below. The facility is comprised of a simulation area with a control room adjoining it. A projected digital image is shown in front of the vehicle, and the driver interfaces with the vehicle's controls as normal.

Figure 4.1 - General view of the simulation lab.

A key feature of the simulator is that it was expressly designed to retain the look and feel of a standard road going vehicle. This entailed maintaining all of the original controls and hiding the experimental apparatus, actuators, sensors and wiring from the driver's view. In practical terms this entailed retaining much of the existing Mondeo mechanical hardware, such as the existing pedal box, steering column, and interior loudspeakers, and interfacing the electronics with them. As an example of this approach, the accelerator pedal remained connected via its original cable to the vehicle's original fuel injection throttle body assembly. This ensured that the accelerator pedal felt life-like in actuation, even through all it had to in the simulation was operate a small potentiometer. This is shown in figure 4.2 below. For the purposes of examining vehicle feedback a high fidelity simulation experience had to be provided where practical, and this was one of the steps employed by the author to help achieve this.

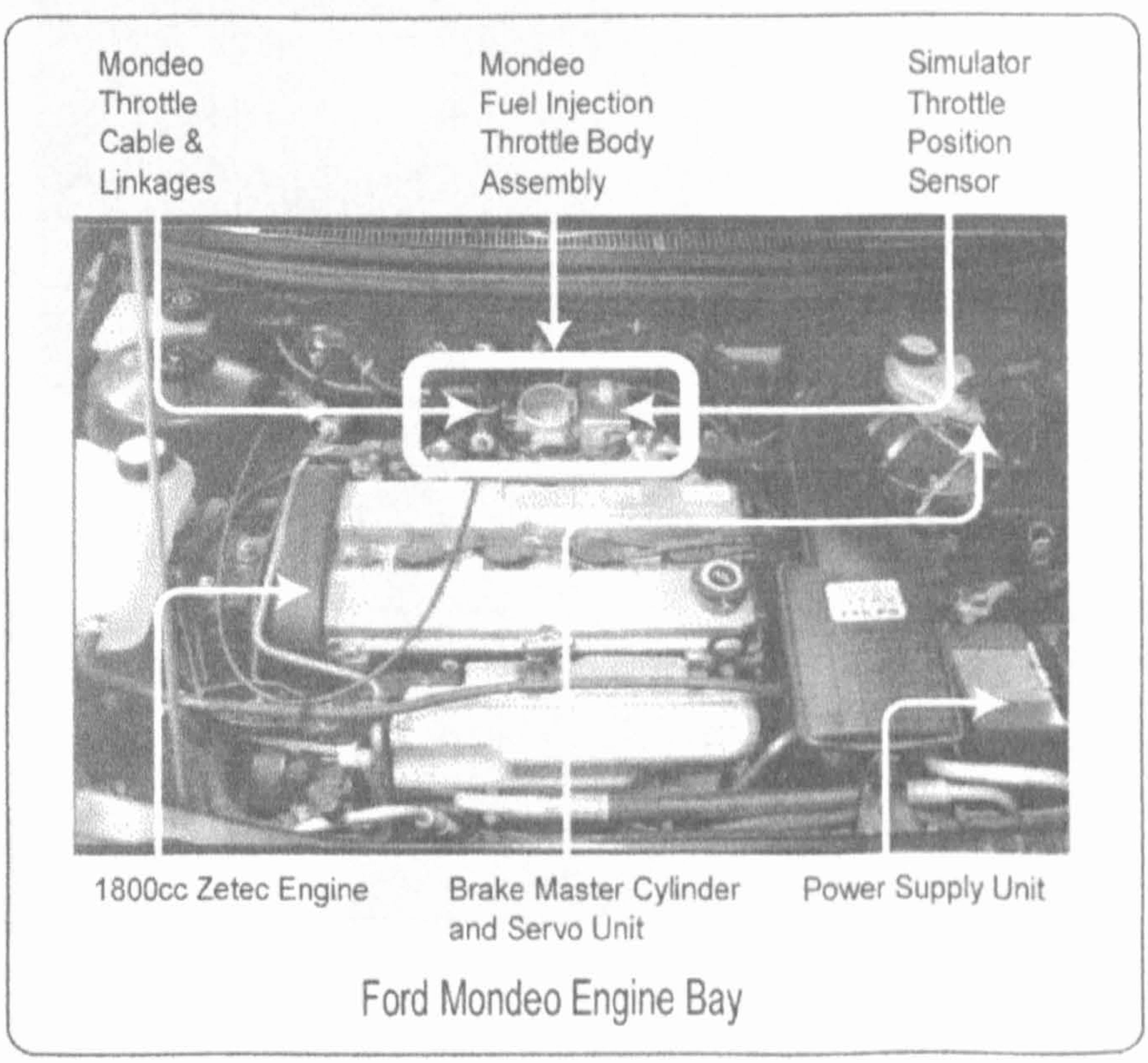


Figure 4.2 - Throttle position sensor attached to the original Ford Mondeo throttle body linkages and cabling to maintain life-like control feel.

The simulator is powered by a 1.2GHz PC computer equipped with Creative™ 3D video acceleration featuring high specification NVIDIA GeForce2GTS™ hardware. It is also equipped with Creative™ audio hardware permitting four channel Dolby Pro Logic™, or six channel Dolby Digital™ surround sound as required. All of the in-vehicle control and actuation devices (apart from the audio system) interface with on board hardware that features a 25MHz co-processor, and this permits a single USB interface between the vehicle and the PC (shown in figure 4.3). This design permits a great deal of future flexibility.

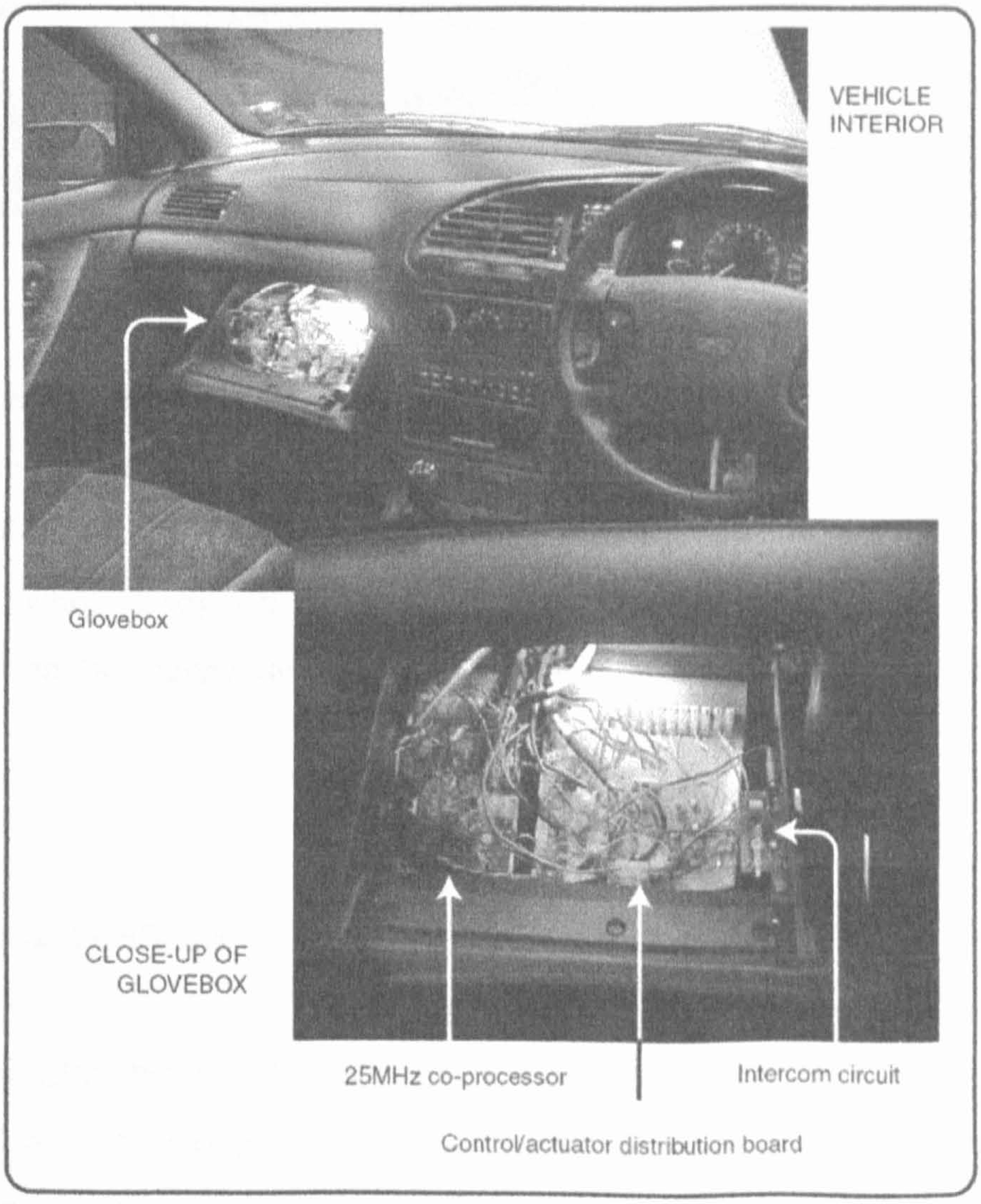


Figure 4.3 - 25MHz on-board co-processor for control actuators and sensors, all hidden within the glove box.

Figure 4.4 - Control room and equipment.

The key feature of this particular simulator is that it was designed and is equipped to provide vehicle feedback through four modalities, representing, therefore, a key manipulation of the *source* of feedback. These modalities are steering force feedback, whole body vibration, audio, and of course visual feedback. Each modality can be independently manipulated from the control room (figure 4.4 above).

4.2.2 Visual Feedback

A Hitachi CPX-985 liquid crystal XGA projector of 3200 lumens output, and 1024x768 resolution is provided. This device projects onto a Harkness-Hall™ professional cinema screen, specified and purpose designed for the driving laboratory. The screen material is non perforated and has a high gain Perlux™ coating. The screen image measures 3.5 metres by two metres, offering a field of view of approximately 60 degrees horizontal and 35 degrees vertical. The visual aspects of the simulator are illustrated in figures 4.5 and 4.6.

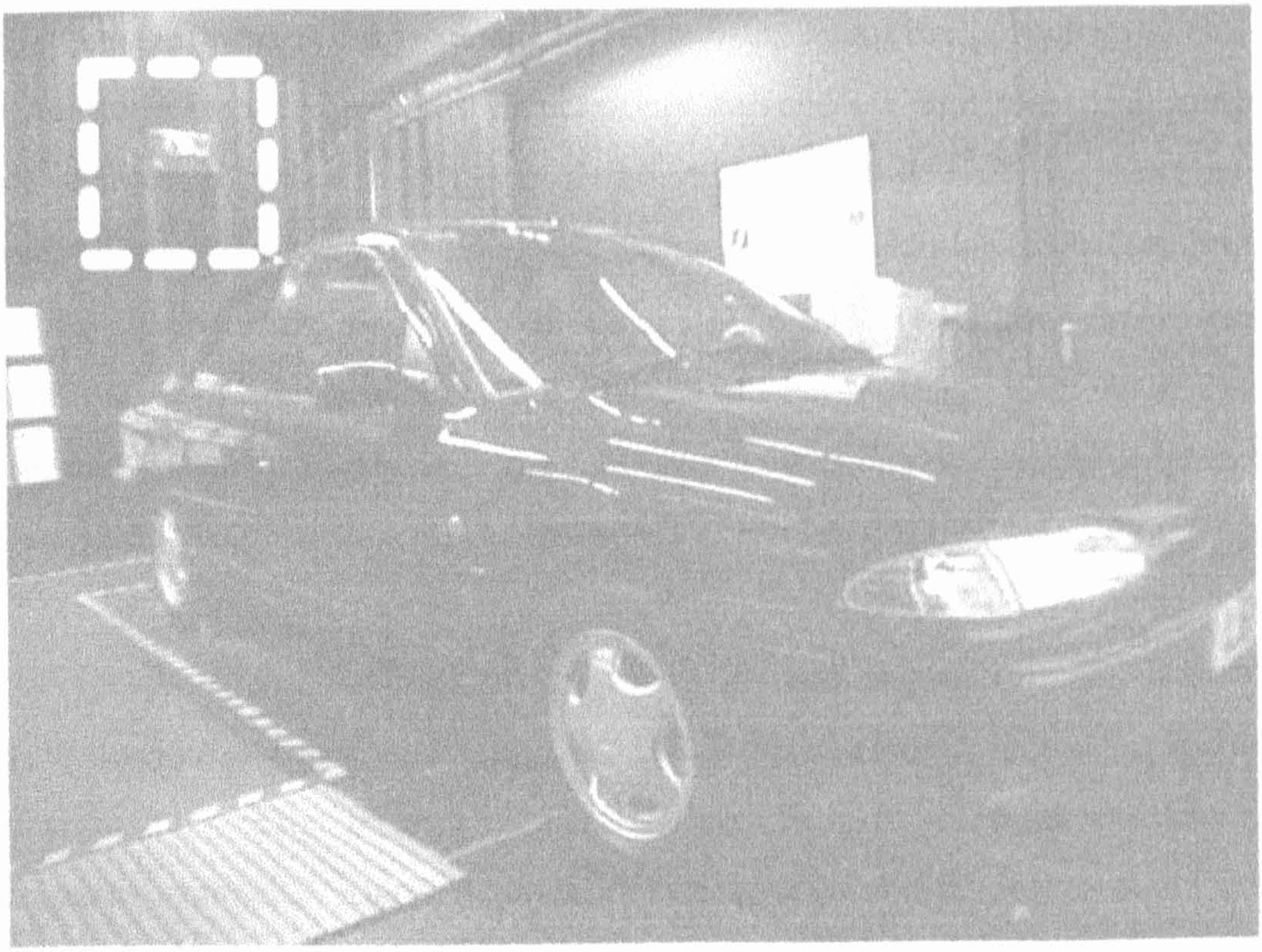


Figure 4.5 – Data projector.

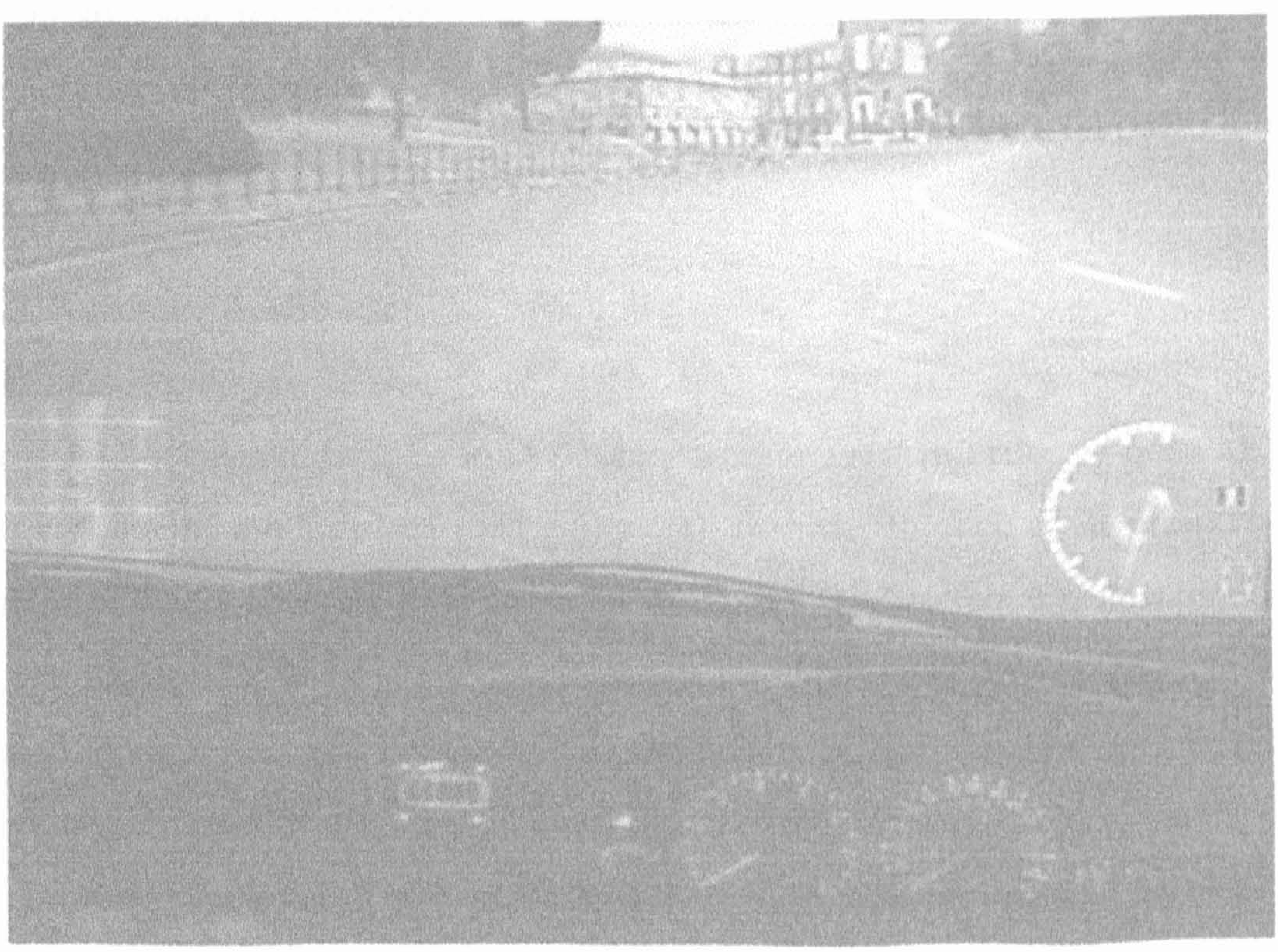


Figure 4.6 - Projected image seen from drivers eye view.

The *temporal* aspects of the visual feedback modality retain the properties of real life driving, the computer being powerful enough to supply a high resolution image in exact relation to the relative speed of the vehicle, and in direct response to the driver's desired speed and trajectory within the simulation (according to the specified characteristics of the car of course). The high resolution helps to ensure that the *content* of the visual scene is accurate and rich, although of course the effect of limited viewing angles and the ultimate restrictions of graphics hard and software impose limitations not encountered in real life driving.

To be specific, visual feedback is comprised of a moving road scene. It features varying types of scenery, including built urban environments, suburban, and rural environments. The scenery also possesses features such as bridges and underpasses, tunnels, crossings, junctions, trees, walls and fences, to name a few. The road itself varies in width and texture, and also featured are pedestrians, road signage and other assorted road furniture. Visual feedback (as in real life driving) provides *direct* feedback for the driver, and the simulation also provides further *explicit* feedback in the form of a numerical speed display, a gear selection indicator, and an analogue rev counter. These are shown in a head-up fashion in the right hand corner of the screen.

4.2.3 Auditory Feedback

The vehicle's original built in loudspeakers were utilised in order to preserve the look and feel of the standard road going car. In order to once again preserve the content of feedback as far as possible, a surround sound system was developed for the simulation. To this end the front interior door speakers were supplemented by a small loudspeaker unit hidden within the centre consol; the rear door speakers providing the bandwidth limited surround sound channels. All of the interior speakers are of moderate power (due to their near field operation), therefore the low frequency audio output was augmented further by a powerful dedicated low frequency sub-woofer unit, specially built by the author to suit the needs of the simulation experiments. This was mounted externally and at the front of the vehicle. In particular, this helped to convey a realistic impression of large scale sounds such as road noise and the impression that engine noises were emanating from the engine compartment. Figure 4.7 below shows a simplified schematic for the audio system and the primary audio components installed in the simulator vehicle.

Audio outputs were derived from the PC sound hardware. These were fed into a Sherwood RV6010R processor and amplifier unit, enabling four channel Dolby Pro Logic™ surround sound to be used for the experiments. The frequency range of the system is approximately 25Hz to 15KHz, and the spectral content of the audio output is adjusted via a 10 band stereo graphic equaliser. Power outputs of 30watts RMS for the rear surround channels, and 100watts RMS for the front speakers and the subwoofer enable maximum sound pressure levels of approximately 103dBA if necessary, therefore able to easily reproduce the *quantity* of audio feedback content quite easily. The surround sound facility also provides a highly realistic spatial effect, such that external sound stimuli occur in their correct spatial location, dynamically changing with the movement of the vehicle through virtual space. Again, this speaks towards the desire to maintain a realistically high state of feedback *content*.

Specifically, the audio feedback was comprised of realistic synthesised engine noises that changed in response to accelerator position, gear selection, and the gradient of the road. Similarly, road noise, consisting of tyre roar (changing according to road surface texture), the sound of the vehicle's wheels traversing bumps and irregularities, and wind noise were presented. Again, these all contingent upon the movement of the vehicle through virtual space, thus retaining the *functional* and *temporal* aspects of feedback normally encountered on the road. Other auditory stimuli included the sound of rain falling on the vehicle combined with the change in tyre noise encountered in wet weather, and also reverberation encountered when driving in tunnels. Finally, a rather unpleasant crashing and/or scraping noise was presented if the vehicle collided with anything.

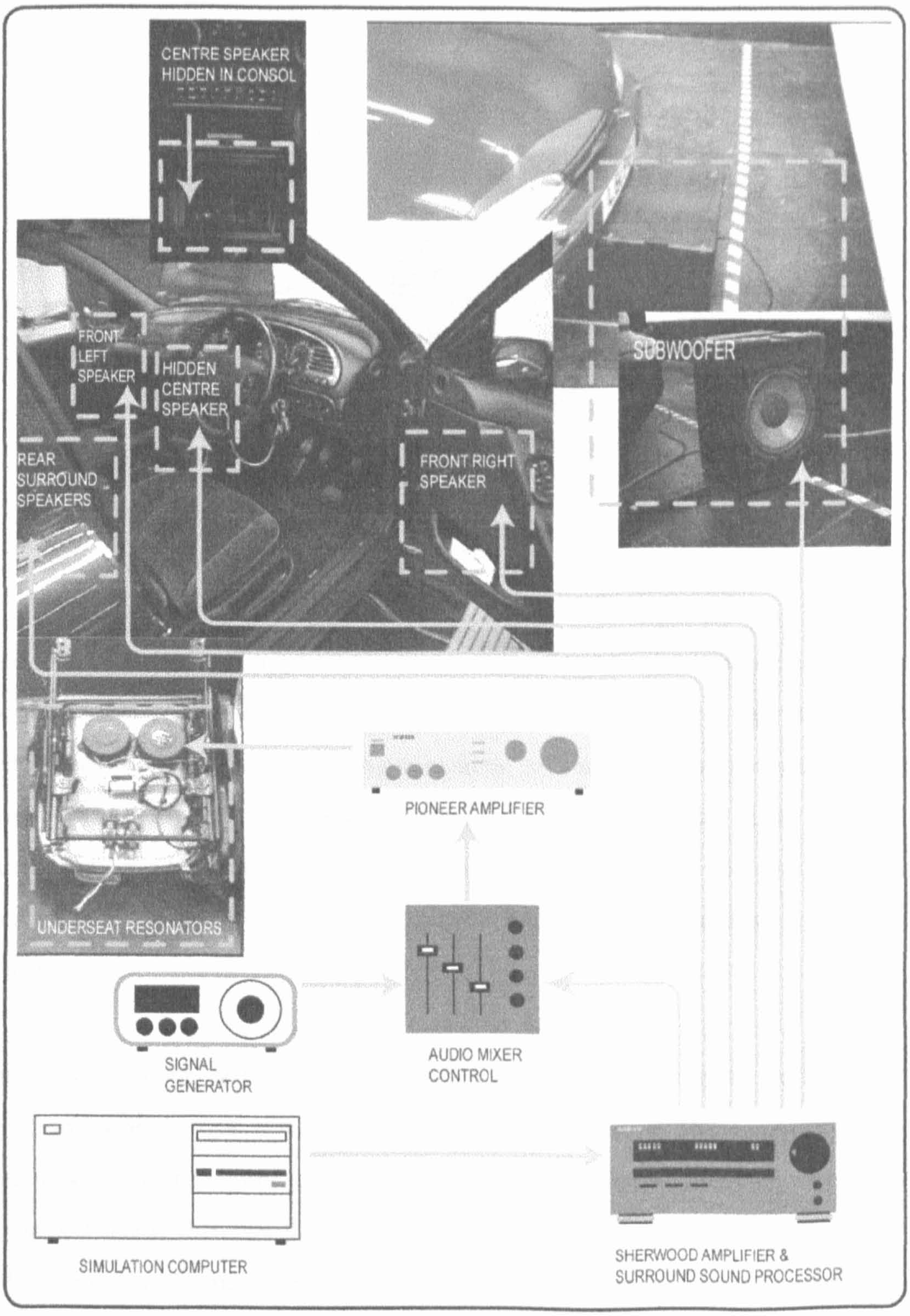


Figure 4.7 - Simplified schematic layout of simulator audio system.

4.2.4 Whole Body Vibration

Linked to the audio system are two electro-mechanical resonators fitted to the underneath of the driver's seat as shown below in figure 4.8.

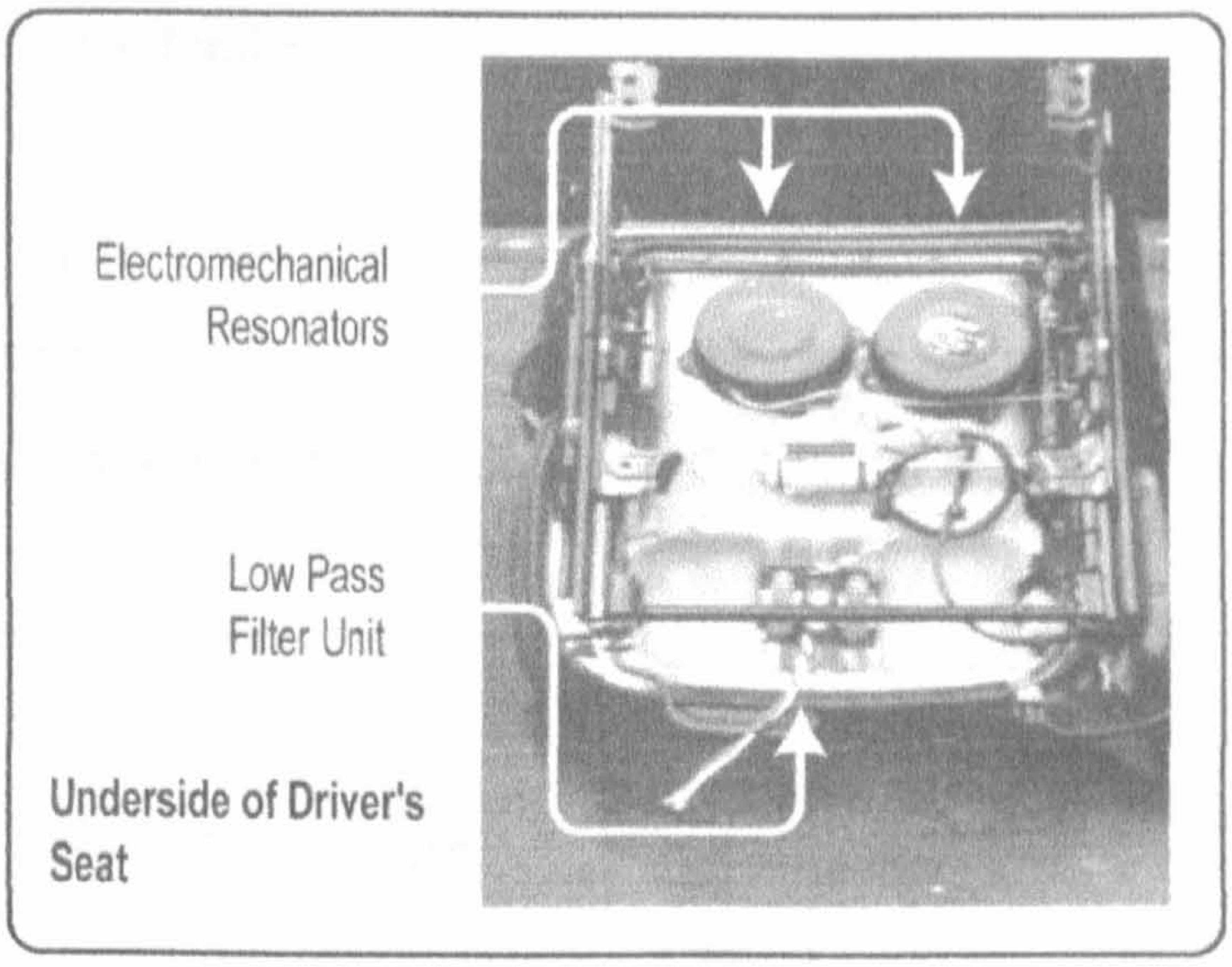


Figure 4.8 - Under-seat electro-mechanical resonators.

This represents a novel application of these low frequency resonator devices, their normal use is to be fitted to dance floors. In their present application, their performance is excellent, providing a realistic sensation (in the absence of a truly moving base simulator) of vehicle movement and vibration. They succeed in transmitting road derived bumps and thumps into the driver, and also providing a background of vehicle vibration. Again, this representing a dimension of feedback *content.*

The resonators are fed from two sources; low frequency inputs from the audio signal and a 50Hz sine wave fed from a signal generator. The signal generator is used to augment the continuous road derived vibrations, so that not only are these sensations heard through the audio system, but they can also be felt through the seat. These two inputs pass through a mixing control to alter the relative proportions of the two signals. The low pass filter unit disposes of unwanted signals above 150Hz, ensuring that only low frequency rumbles are passed to the driver, and that the driver can no longer spatially locate the source of the low frequency sounds (Moore, 1982). This is also fitted underneath the seat. Power amplification supplies each resonator with their maximum rated 50 Watts RMS. The approximate power spectrum of these signals is similar to that created when driving quite rapidly over a cobbled road surface, although vertical displacement of the seat and the driver is considerably smaller (Mansfield & Griffin, 2000; Tempest, 1976).

4.2.5 Steering force feedback

The original Ford Mondeo steering column is retained but is disconnected from the physical steering system. At the end of the original steering column sub-assembly a torque motor and position sensing unit is fitted (figure 4.9).

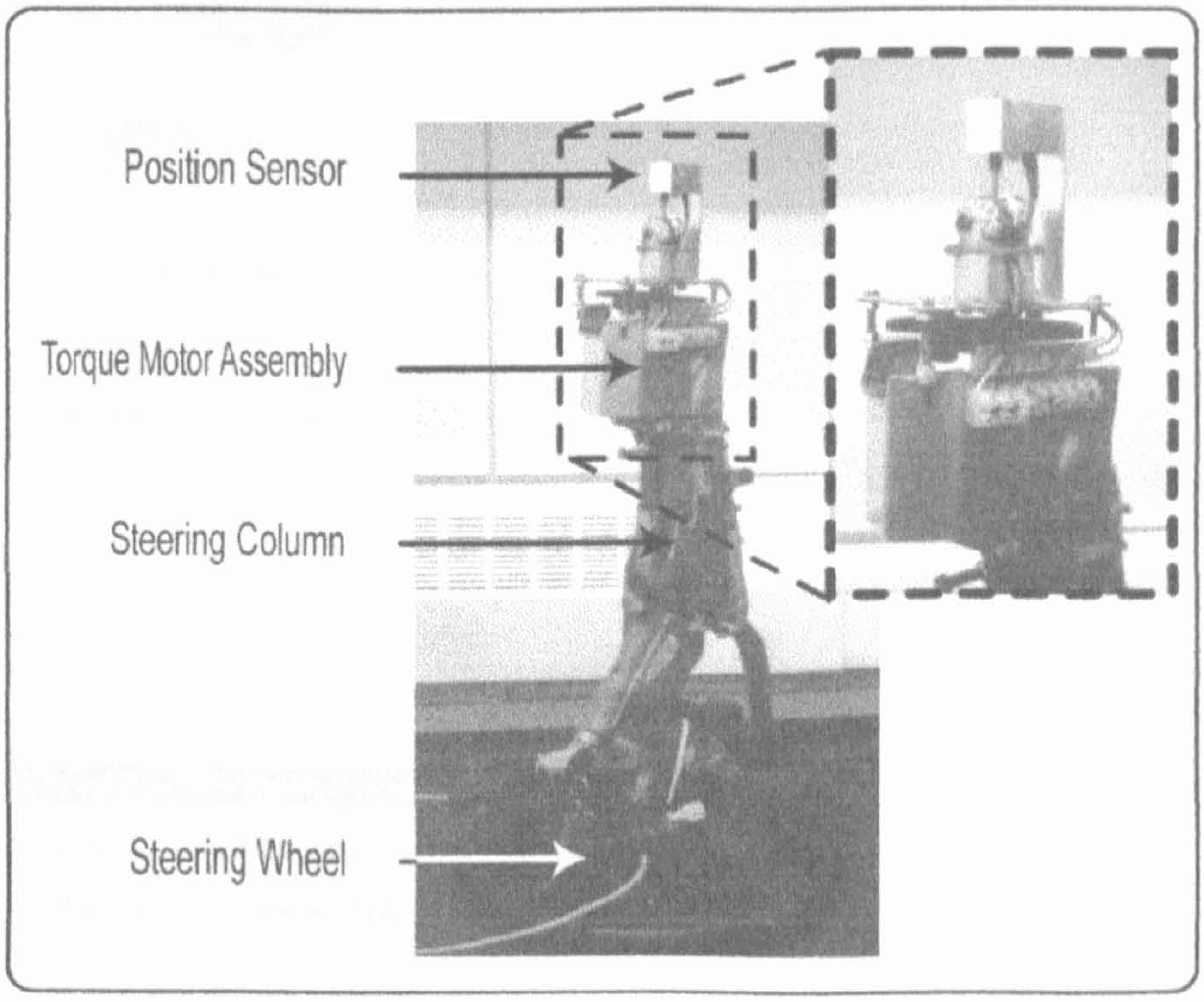


Figure 4.9 - Steering force feedback hardware.

Steering force feedback is capable of high resolution, and is adjustable through a wide range of parameters via control panels provided by the simulation computer, and shown below in figure 4.10. Passive force feedback (related to disturbances involving the virtual road surface), and self centreing force can be defined through four levels. The maximum *passive* and aligning force at the steering wheel rim is 1.25Nm, sufficient to provide a realistic impression of steering feel and force feedback, but admittedly still rather on the low side compared to a real life road vehicle (Curtis, 1983).

Further steering parameters concerning the precision of the steering around the centre point (the dead zone), and the sensitivity (or gain) of the steering towards control inputs could also be defined through the proprietary software, as shown in figure 4.10 below.

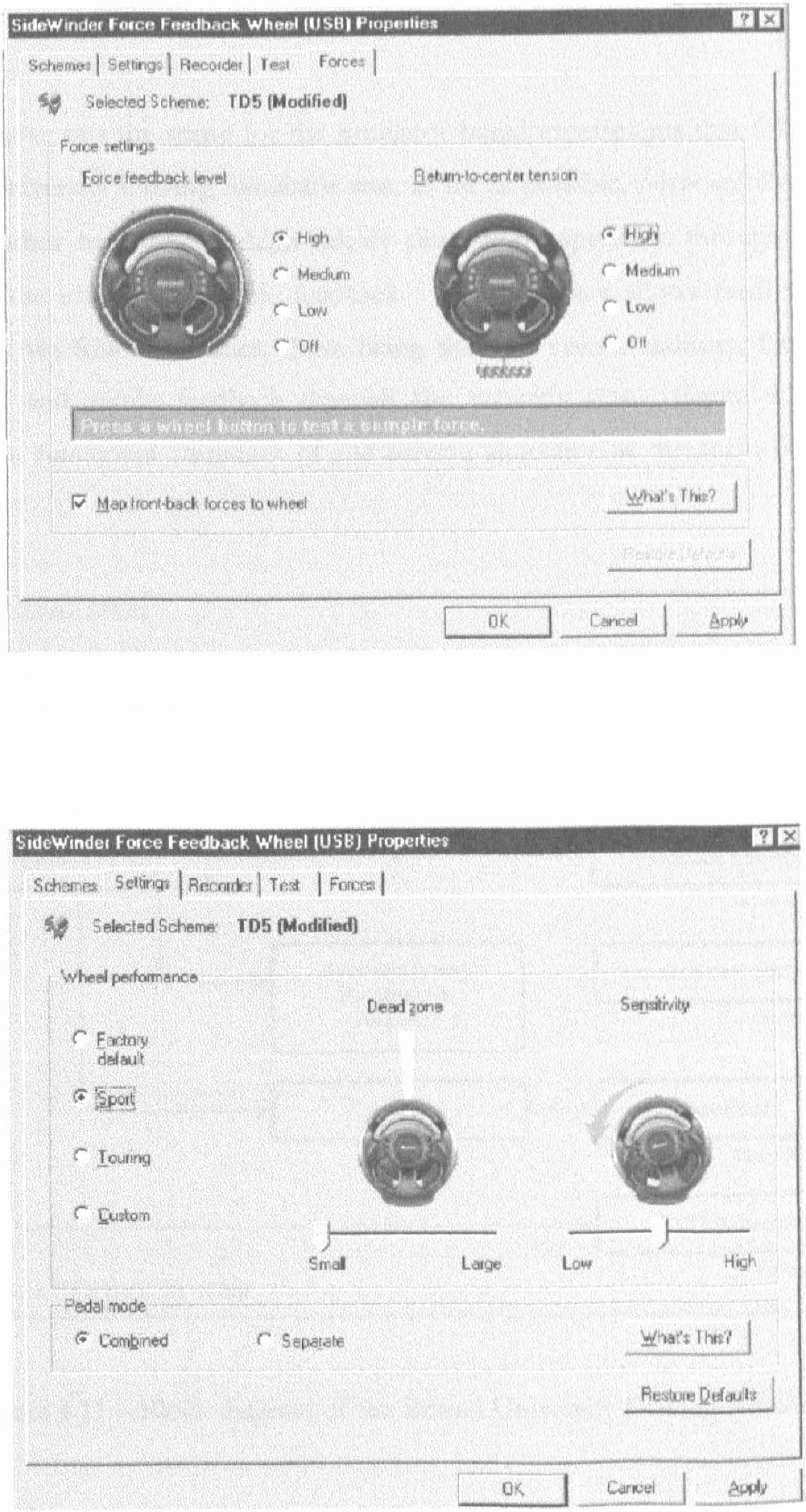


Figure 4.10 - Control panels to adjust steering force feedback parameters including steering centre point vagueness and steering sensitivity.

4.3 SUMMARY

This Chapter sets the scene for the simulator based experiments that follow. The Brunel University Driving Simulator was, as far as possible, purposefully designed by the author to provide a high fidelity simulation experience through which to examine the effects of vehicle feedback. The simulator allows feedback to be presented via four modalities, these being through vision, auditory, tactile force feedback, and tactile feedback through the vehicle's seat. Figure 4.11 below presents a functional summary of the driving simulator in the form of a block diagram.

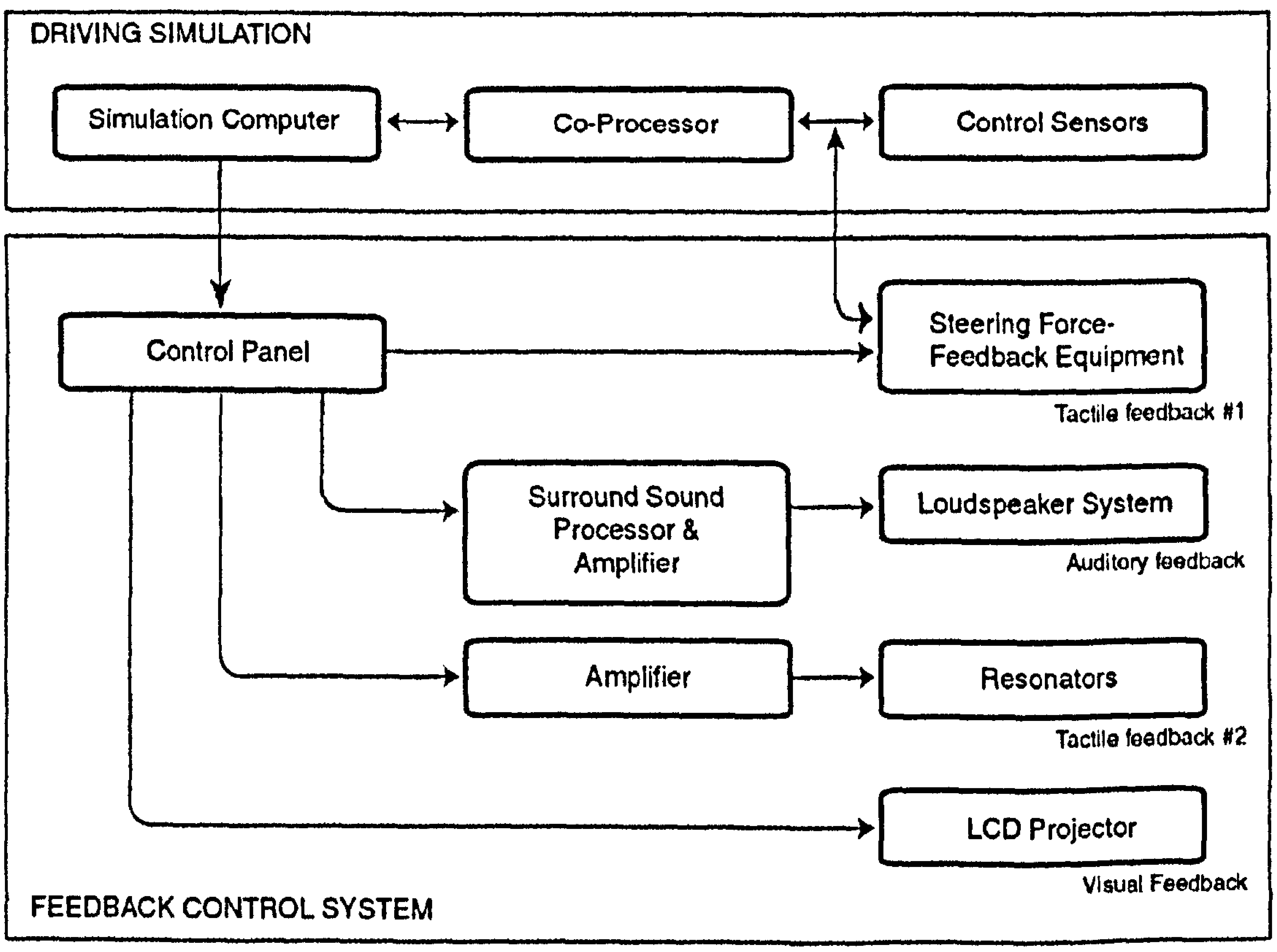


Figure 4.11 – Block diagram of the Brunel University Driving Simulator.

Whereas the on-road study measured all aspects of feedback (content, timing and source) as they occur on-road, the simulator only manipulates the *modality* of feedback presentation. As specified by the definition of feedback earlier, regardless of whether the source of feedback information is direct or indirect, reactive or passive, explicit or implicit, this information still has to pass through the various sense modalities. In attempting to maximise (as far as possible) the fidelity of the simulation experience, what is in effect being *designed* is the nature of direct/indirect, reactive/passive, explicit/implicit feedback, the dimensions of timing and to some extent content of feedback. In whatever case, these components of the source of feedback all rely on the role of the sense modalities, and the temporal and content properties of feedback are also heavily influenced by the modality through which feedback information is carried. The modality of feedback presentation therefore represents a powerful feedback manipulation.

An important point in terms of feedback content, is that the quantity of feedback, its richness, accuracy or otherwise is *not* manipulated as an independent variable and remains at a fixed level. Whatever feedback information is being carried through the various sensory modalities remains the same, though contingent upon the current simulation of the road environment. Of course, the simulation preserves the functional relationships encountered in normal driving, so that the information can still be defined along the lines of source, content and timing, but nevertheless, each modality is carrying a simulation of the information that is *normally* carried by that modality of feedback. Therefore the simulation switches the source of feedback (derived from the sense modalities) on or off in a binary fashion. What it does not attempt to do is vary the *quantity* of feedback presented through each channel beyond that dictated by the normal changing driving situation. This is an important point.

In summary, the type of information presented to the driver is defined by the design of the simulator and the preservation of life-like functional and temporal relationships. The modality of feedback presentation largely dictates whether this information reaches the driver or not, and therefore represents a powerful manipulating feedback variable. Further enhancements to the driving simulator, or perhaps a different experimental paradigm altogether would be required to alter feedback significantly on the other dimensions of timing, content, or other aspects of the sources of feedback, for example, turning implicit feedback into explicit feedback, and so on.

In conclusion, the development and design of the Brunel University Driving Simulator is a reflection of how the issue of feedback has progressed from the literature and survey up to the exploratory level of analysis. The exploratory level of analysis, as encapsulated in the on-road study has provided the level of detail necessary to design the simulator appropriately as well as generate further valid research hypotheses. It also provides a useful estimate as to anticipated effect sizes when feedback is manipulated as the independent variable, and psychological factors such as situational awareness and mental workload measured as the dependant variables. The simulation paradigm will take this further and begin to provide a detailed substantive understanding of the feedback requirements of drivers, helping to substantiate and increase the ability of the feedback framework to help support vehicle design decisions.

Chapter 5

Driving Simulator Experiment

5.1 INTRODUCTION

5.1.1 Background

Increasing SA and optimising mental workload are important design objectives if the aims of safety efficiency and enjoyment are to be met (Adams, Tenney, & Pew, 1995; Endsley, 1995b; Endsley & Garland, 2000; Stanton & Young, 1998; Young & Stanton, 1997). According to the feedback framework and the results of the on-road study in Chapter Three, feedback, situational awareness, and mental workload are closely intertwined. Increased vehicle feedback provided increased SA within the on-road study, as well as showing an ability to favourably interact, or even possibly to help optimise MWL. Against this background the interest within this Study is to move the debate from the exploratory level of Chapter Three into the experimental level; to further examine the substantive relationship between situational awareness and feedback, and mental workload and feedback. To deal with SA first, this involves eliciting the situational awareness requirements at each stage of the driving task, and measuring driver's performance against them using vehicle feedback as the independent variable within the Brunel University Driving Simulator.

5.1.2 Measuring Situational Awareness

A range of tools and methods exist for the measurement of situational awareness. During the on-road study it has been possible to categorise concurrent verbal reports of driving task enactment and to use this as evidence of SA. The subjective Situational Awareness Rating Technique, or SART, (Taylor, et. al., 1993) has also been used as an interesting contrast, and is still being used for this purpose within Part I of the present study. As exploratory methods these tools are entirely appropriate, but not without disadvantages. The concurrent verbal protocol procedure presents only what the driver consciously wants or has the time to talk about, and is therefore often related to mental workload (Endsley, Sollenberger, & Stein, 2000). Similarly, the SART derived scales seem to suffer from the fact that self awareness of SA is notoriously poor (Endsley, 1995b).

Other methods that are argued as being more 'objective' include various physiological measures such as eye tracking, electroencephalographic methods, or to employ external task measures or imbedded task measures. Alternatively, SAGAT (Situation Awareness Global Assessment Technique) is offered by Endsley (1988) as a purpose designed and supposedly *objective* method for measuring SA. Objective should be carefully defined here as *"external to the mind, actually existing"* (Allen, 1984, p. 505). SAGAT is a probe recall paradigm, which in a practical sense involves freezing the experimental scenario and then accurately probing situational awareness by asking questions regarding the current situation. The probe recall procedure is of course problematic for naturalistic driving as the driving scenario cannot be easily frozen, unless another driver assumes control with a vehicle equipped with dual controls or some similar (rather hazardous) procedure (Endsley & Garland, 2000). Of course, using a driving simulator allows this 'freeze technique' to be readily applied, but the trade-off for experiments concerned with vehicle feedback can be a potential loss of fidelity compared to naturalistic driving. In the present case every reasonable attempt was made to ensure that the Brunel University Driving Simulator provided a realistic and immersive simulation experience; certainly the main functional and temporal aspects of real life driving are maintained.

Within SAGAT the participant's performance on the probe questions during every pause in the simulation can be compared to the 'actually existing' objective state of the world. It is through this procedure that an objective measure of SA is said to be derived (Endsley, 1988). However, probe recall/freeze techniques and others like it are argued as being, to a greater or lesser degree, unavoidably *subjective* (Annett, 2002). SAGAT relies on the contents of participant's memory, and the participant has to cognitively appraise their conscious experience; a process that of course is subjective (Annett). The SAGAT probe questions tend to enquire about the inner experience of qualities that are external to the observer. But even these *external* qualities, used as a reference for the subjective ratings are often still open to interpretation. In its favour SAGAT ameliorates these effects by interpreting the objective state of the world with reference to data from simulation computers backed up in some cases by teams of experts (Endsley). Where the method becomes weaker in respect of the objective versus subjective debate is in the evaluation phase. Normally SAGAT derives various percentage correct scores or composite SA scores *directly* from subjective ratings of the objective state of the simulation. It is argued here that these measures are subjective precisely because they are a *direct* index of an individuals cognitive appraisal of a multidimensional construct(s), and thus lack quantitative structure.

5.1.3 Signal Detection Theory

Signal Detection Theory (SDT) offers a paradigm under which more objective measurement and evaluation can proceed. It does this with reference to psychophysics; by measuring *sensitivity* to stimuli. For the purposes of this Study it is possible to move away from scales that might probe multidimensional subjective constructs such as *"which aircraft is your highest priority threat"* (Endsley & Garland, 2000, p. 6), to instead *"rate your level of confidence that a particular feature/event/situation in the environment is either present or absent"*. Here the subject is simply being probed about their *sensitivity* towards stimuli and events in the environment, and these stimuli represent components of the individuals SA. Obviously this evaluation is performed by the individual subjectively, but their publicly observable performance, viz., sensitivity to the probe stimuli *can be objectively measured*; just as a loudspeaker can be measured for output contingent upon a given input (Annett, 2002).

Remaining with the loudspeaker example for a moment, it does not matter what the individual loudspeaker is actually doing internally with the input (for example, the minutia of material properties, magnetic field densities and electron flow are hard to know for definite), but the publicly observable device output can be *measured* (in terms of decibels and hertz, for example) with a high degree of confidence. Although the inner experiences of participants are subjectively rated (and therefore also hard to know for definite), their observable output in terms of *sensitivity* towards different stimuli *can* be measured with the same high level of confidence as the sensitivity of the loudspeaker for a given electrical input. Conceptually this approach is very neat. The sensitivity measurement possesses a quantitative psychophysical structure, refers to externally existing and publicly observable events, and can be easily compared across individuals and experimental scenarios. Therefore this approach is much more objective when compared to direct subjective ratings of multidimensional constructs such as that normally embodied within SAGAT.

In Part II of the present Study a probe recall paradigm akin to SAGAT is employed, but drivers responses to stimuli are not directly compared to the multi dimensional objective state of the world in terms of subjective measures, such as percentage correct responses. Instead, driver's responses versus the objective state of the world are transformed into a measure of sensitivity. Therefore, this Study uses driver's subjective confidence ratings to measure *changes in sensitivity* towards SA probe items, dependent upon different vehicle feedback conditions. The relationship between correct and incorrect responses to the presence or absence of SA stimuli, contingent upon vehicle feedback, can be readily expressed using a Signal Detection paradigm (this is explained in more detail in the Results section). This is used to derive the sensitivity measure d' (d-prime), and each feedback condition presented to drivers can be expressed with reference to this.

In the present Study the change in driver's *sensitivity* (d') towards stimuli in the driving environment, contingent upon vehicle feedback is to be examined. This represents a departure from usual SA methods such as SAGAT. In departing thus, it is desired to at least partly address some of the concerns raised in the objective versus subjective debate. In combination with this, sensitivity, from a design perspective, can be argued as offering a much more useful and transferable metric through which to gauge the effect of feedback and possible consequences on resultant SA. d' also expresses the ability of an observer rather better than merely examining percentage correct responses because it takes into account not just correct responses, but also incorrect responses, and can be measured across a number of observer decision criterion points. Under this taxonomy it becomes possible to examine the effects of different permutations of vehicle feedback in terms of the additional sensitivity that each permutation may offer towards SA stimuli, over and above a baseline visual feedback condition.

5.1.4 Measuring Mental Workload

The attention now turns to the content of Part III of the Study, and the issue of driver mental workload. A number of interesting findings in respect to MWL and feedback have been uncovered by prior exploratory work. The main aim of Part III of the present Study is to test the robustness of these findings under a much more controlled simulator environment, and to further enhance the feedback framework in light of them. This moves the debate on neatly once again, from the exploratory to the experimental. To this end, the same NASA TLX mental workload rating procedure is employed. This is a multidimensional subjective rating technique that derives the direct opinion of the individual in terms of their experience of the task (Hart & Staveland, 1988; Tsang & Wilson, 1997). This approach is in contrast to the objective measures sought for the SA side of the simulator studies.

As a concept, MWL does not lend itself very well to the psychophysical measures employed to analyse SA. MWL can be studied with what some researchers might call objective methods such as primary or secondary task measures, but primary task measures were not appropriate for this Study as each driver had to remain at a fixed speed (and did so remarkably consistently). Unfortunately, in this case variance around the target speed could not be measured. Consequently, no speed differential data could be used as a primary task measure, that is assuming that higher or lower speed implies better performance? This decision of course being a subjective one. The number of collisions were also too few to be meaningful in any statistical sense, and the simulator was not able to provide any further telemetry such as throttle position, lane deviance etc. for use in primary task measurement. This, incidentally, would be a particularly useful follow on. Similarly, the simulator was not equipped to provide secondary task measures, although these would likely have interfered too much with the SA analysis (occurring at the same time) even if they were used. Physiological measures are another avenue, but ultimately suffer from the same objectivity pitfalls as the NASA TLX in terms of interpreting the spectral content of EEG activity, skin conductance and/or blink rate as a metric for workload. This interpretation being, once again, essentially subjective.

The NASA TLX scale was chosen for the current Study for much the same reasons that Endsley & Kaber (1999) employed it in similar circumstances. Namely that the measure is argued as coming *"closest to tapping the essential essence of mental workload and provide*[ing] *the most generally valid and sensitive indicator"*, (Hart & Staveland, p. 141). This is not to say that the NASA TLX measure is in any way perfect, but its sensitivity to task manipulations is backed up by empirical validation of the various measurement scales such as that performed by Vidulich and Tsang (1986). Furthermore, subjective measurement in this case has the advantage of being fairly unobtrusive, easy to implement, easy for the participant to complete, and quick; with the participant in this Study required to complete the scale immediately after a simulation freeze. These are important advantages in the context of the present probe recall 'freeze' paradigm, even though it has been shown that reliable ratings of MWL can still be given up to 30 minutes after the event (e.g. Moroney, Biers & Eggemeier, 1995). Probably the most useful advantage in this specific instance is that the measure was used in an earlier study, and therefore it is interesting to use its inherent transferability to determine if the same measure can yield similar experimental effects within a new and more rigorous experimental paradigm.

5.1.5 Driver Information Needs

Some estimates assume that 90% of driving task enactment depends upon the visual feedback channel (e.g., Olson, 1993), although quite how these estimates are arrived at is unclear. Either way, it does rather deny the existence of other feedback modalities in influencing SA and MWL. With reference to the exhaustive HTA of driving presented earlier on in Chapter Two it is surprising how much information drivers use and need from other senses. Driving is undoubtedly dominated by vision, and as such by far the largest impact upon MWL and sensitivity towards SA stimuli would be derived from vision alone. Obviously drivers would hardly be capable of driving at all without the aid of visual feedback; clearly under such a condition MWL would be extremely high. In comparison, it would still be possible for drivers to drive a car fairly satisfactorily without any auditory or tactile feedback. But of course, user-centred design operates at a far higher level than merely satisfactory, and the on-road studies in Chapter Three show the very positive effects of vehicle feedback explicitly. The interest in the present Study is to gauge the *additional* contribution that the remaining sense modalities make towards driver SA and MWL. This concept is shown for SA in figure 5.1 below, whereby working from the baseline of vision's contribution to SA it is possible to examine the *additional effects* of tactile and auditory feedback.

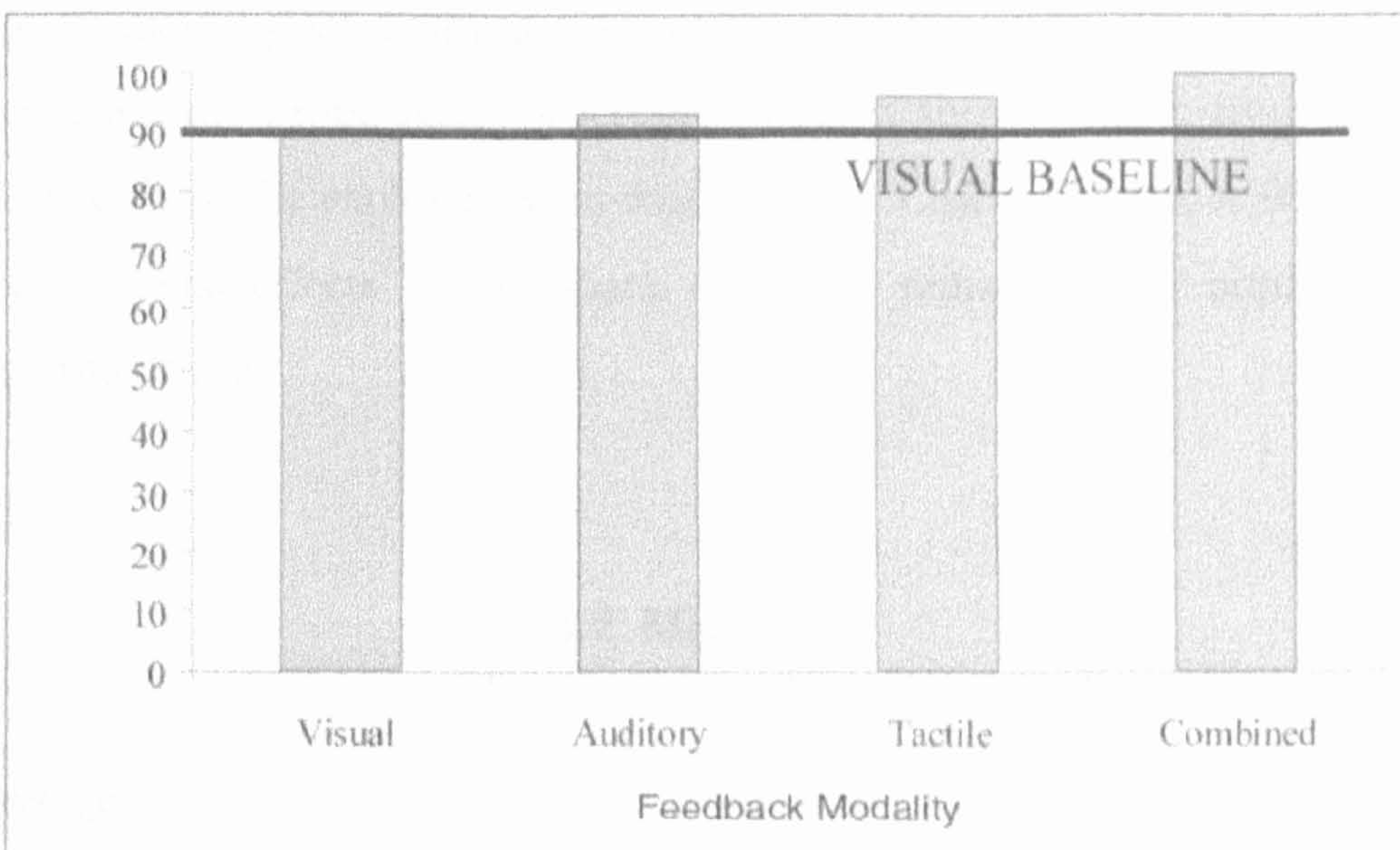


Figure 5.1 - Hypothetical situational awareness contribution provided by visual, auditory, tactile, and cumulative combined feedback modalities.

For illustrative purposes only figure 5.1 clearly shows that the largest share of SA is assumed by vision alone, lets assume 90%. The graph above shows the additional contribution to SA that other feedback modalities may make, and it is this top area of the overall graph that is being examined. As such it is likely that changes in SA sensitivity will be relatively small, but nonetheless meaningful in terms of vehicle design.

Further recent studies provide some insights as to what results might be reasonably encountered with respect to vehicle feedback as the independent variable. Horswill and McKenna (1999), Evans (1970), and Matthews and Cousins (1980) all cite the effect of auditory feedback in driving. Auditory information appears to be quite heavily implicated in accurate estimations of vehicle speed, with reduced auditory feedback generally tending to make drivers increase their speed. From this it might be anticipated that auditory feedback would feature prominently in the results. Tactile feedback and the role of steering feel has been cited already by Jacobson (1974) and Joy & Hartley (1953/4). This, and driving "by the seat of the pants" (and other such notions), nevertheless seem to at least approximate with research conducted on these modes of tactile feedback in other domains (for example, Akamutsu, 1992; Akamutsu, MacKenzie, & Hasbroucq, 1995; Sklar & Sarter, 1999). Overall, it is anticipated that changes in vehicle feedback will yield significant changes in sensitivity to SA stimuli and NASA TLX responses using the probe recall procedure outlined above. Aside from the tentative results gained from the exploratory on-road study in Chapter Three, at the moment the exact experimental effects per feedback condition remain largely unpredictable, and therefore data driven.

5.2 METHOD

5.2.1 Design

The experiment was based on a probed recall paradigm using a driving simulator and a pre determined virtual road course. Participants had to complete rating scales during 36 pauses in the driving simulation. These pauses were placed at randomly varying time intervals along the virtual road course and no prior warning was provided. The first set of rating scales probed the participant's confidence level, along a seven point confidence scale, as to the presence or absence of probe stimuli in the environment. There were seven probe items for each pause in the simulation. Probe items were derived from a Hierarchical Task Analysis of Driving enabling the information requirements of each category of driving task enactment to be gathered. The probe questions were identical for all participants. Participants were also required to complete a 20 point scale that asked them to subjectively rate the state of their situational awareness, before having to complete the NASA TLX mental workload rating scales. Responses to the rating scales were dependant upon vehicle feedback that had eight conditions, and was altered between conditions (or made to appear to be altered) after every pause in the simulation. In order to control for differences in the road simulation per pause, every participant had a unique, fully randomised presentation of different feedback conditions across the 36 simulation pauses.

5.2.2 Participants

5.2.2.1 General Characteristics

Thirty five drivers took part in the experiment. This number was arrived at with reference to issues of statistical power (see later sections). Participants were members of the public recruited through a leaflet drop conducted in the local area within a one mile radius, advertisements in petrol stations and supermarkets within a five mile radius, and also via an advertisement on Jazz FM (a major commercial radio station covering the whole London metropolitan area within a 50 mile radius). Staff and student members of Brunel University were also recruited via posters and word of mouth.

Despite protracted efforts to the contrary, around three quarters of the participants were male (77%), though a still useful number of female drivers did respond (23%). All age groups had some representation, from 17 years through to 61-70 years. The modal age category was 21-25. If drivers had less than six years driving experience they were regarded as novice drivers, and in this case represented 42.9% of the population, the remaining 57.1% having more than six years and being regarded as experienced drivers. The majority (54.3%) travelled approximately average yearly mileages of around 12000 miles, the remainder travelling more or less than average in roughly equal proportions. 11.4% of drivers had incurred some form of endorsable driving penalty, and only 14.3% had passed any kind of advanced driving test. 22.9% of drivers were also licensed to ride a motorbike. With reference to the operational definitions for high and low feedback cars defined in Chapter Three, the vast majority (76.5%) normally drove what can be regarded as 'low feedback' vehicles.

5.2.2.2 Psychological Characteristics

Drivers were also measured on a number of psychological dimensions, notably the Driving Style Questionnaire (West, et. al., 1992), the MDIE Locus of Control Questionnaire (Montag & Comrey, 1987), and some question items probing virtual reality involvement drawn from Witmer & Singer (1998). The responses that the sample provided to these questionnaires were tested for normality using the Shapiro-Wilk statistic.

The driving style questionnaire measures dimensions of speed (mean rating of 11.46, SD.=2.98, n=35), calmness (mean=9.71; SD=1.53), focus (mean=11.94; SD=2.38), social resistance (mean=7.06; SD=1.71), and deviance (mean=3.31; SD=1.69). Of more interest is that apart from the dimension of focus, all the other scales of driving style depart significantly from assumptions of normality ($p<0.05$). With reference to histograms of the respective scores it can be noted that three dimensions in particular demonstrate a marked *systematic* skew in the distribution of scores. These are dimensions of speed, calmness, and deviance. They are shown in figures 5.2, 5.3, and 5.4.

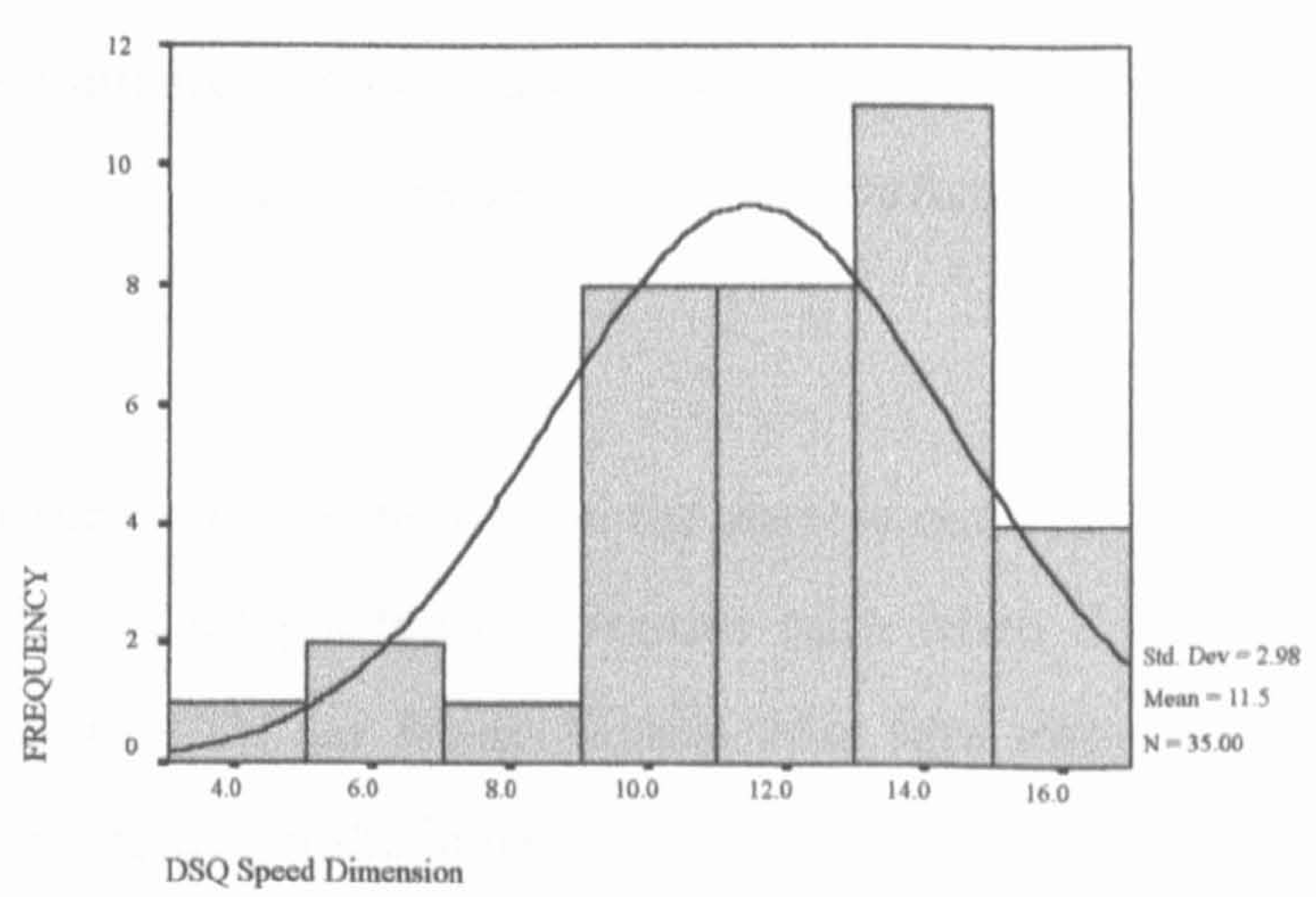


Figure 5.2 - Histogram showing distribution of scores on the driving style questionnaire speed dimension, with higher scores indicating that the participant drives faster.

For the speed dimension it is clear that the skew is towards higher scores. This would indicate that DSQ questions such as *"do you exceed the 70MPH speed limit on motorway journeys"* would have received ratings more towards the 'frequently', or 'often' end of the rating scale. In the present Study participants rate quite highly on this dimension, meaning that they are likely to drive fast, and sometimes in excess of the speed limit.

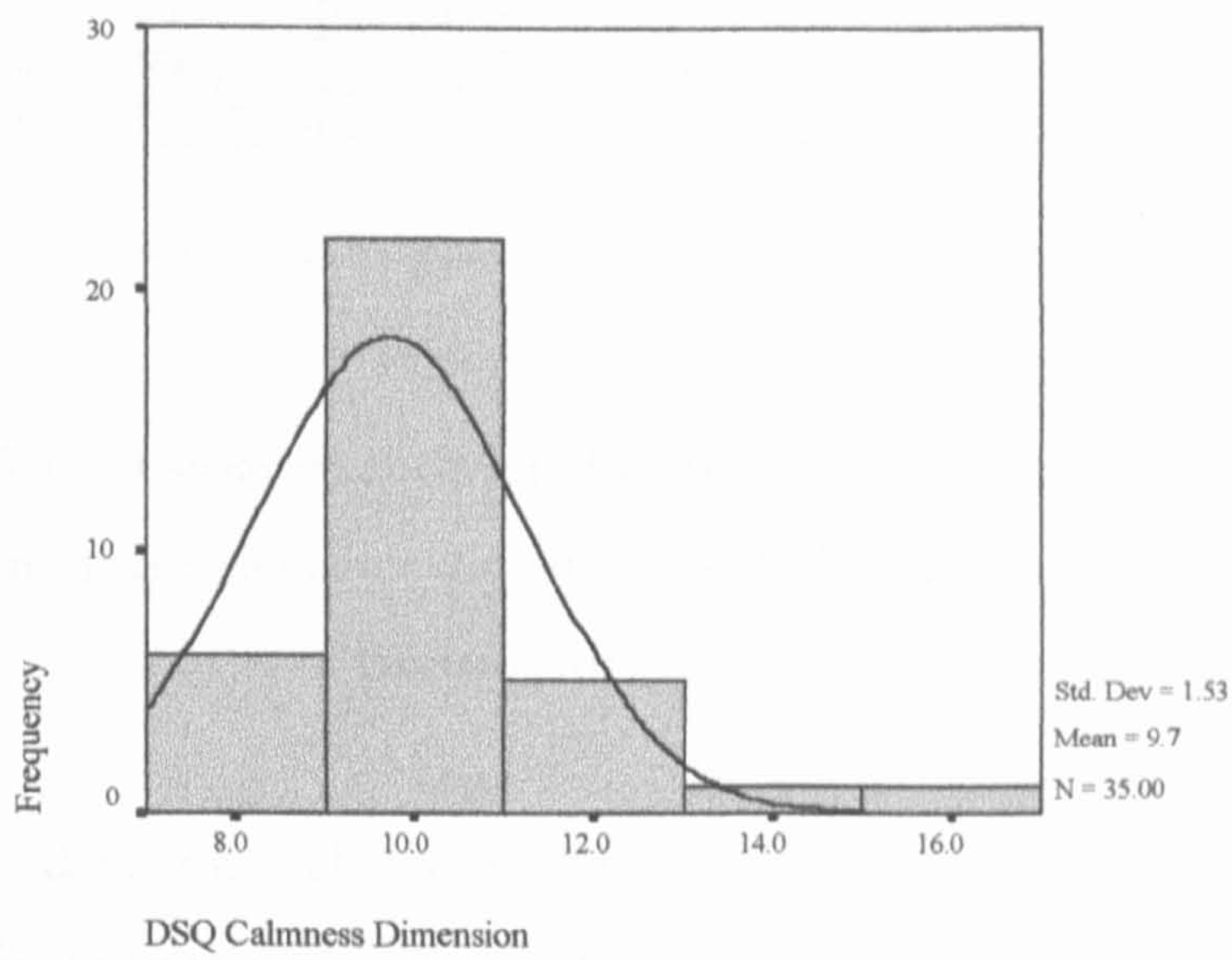


Figure 5.3 - Histogram showing distribution of scores on the driving style questionnaire calmness dimension, with lower scores indicating that participants remain calm when driving.

Conversely, for the calmness dimension the skew is markedly towards lower scores. This indicates that drivers overall tend to remain calm when driving, with DSQ ratings on dimensions such as, *"Do you become flustered when faced with sudden dangers while driving?"*, generally receiving scores at the 'never' or 'infrequently' end of the scale.

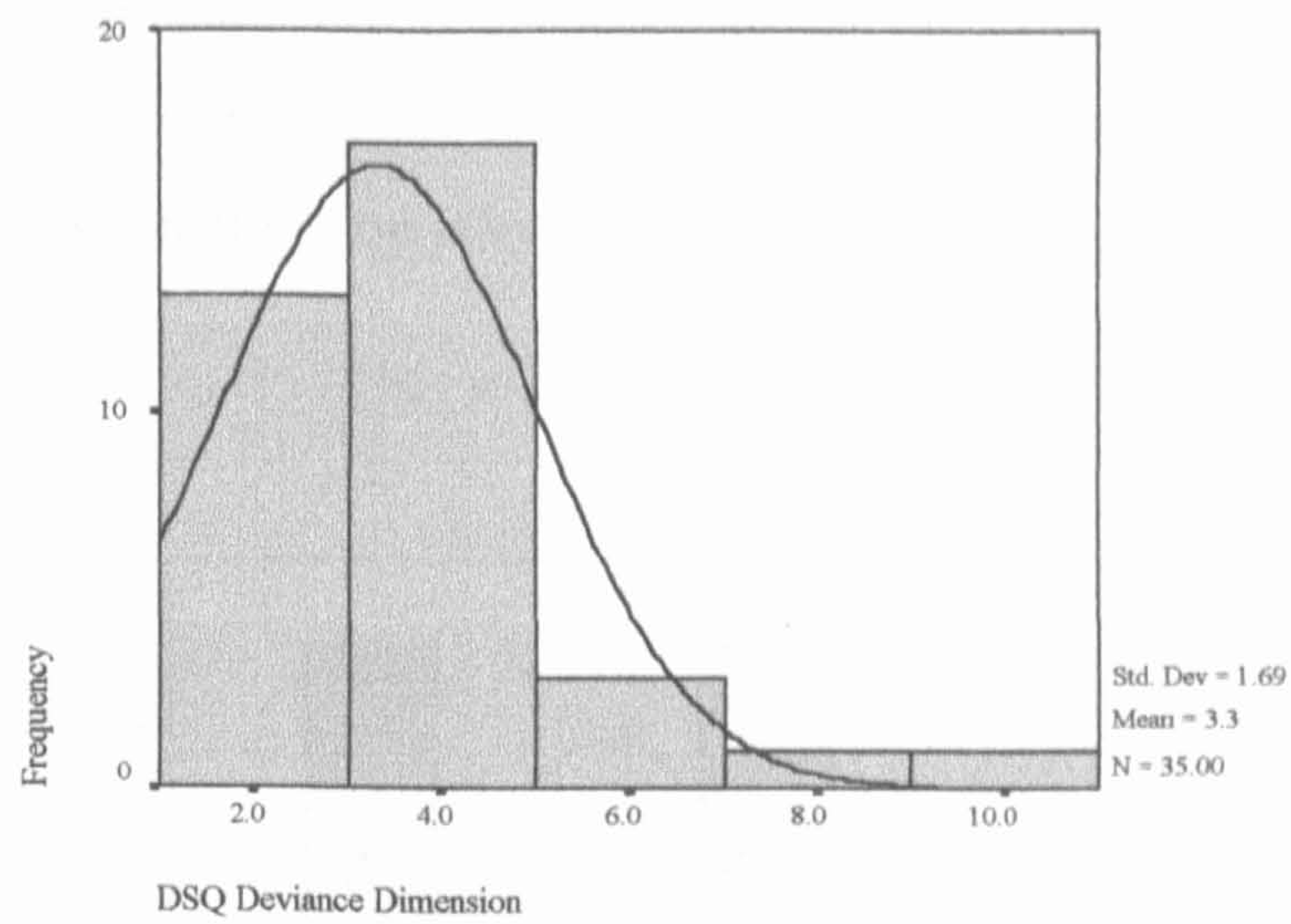


Figure 5.4 - Histogram showing distribution of scores on the driving style questionnaire deviance dimension, with lower scores indicating less deviant driving behaviours.

Once again, the deviance scale shows a bias towards lower scores. This indicates that most drivers adhere to the Highway Code, and do not tend to drive in a particularly anti social manner. It is interesting to note that even lower deviance scores than these were gained in the on-road study, albeit with a much smaller sample size. Overall, the driving style questionnaire provides a useful means of describing the sample of participating drivers in terms of six key dimensions of driving style. As such, it would seem that normal drivers tend to remain calm, and within the ordinances of the Highway Code, but also tend to drive quite fast.

The MDIE locus of control questionnaire measures Locus of Control, or the perceived source of one's behaviour. This perceived source of behaviour is seen as originating either internally within the individual, or externally from outside the individual. This notion is captured within the MDIE dimensions of externality and internality. Across these two dimensions the sample was found via the Shapiro-Wilk test to be normally distributed, with the internality scale positing a mean score of 51.60 (SD=11.18), the externality scale a mean score of 27.57 (SD=6.63). Overall this indicates that drivers are generally disposed towards an internally centred locus of control. This has been implicated in more adaptive behaviours and reductions in accident rates (Montag & Comrey, 1987; Parkes, 1984).

For the driving simulator involvement questions the Shapiro-Wilk statistic posited a significant departure of the scores from normality. Reference to the histogram in figure 5.5 suggests that the distribution is in fact bi-modal.

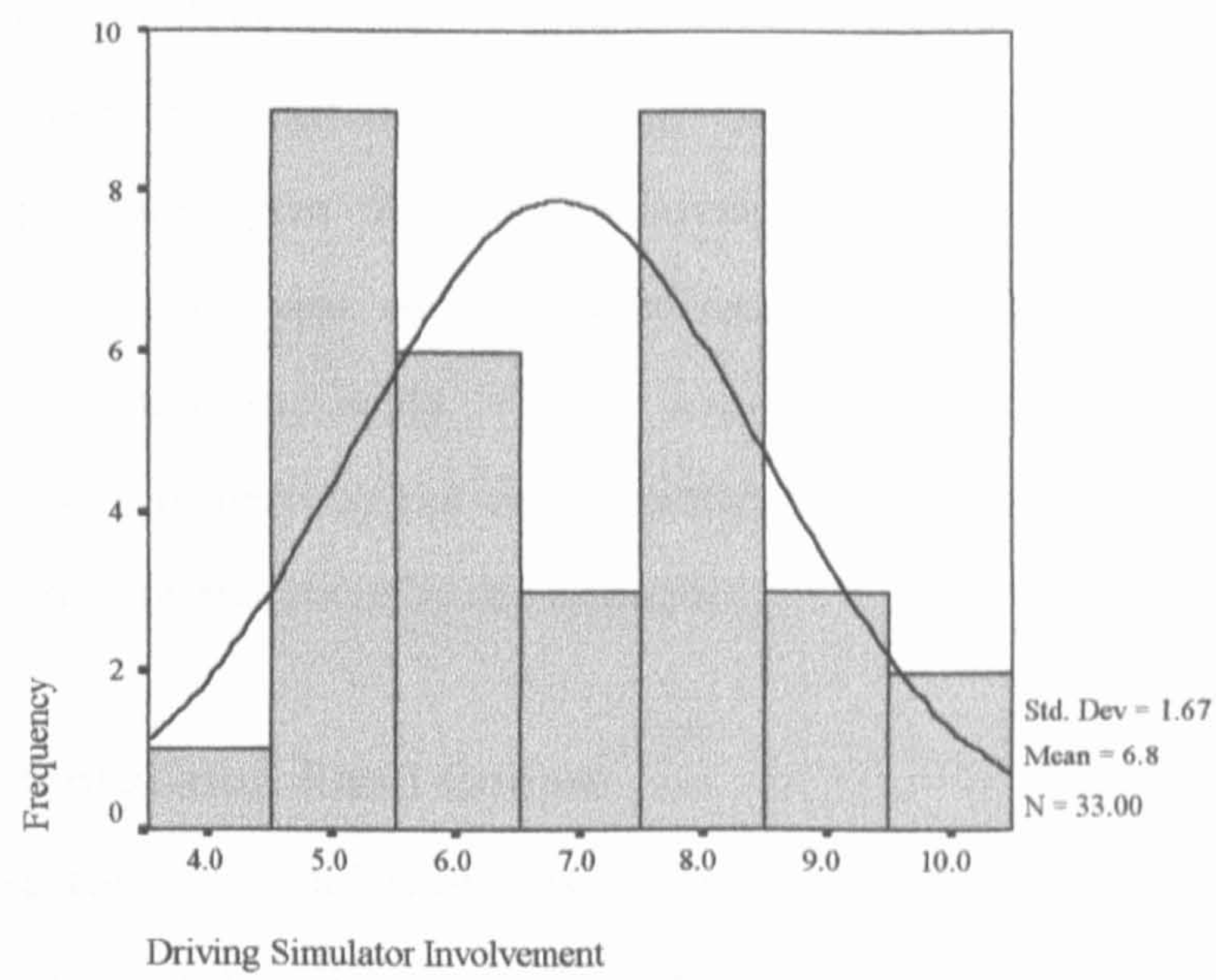


Figure 5.5 - Histogram of driving simulator involvement question scores, with higher scores indicating more involvement.

The maximum attainable value for the involvement questions was 16, indicating that the participant would be totally immersed in the simulation experience. As it happens one modal group falls half way along the scale at a score of eight, the other modal group at five. This indicates that on the whole people are either moderately involved or they are not particularly involved. An exploration of the other between subjects variables (such as gender, or locus of control) in order to discern some form of covariance or association proves inconclusive. Driving simulator involvement therefore shows an interesting dichotomy, and is a useful check on the perceived fidelity of the simulator. At this stage it seems to be occurring independently of other factors. Functional relationships are maintained in the simulator along with commendably high fidelity. It can be regarded, therefore, that a certain degree of reassurance exists that at least some of the participants are finding the simulation to be adequate – it could be much worse.

5.2.3 Materials and Methodology

5.2.3.1 Driving Simulator

The Brunel University Driving Simulator is based on a Series One Ford Mondeo, and is fixed base. A high resolution image is projected onto a screen in front of the car, and the driver interacts with the controls as normal. A simulation computer manipulates the visual scene dependant upon the driver's control inputs. The simulation, aside from visual feedback also provides auditory feedback, tactile steering force feedback, and tactile feedback through the seats. These sources of feedback can be independently switched on or off remotely by the experimenter. Chapter Four deals in greater depth with the design and construction of the simulator.

5.2.3.2 Simulation Road Course

The road course for the simulation was designed to offer a balanced mix of different road types and conditions, all presented in high resolution. An example road scene is shown below in figure 5.7.

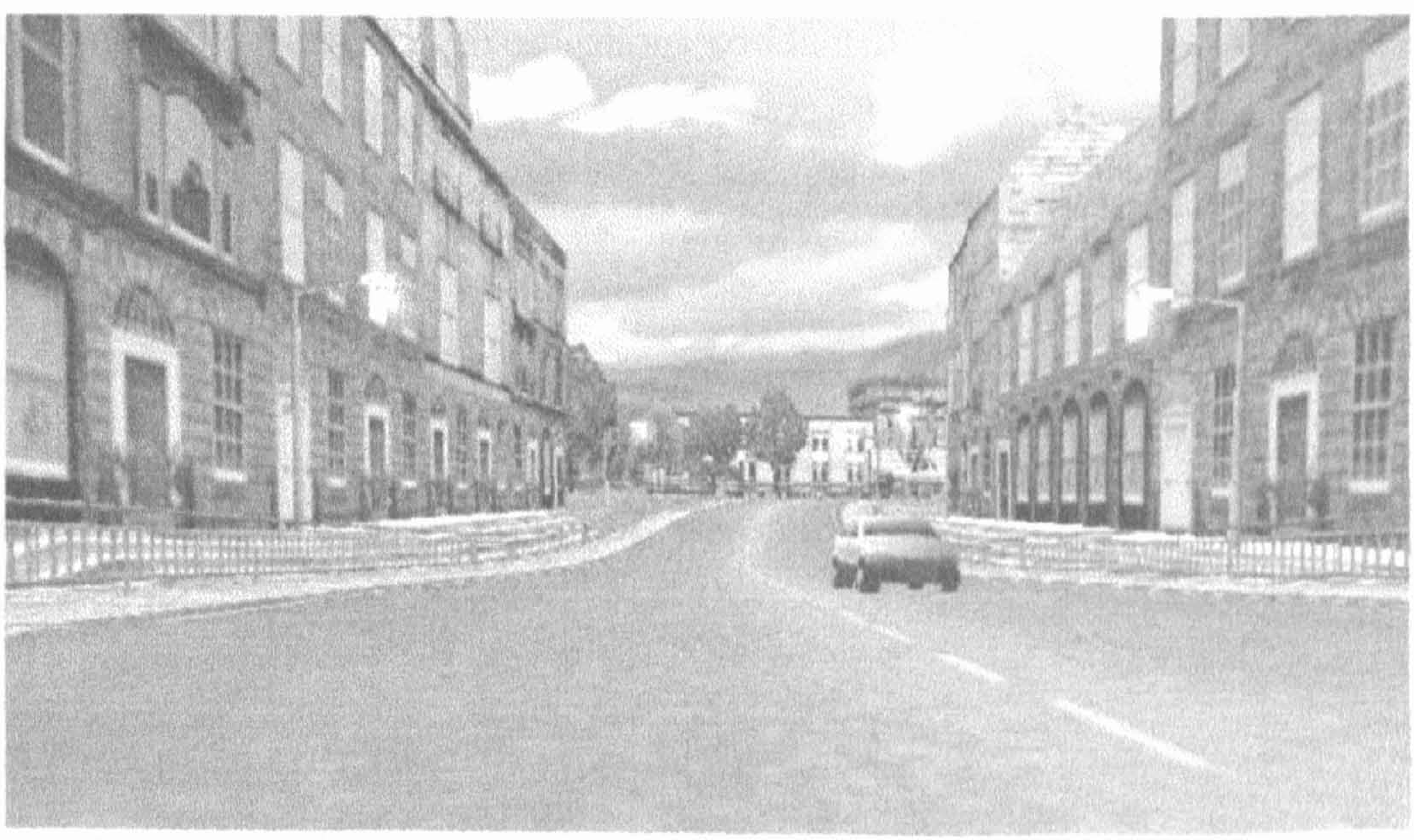


Figure 5.6 - Typical road scene within the simulation.

The experimental virtual road course is 24 miles long and features country roads, suburban roads, inner city roads, and dual carriageways in town and open country. The road surface is predominantly tarmac, although short sections featured cobble stones and other surfaces. There are five tunnels, one railway level crossing, and no less than 36 definable junctions. The driver had right of way/priority for the duration of the run, and there was no other traffic. However, it does rain at a predetermined point for a distance of one mile, and there was snow on the road for three miles. For the remainder of the course the conditions were clear and dry.

The experiments required that there were 36 pause points along this 24 mile route. Roadside features were pre-defined and used by the experimenter to pause the simulation at the correct set point. These features were not overt, and the driver was at no time primed with knowledge of when the simulation was to pause. The pre-defined simulation pause points are presented in full in Appendix G. When travelling at 70mph, the pauses occurred at a mean of 36 seconds apart, the minimum pause interval being just nine seconds, the maximum being one minute 30 seconds. An informal heuristic offered by Endsley and Garland (2000) suggests a minimum interval period of one minute between pauses, this figure is derived from research in the domain of aviation. It was discovered through pilot investigations conducted for the purposes of this research (in the domain of road transport) that, for the most part, a minimum pause interval of at least 20 seconds should be sought, and this was achieved in virtually all cases.

5.2.3.3 Vehicle Feedback Experimental Conditions

These feedback facilities enabled a combination of vehicle feedback modalities to be presented. Eight feedback conditions were presented to drivers, and these were comprised of the following:

(1 Feedback Modality)

Condition 1	Visual feedback only (**Baseline**)

(2 Feedback Modalities)

Condition 2	Visual + Auditory
Condition 3	Visual + Steering Force Feedback
Condition 4	Visual + Under-seat Resonators

(3 Feedback Modalities)

Condition 5	Visual + Auditory + Steering Force Feedback
Condition 6	Visual + Auditory + Under-seat Resonators
Condition 7	Visual + Steering Force Feedback + Under-seat Resonators

(4 Feedback Modalities)

Condition 8	Visual + Auditory + Steering Force F/B + Under-seat Res.

5.2.3.4 Probe Items for Situational Awareness Subjective States

The first of the two simulator based studies relies on probing driver's situational awareness during these pauses in the simulation. To this end, a pool of probe questions were developed. Development of the probe items, or probe questions, relied on the Hierarchical Task Analysis of Driving reported in Chapter Two. The HTAoD offers five categories of driving task enactment. These are Core Driving Tasks, Basic Driving Tasks, Specific Driving Tasks, General Driving Tasks, and Global Driving Tasks. The HTAoD tool was employed to systematically and exhaustively elicit the situational awareness requirements of each driving task category. This analysis proceeded at the HTA 'Sub-Goal' level, and not at the level of individual tasks and operations. Endsley and Garland (2000) argue that goals, as distinct from tasks, provide the proper basis for decision making. Other advantages are that the derived situational awareness requirements are taken out of a detailed context applicable to only a narrow domain, or even a specific vehicle, and that they do not favour any particular feedback modality. This process yielded a comprehensive pool of SA requirements, some overlapping, and some outside of the purview of the intended driving simulation.

Relevant SA requirements, totalling 47 in number, were assembled and worded into probe items. This rewording relied upon the earlier on-road study presented in Chapter Three. This previous study involved normal drivers providing a concurrent verbal protocol as they drove on public roads. The language and semantics used by normal drivers were referenced so that the probe items remained relevant and meaningful. Due to the fact that the probe items are designed to elicit a response along a scale ranging from 'Yes! the statement is undoubtedly true', through to 'No! the statement is definitely untrue' the probes share some similarities to an attitude statement. As such, Oppenheim's (2001) guidelines were followed in order that the statements would succeed in eliciting a definite response, rather than encouraging mid point or 'unsure either way' responses. Therefore, once the SA requirements had formed the basis for the probe item, care had to be taken to derive a probe question that essentially asked whether this SA requirement had been met; in terms meaningful to everyday drivers. An example of this process is shown below.

Example Situational Awareness requirement at Sub Goal 3.1 'Directional Control'
Driver needs to know how fast this corner could be negotiated
Related Verbal Protocol Commentary Supplied by Normal Driver on Public Road

"Sign up there telling me the road's bearing round to the right..."
"...can't really see round it very well..."
"Ok, driving on through..."
"...could've gone a bit faster I think..."

Having established the SA needs for that particular task step, and received a measure of the language used by normal drivers, this is then employed to derive an effective attitude statement as follows, for example:

Revised Probe Item for Driving Simulation
I could've taken that corner a fair bit faster

This process allowed situational awareness requirements to be not only systematically and exhaustively gathered, but to be couched firmly within terms of reference that are easily understood and meaningful to normal drivers, and furthermore, will elicit a definite response along the confidence rating scale. Hence the fairly casual and colloquial language employed in the probe items provided to participants, and the definite assertions that they seem to make. For the sake of illustration, other probe items included the following; *This is a smooth well surfaced road; my speed was 70MPH or very close; there's some kind of warning sign on the right; the car's engine really pulls well/is responsive.* It can be gathered that the probes are wide ranging, and are not biased towards any particular feedback modality.

To further verify this process, the finalised probe item pool was categorised into the three levels of SA, these being perception, comprehension, and projection (Endsley, 1988). An independent rater performed the same categorisation, and an index of shared meaning and reliability was established through Pearsons correlation. This produced a reassuringly high measure of association, $r=0.78$, that was statistically significant ($p<0.01$, $n=47$); thus indicating that the probe items are reliably measuring situational awareness at the defined levels of SA. All three levels of SA were represented in approximately equal proportions within the probe item pool, and, furthermore, they did not favour any particular feedback modality. To emphasise again, this was easily achieved as the probes were derived from HTAoD Sub-Goals. Therefore they were not at a sufficiently microscopic level to probe *specific* sensory stimuli; rather they were couched at the level of what situations or events were present or absent. This decision typically resting on a *range* of sensory inputs.

5.2.3.5 Objective States for the Situational Awareness Probe Items

Having developed the SA probe items, items that measure the driver's *subjective* inner experiences during the simulation, an *objective* frame of reference for the probes then had to be established. At any given pause in the simulation the objective, real, and measurable state of the world was known as it referred to the probe items. For example, *"I could've taken that corner a fair bit faster"* could be true for pause number three (where the corner could be safely negotiated at 100mph), but untrue for pause number 30 (where the vehicle was in actual fact on or near its limits). The underlying logic is that a comparison of *subjective* confidence ratings compared to *objective* criteria provides the basis of a measure of sensitivity (Endsley, 1988). In other words high sensitivity would imply that drivers subjective ratings were in accordance with the true objective state of the world, and vice versa. Changes in this sensitivity according to the type of feedback presented to the participants is one of the central questions.

In order for the assumptions, or the objective reality underlying the subjective probe items to hold true, the driver had to drive over the course at 70mph and on the left hand side of the centre line. The objective assumptions were fairly robust, and provided that the driver enacted these instructions then their responses on the probe items could be accurately compared with the objective state of the world.

5.2.3.6 Mental Workload Scales

As well as the situational awareness probe items, 36 mental workload questionnaires were included in the experiment, one for each simulation pause. These were the NASA TLX (Hart & Staveland, 1988), and as well as answering the SA probe items during each pause participants were required to fill out this as well (Appendix H).

The NASA TLX scales are comprised of six sub-scales. All of the scales ranged from one to 20 and were as follows: Mental Demand, Physical Demand, Temporal Demand, Effort, Performance, and Frustration. These scales ask the participant about their behaviour, the current dynamics, and psychological impact of the task. The scales were originally derived from 16 experiments and have been shown to provide a sensitive estimate of workload (Hart & Staveland, 1988). Each sub scale can be analysed separately, or an Overall MWL score can be obtained by averaging the scores across all the sub-scales.

5.2.3.7 Response Booklet

Each participant was provided with a comprehensive response booklet (a full copy of which appears in Appendix H). This was comprised of a consent form, a demographics information form, the Driving Style Questionnaire (DSQ) (West, et. al., 1992) and the locus of control MDIE questionnaire (Montag & Comrey, 1987). There followed explicit written instructions as to what was required of the participant during the experiment, including details on how to fill out the rating scales. There were five sheets of rating scales and TLX questionnaires for the practice simulation, and 36 rating scales/TLX questionnaires, suitably numbered, provided for the experimental phase.

The rating scale is seven points ranging from yes, the statement definitely represents the true state of the world just prior to the pause, ranging through unsure either way, right up to no, that is definitely not a true representation of the state of the world prior to the pause (figure 5.8). To be explicit, the participant was instructed to use the scale to indicate 'how true do you think the statement is'. For example, a score of one would imply that the driver thinks the statement 'I could've taken that corner a fair bit faster' is definitely true, and that they could have indeed gone faster around that particular corner.

x. I could've taken that corner a fair bit faster.

YES!			NOT SURE			NO!
1	2	3	4	5	6	7

Figure 5.7 - Example of probe item confidence rating scale.

There are seven of these scales provided for every one of the 36 pauses. Probe items one to five of any given pause relate *directly* towards categories one to five of the HTAoD. Items six and seven are situation specific probes, not systematically related to the HTAoD, but nonetheless measuring situational awareness in the same way. This is an important point that needs to be emphasised again; probes one to five (out of seven) are related directly to categories one to five of the HTAoD, probes six and seven are situation specific probes of a random nature.

Theoretically speaking this scale is a 'confidence rating scale' and offers three decision criteria for any subsequent analysis. If a conservative response criteria is adopted then only a 'definitely' response (i.e. a one or seven along the scale) is accepted as representing a correct response. If a medium response criterion is adopted then any response equal to or greater than 'quite sure' (i.e. two or six) is accepted as a correct response. As such, a risky response criterion is when any response is greater than the 'might be' response (i.e. three or five) is accepted. An 'unsure either way' response is not included in the analysis.

The probe questions were randomly selected for each of the 36 pause points (from the probe pool that was applicable to each of the seven scales respectively). The response booklets were, however, identical for each participant. Figure 5.9 illustrates this approach for extra clarity.

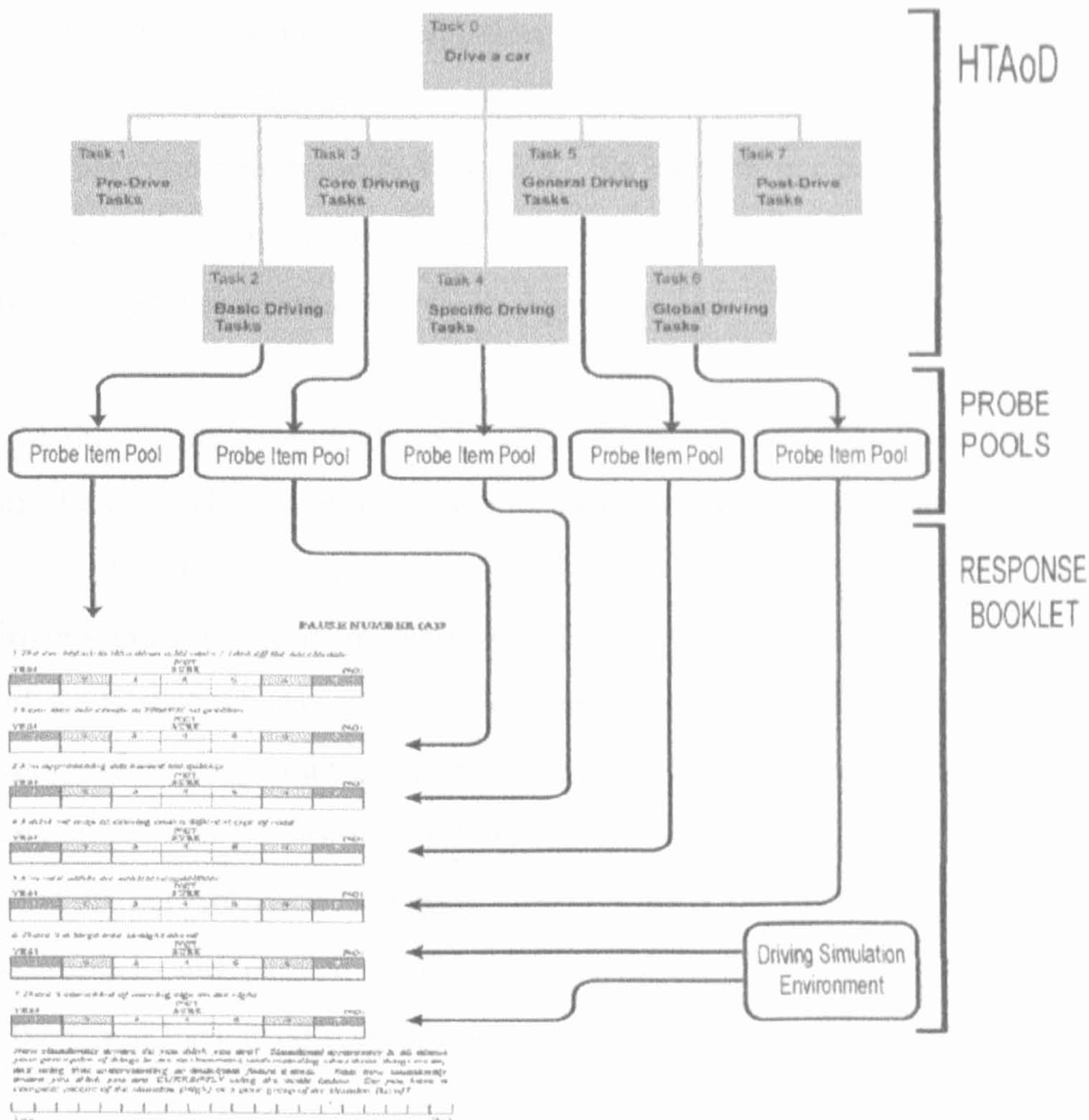


Figure 5.8 - Response booklet probe items one to five derived from HTAoD, items six and seven directly from the simulation environment.

At the bottom of each page was a further 20 point scale for drivers to indicate the perceived strength of their own situational awareness, this scale is shown in figure 5.10. below with its accompanying instructions. This scale was drawn from the Situational Awareness Rating Technique (SART) scale (Taylor, et. al., 1993).

How situationaly aware do you think you are? Situational awareness is all about your perception of things in the environment, understanding what those things mean, and using that understanding to anticipate future events. Rate how situationaly aware you think you are CURRENTLY *using the scale below. Do you have a complete picture of the situation (High) or a poor grasp of the situation (Low)?*

Low **High**

Figure 5.9 - Self perceived situational awareness scale.

In summary, for each pause in the simulation the response booklet provided one sheet with the seven situational awareness probe items, and one self perception of SA rating scale, and one sheet containing the NASA TLX. Two sheets per pause. The bulk of the response booklet was comprised of these two questionnaires per simulation pause, and they appeared to the participant as shown in Appendix H.

Experience in the simulator with these booklets demonstrated that participants quickly engaged with the probed recall paradigm, and took only around one minute to complete all of the scales for a given pause point. This bodes extremely well for accurately assessing driver's current SA from memory. Endsley (1995b) reports on this issue of memory and finds that SA can actually be assessed for up to six minutes following a pause. Passing reference should be made to implicit memory, that is, driver's might be using memory stores that are not available for conscious inspection, but, nonetheless still exert an effect on performance. Gugerty (1997) reports on this issue with evidence to suggest that implicit and explicit memory stores (if they exist at all) access the same knowledge base, and have no discernable *separate* effect in terms of reporting upon SA.

The response booklet ended with four questions enquiring into driving simulator involvement; these questions drawn from the virtual reality presence/involvement questionnaire of Witmer & Singer (1998). These scales were provided to assess how realistic participants found the simulation, and represents a useful check on simulator fidelity. Finally, space was provided for the participant to note any comments that they might wish to make about their performance, their experiences of the drive, the adequacy of the driving simulation, etc.

5.2.4 Procedure

5.2.4.1 Equipment Checks

The very first step was to ensure at the outset of every trial that the simulator was correctly calibrated, and that the controls and feedback actuators were functioning correctly. Every participant had a unique randomised combination of feedback conditions pertaining to each of the 36 probe pause points, and this was also double checked.

5.2.4.2 Health and Safety Information

The participant was then introduced to the driving lab. This involved explaining basic Health and Safety information, and some basic instructions for the simulator (which were also provided on a card within the simulator vehicle). A consent form to be signed by the participant explained their ethical rights as an experimental participant. These were also emphasised by the experimenter. Particular reference was made to 'simulator sickness', and participants were warned of early symptoms and shown to the provided sick bag should it become necessary; fortunately the attrition rate due to simulator sickness was extremely low.

5.2.4.3 Pre-Drive Questionnaires

The participant then completed a straightforward demographics information sheet and the MDIE Locus of Control questionnaire.

5.2.4.4 Experimental Briefing

The participating drivers had comprehensive written instructions provided to them as to what was going to be happening during the experimental phase, and these were backed up by the experimenter. It was explained that the simulation would pause (with the screens going blank) and that this was the cue to complete the probe item scales *and* the NASA TLX questionnaire. Drivers were advised that their initial response was the best one and to complete the scales as quickly as they could.

The experimenter also explained the various features provided within the simulation (the speedometer, rev counter, gear indicator, intercom etc) and useful hints and tips for remaining at 70mph were offered. At every stage the need to remain as close to 70mph and on the left hand side of the road was emphasised. On the other hand, the participant was also informed that apart from these specific instructions that they should relax, drive normally, and enjoy the experience. Questions from the participant were dealt with at this stage.

5.2.4.5 Practice Drive

An easy six mile practice route was provided and drivers were required to drive over this to warm up prior to the experimental phase. In the initial phases they were encouraged to be uninhibited and to drive as fast as they liked. After the first of five practise pauses (and five groups of practise probe item/MWL scales) drivers were encouraged to stick as closely as possible to 70mph and to drive on the left hand side of the road. With a little practice all of the drivers could do this quite tolerably and with relative ease.

5.2.4.6 Experimental Phase

After dealing with any remaining questions, the experimental drive commenced. This followed the procedure presented in the flow chart below (figure 5.11).

5.2.4.7 Post-Run Questionnaires

After the final pause in the simulation, the driver was asked to complete a final virtual reality involvement questionnaire. Space was also provided for the driver to make any comments they felt pertinent.

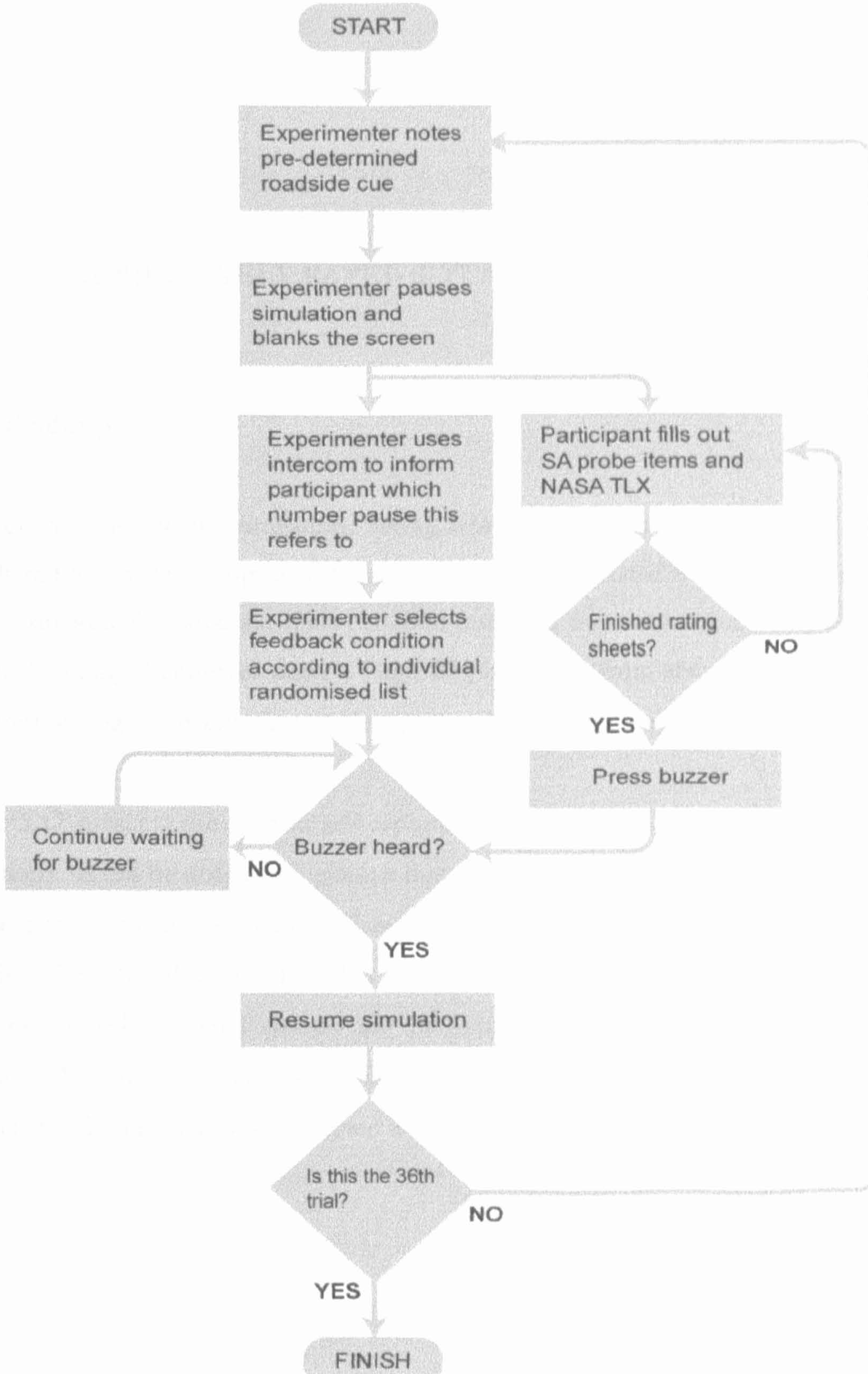


Figure 5.10 - Experimental procedure flow chart.

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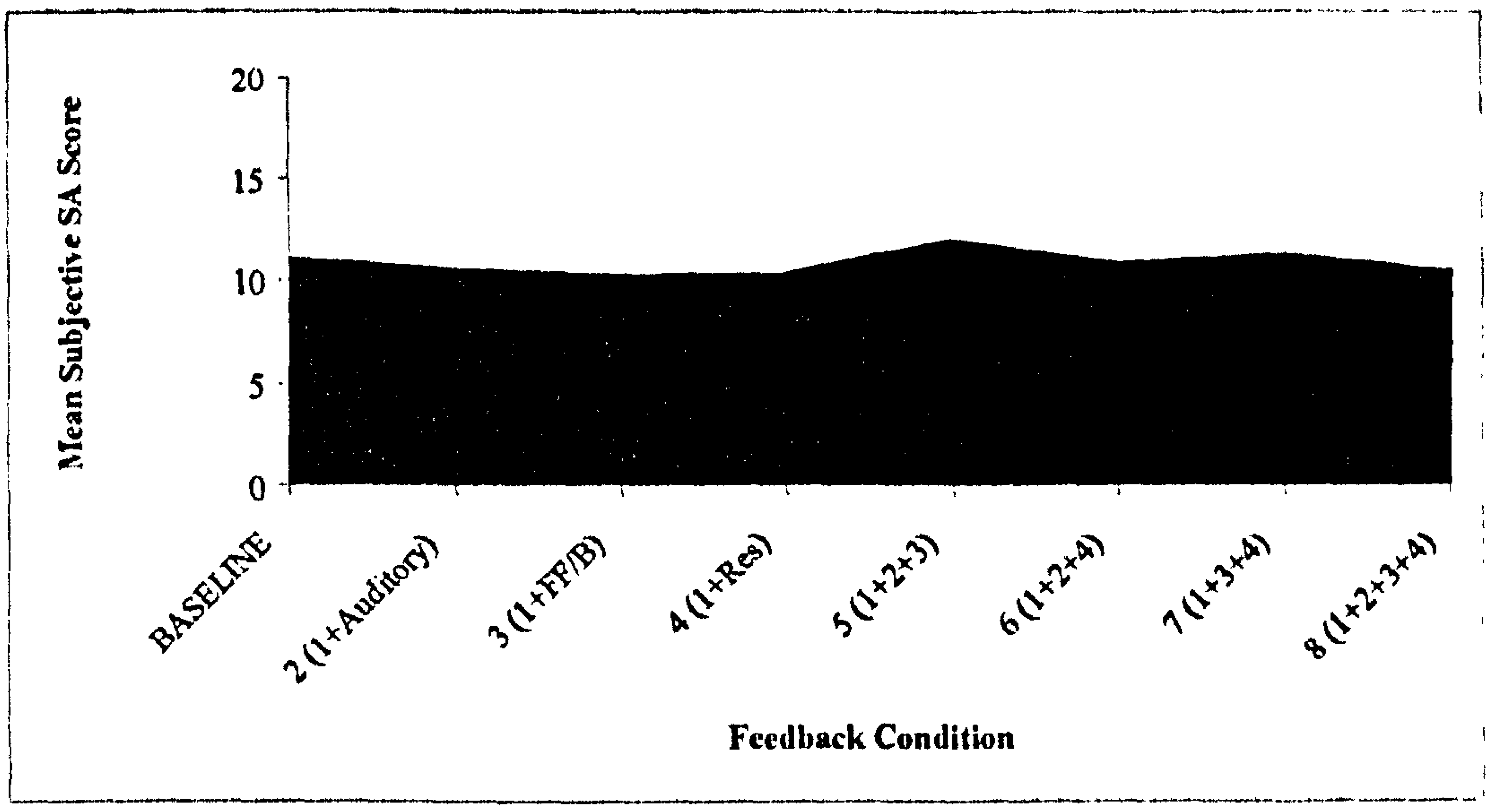
5.3 RESULTS PART I
SUBJECTIVELY RATED SITUATIONAL AWARENESS

5.3.1 Findings

After every pause in the simulation, during which the feedback status of the simulator was altered (or made to appear to be altered), participants rated their own self perceived level of situational awareness. This occurred just once for every simulation pause. They did this by rating themselves along a single 20 point scale from zero (a poor grasp of the situation) through to twenty (a complete picture of the situation).

Figure 5.12 presents the median self reported SA score for each of the eight feedback conditions. It can be noted with interest that all of the scores hover around the midpoint of the scale (around 10 points), demonstrating neither strong or weak overall self perceived SA. It will be recalled that during the on-road study absolute values on the same rating scale hovered around the 15 point, or three quarter mark. The lower absolute SA seen here could well reflect the nature of the simulation environment, and the fact that driver SA was being tested in a more overt and demanding manner.



BASELINE	2 (1+Auditory)	3 (1+FF/B)	4 (1+Res)	5 (1+2+3)	6 (1+2+4)	7 (1+3+4)	8 (1+2+3+4)
11	10.5	10.2	10.3	12	10.8	11.3	10.4

Figure 5.11 - Median self report situational awareness scores for each feedback condition.

Between subjects variability yielded a large quantity of outliers precluding the efficient use of an ANOVA for which this data would ordinarily lend itself. The Friedman test was performed instead. Under which, no significant differences were detected in self perceived SA ratings according to the feedback condition presented (Chi-square=8.59; df=7; p=ns). This implies that self perceived SA is not dependent upon the feedback status of the simulator, and concurs exactly with those findings presented earlier in the on-road studies (Chapter Three).

5.3.2 Power Analysis

5.3.2.1 Introduction

Power analysis reflects the ability of a methodological and statistical procedure to reliably detect the occurrence of some phenomena under examination should that phenomena actually exist. The key parameters are effect size, power, and sample size (Kraemer & Thiemann, 1987). For example, a very large sample size would be required to detect a small effect size with a high degree of confidence, or power. Conversely, only a relatively small sample size would be required to detect a large effect, with reasonably low power.

5.3.2.2 Proving the Null Hypothesis

Caution must be exercised in interpreting the results of subjectively rated SA. In theoretical terms it is not easily possible to suggest that the null hypothesis that has just been 'proven' here is exactly zero. Rather, it is suggested that the null hypothesis, and any effect size thereof is not zero, but is so small as to be *meaningless* as well as not statistically significant (Cohen, 1988; 1990). This argument can be formalised with reference to power analysis. Power analysis offers a means of defining the limits of detectibility for this experimental scenario, and within what limits the results become meaningful in a practical or applied way. In terms of theoretical considerations the effect size *should* be zero, because drivers cannot be aware of SA that they are not receiving (Endsley, 1995b;1988), although in the present Study drivers are subjected *interchangeably* to different feedback conditions, so in actual fact could be potentially more likely to have increased self awareness. Even if there *is* some very small effect, it has to be argued whether it is *too* small; rendering it meaningless in real world design terms.

The cornerstone of power analysis is to estimate the anticipated effect size. Effect size is *"the degree to which the phenomenon is present in the population"* (Cohen, 1988, p. 9). Is the experimental effect likely to be a barely detectable nuance at the limits of detectibility (a small effect), or is it a phenomena that is obvious for all to see (a large effect)? In recognition of the difficulty in calculating effect sizes for some procedures, Cohen (1988; 1992) offers a scale free and continuous effect size index. From this index certain effect size conventions, or guidelines, are derived for small, medium, and large effects. In this case the interest is to see how powerful the test is in order to detect large or medium effect sizes, effect sizes that would be quite apparent to the observer. Both of these levels can be argued as being rather more meaningful in practical terms. Using GPOWER, a power analysis computer program (Faul & Erdfelder, 1992), 181 participants would be required in order to be able to detect with an 80% probability *small effect sizes*, across eight feedback conditions. It is argued here that this is totally inefficient of time and resources because even if a small effect was detected, what does it mean? Does it mean a change of 0.25 points along the SA rating scale? If so, does a change of 0.25 points along the scale significantly reflect upon driving safety, efficiency, or enjoyment? It is unlikely to do so.

As it stands the current experiment, with N=35, is able to detect medium effect sizes with 80% power (using the GPOWER program). The disadvantage in using a scale free index of effect size (Cohen, 1988) now becomes apparent. This is because the absolute values of medium or large effect sizes, or even the *difference* between medium and large effect sizes as they refer to the subjective SA scale are unknown. However, estimates can be made with reference to the data. Here it can be noted that the highest median score occurred in condition five, and was 12. The lowest score was 10.2 and occurred in condition three. The difference between these minimum and maximum values is a difference along the 20 point scale of 1.8. Therefore, given that the procedure was powerful enough to detect medium (or larger) effects with an 80% probability, and that *none were found*, it follows that differences of a magnitude *greater than* 1.8 would be required for a medium effect to be detected. If such differences were detected, they would represent changes of a magnitude of 10% or more along the subjective SA scale. It would still have to be argued how these very small changes directly relate to driver performance.

In summary, no systematic or significant differences were detected for self reported SA according to feedback condition. With due regard for issues of statistical power and the null hypothesis it can be concluded that overall self awareness of SA, and more concerningly, any shortfall in perceived SA is poor. These findings accord precisely with those found in the on-road studies (Chapter Three).

• • •

5.4 RESULTS PART II
OBJECTIVE SITUATIONAL AWARENESS

5.4.1 Background

Part II of the results analyses the effects of sensitivity towards the SA related stimuli, using the confidence rating scales, dependent upon the eight vehicle feedback conditions. A measure of sensitivity is gained by comparing the subjective rating scales with the known objective state of the world, and transforming them into a measure of sensitivity using the psychophysical technique of Signal Detection Theory (SDT). The origins of SDT are in the detection (by human listeners) of auditory stimuli (the *target* or *signal*) in amongst a background of random white *noise* (Green & Swets, 1966). In the present experiment, the baseline feedback condition (visual stimuli only) is regarded conceptually as the 'noise' trial. The other feedback conditions are all superimposed over the top of the visual baseline condition and represent seven further and distinct signal trials.

The feedback conditions were allocated randomly for each participant. Table 5.1 below shows the total number of signal and noise trials presented within two levels of analysis. Firstly the number of trials pertaining to *individual probe* items, of which there were seven per pause, five of these being related *individually* to each of the HTAoD categories. Secondly, if the *sum* of the trials across the seven constituent probe items per pause are taken, this represents *overall probes* in table 5.1 below, for N=35.

Table 5.1 - Number of signal and noise trials per feedback condition in the overall and individual HTAoD category analysis of d' (N=35).

	No. of Trials		
Feedback Condition	**Individual Probes**	**Overall Probes**	**Type**
Visual 1	**140**	**980**	**NOISE**
Vis + Aud **2**	154	1078	Signal
Vis + FF/B **3**	136	952	Signal
Vis + Res **4**	157	1099	Signal
Vis + FF/B + Aud **5**	126	882	Signal
Vis + Res + Aud **6**	151	1057	Signal
Vis + Res + FF/B **7**	160	1120	Signal
Vis + Aud + FF/B + Res **8**	140	980	Signal
Total Stimuli Presentations	**1164**	**8148**	**Signal**

The randomisation of feedback conditions for each driver explains the gently varying numbers of trials per feedback condition. Once missing or corrupted data had been omitted from the analysis, this leaves a mean of 233 probe item questions completed by each driver during the simulation.

5.4.2 Data Reduction

The data from the response books consisted of *subjective* ratings of confidence as to the presence or absence of SA related stimuli. Figure 5.13 below shows that the scale runs from one (very confident that the probe item is true) through to seven (very confident that the probe item is untrue). To use the phrase 'stimuli' is to couch the explanation in psychophysical terms, more accurately in the present case is that stimuli referred to the *state of the situation.* This is what the probe items were probing. In other words, particular features of a situation during a pause in the simulation were being probed in a more or less identical manner as you would probe a simple stimuli in an auditory detection experiment.

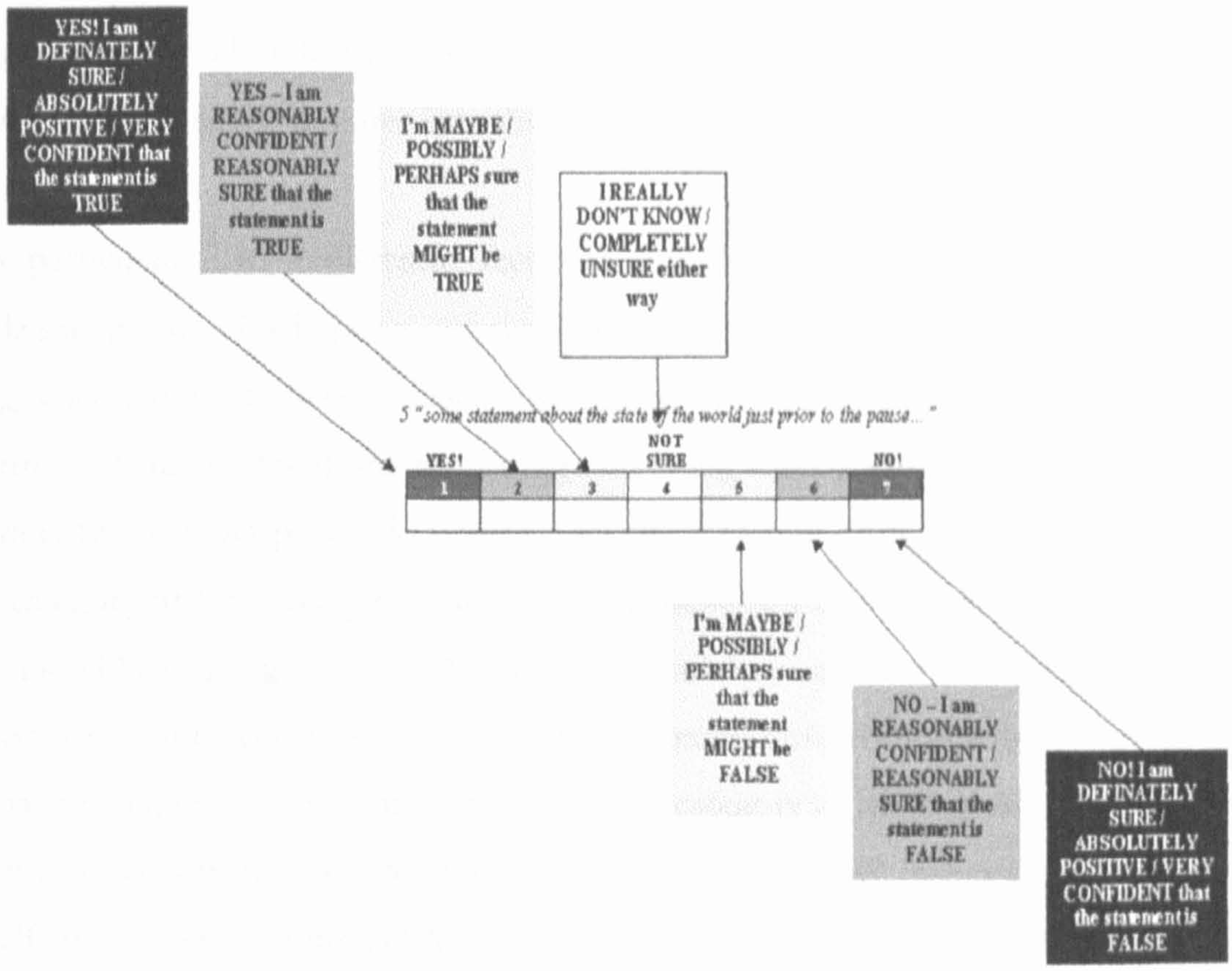


Figure 5.12 - Rating scale scoring.

Compared to the subjective confidence ratings supplied by the participants, the *objective* state of the world, the reference point to be compared, would either be represented in the analysis as a one or a seven (i.e. Yes, stimuli present, or No, stimuli is not present). The driver's subjective confidence rating scores were entered into the analysis directly against the scores pertaining to the objective state of the world. The responses provided by the drivers were then organised into the following taxonomy. If the driver rated confidence that a stimuli *was* present and it was, then this is a Hit (H). If the stimuli was rated with some degree of confidence that it was *not* present, and objectively it was not, then this is a Correct Rejection (CR). A Miss (M) is when confidence is expressed that the stimuli was *not* present and objectively it was, and a False Alarm (FA) is confidence being shown that a stimuli *is* present when in fact it is not. This taxonomy of Hits, Misses, False Alarms, and Correct Rejections (H/M/FA/CR respectively) forms the basis of SDT (Green & Swets, 1966).

Three decision criteria were also defined. A Conservative (Con) criterion would be only to accept *very confident*, i.e. just one or seven scores into the analysis. A Medium (Med) criterion would permit scores of greater than two or six into the analysis, or scores representing greater than *reasonably confident*. The Risky (Risk) criterion would accept any ratings above or below four, thereby the participant would only have to be *maybe/possibly confident* for their rating to enter into the analysis.

Each participant had a different feedback condition randomly presented after every simulation pause. Each pause required seven probe items to be completed using the rating scales, five of these scales being directly related to HTAoD categories of task enactment (Chapter Two), the remaining two being merely situation specific probes. To reiterate, the analysis proceeded on two levels. On one level of analyses the scales for each category of the driving task are analysed *individually* by looking at performance *within* each individual rating scale. The individual analysis permits SA performance to be gauged for each category of driving task enactment, answering the question about what feedback is required to increase SA *within* what category of driving task. In other words, the individual driving task categories represent five *separate* dependent variables. The overall analysis ignored the HTAoD categories and analysed all of the seven rating scales *combined* per pause. This level of analysis in effect *controls* for driving task category, permitting the SA requirements of the total driving task to be gauged.

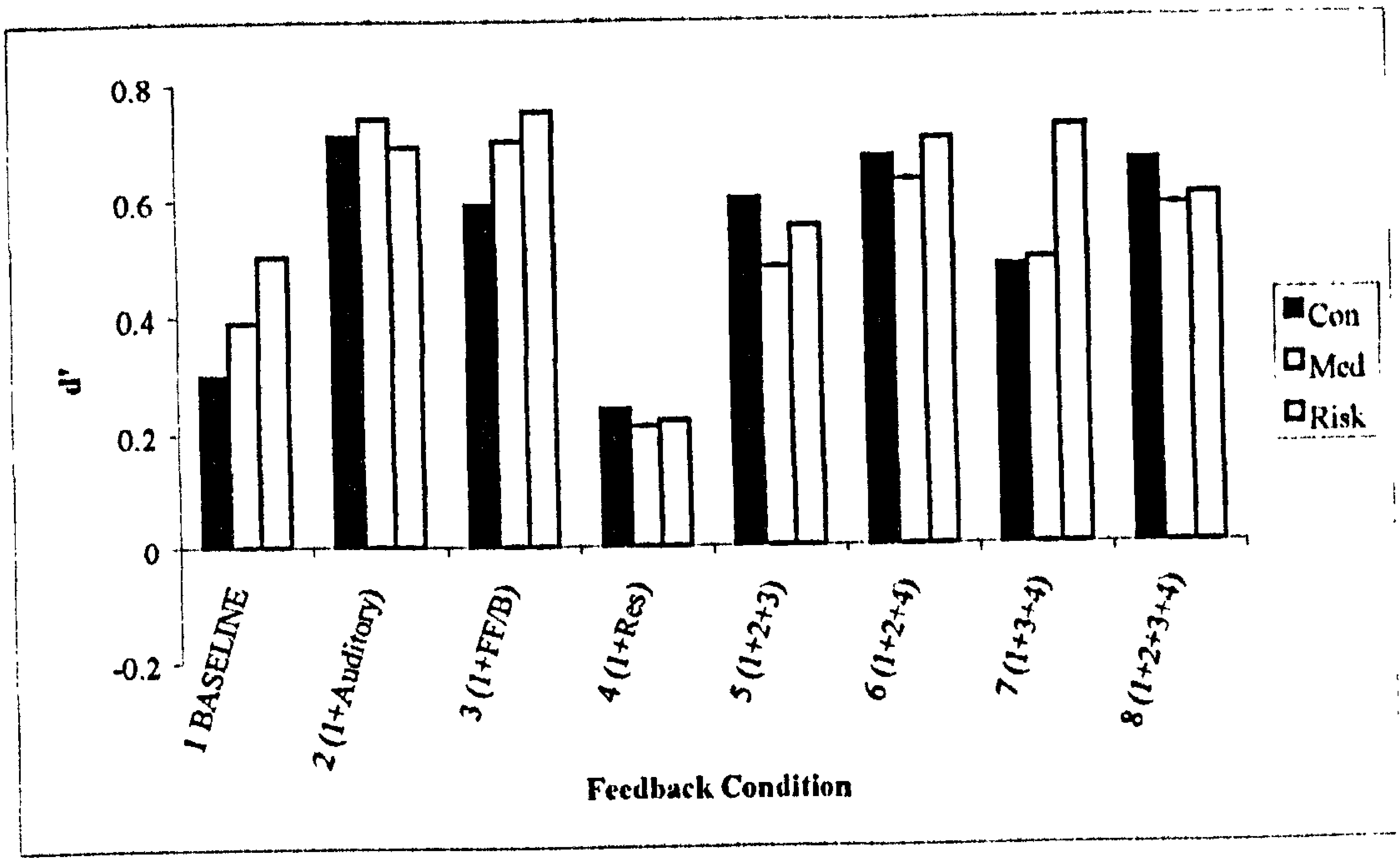
The next phase of the analysis was to sort the data according to feedback condition, and sum the Hit, Miss, False Alarm, and Correct Rejection scores for each condition. Regardless of whether the Hit and False alarm rates were summed for each *individual* HTAoD category of probe item, or grouped together to form an *overall* response for each feedback condition, they were all required to be converted into proportions. For the HTAoD category analysis (taking individual probe items separately), this involved dividing the summed Hit and False Alarm scores by the number of times that feedback condition occurred. For the overall level analysis (adding together all seven probe items within a pause point), this involved dividing the H and FA rates by the number of times the feedback condition occurred, multiplied by seven (because the seven rating scales had been grouped).

5.4.3 Calculation of Sensitivity Measures

The nature of the proportions data meant that there were a number of instances where the value zero was obtained, and a much lesser amount of proportions that assumed the value of one. In subsequent procedures for SDT that rely on the calculation of Z scores, values of zero and one cause infinite values, and significant problems in the derivation of accurate sensitivity measures. A correction factor procedure derived from Snodgrass and Corwin (1988), and MacMillan and Creelman (1991) was therefore applied to the proportions data. The correction factor procedure went as follows. The proportion data had $1/(2N)$ (or a value of 0.01) added to *every* proportion data point. Occasional values of one, or where this blanket procedure had caused values to exceed one, had $1\text{-}1/(2N)$ inserted in their place. Therefore values of one or greater were converted into 0.99. Under this procedure values of infinity were avoided in subsequent Z scores. From the proportion data, now suitably corrected, Z scores were computed. d' is calculated from these Z scores using the following formula:

$$d' = z(H) - z(FA)$$

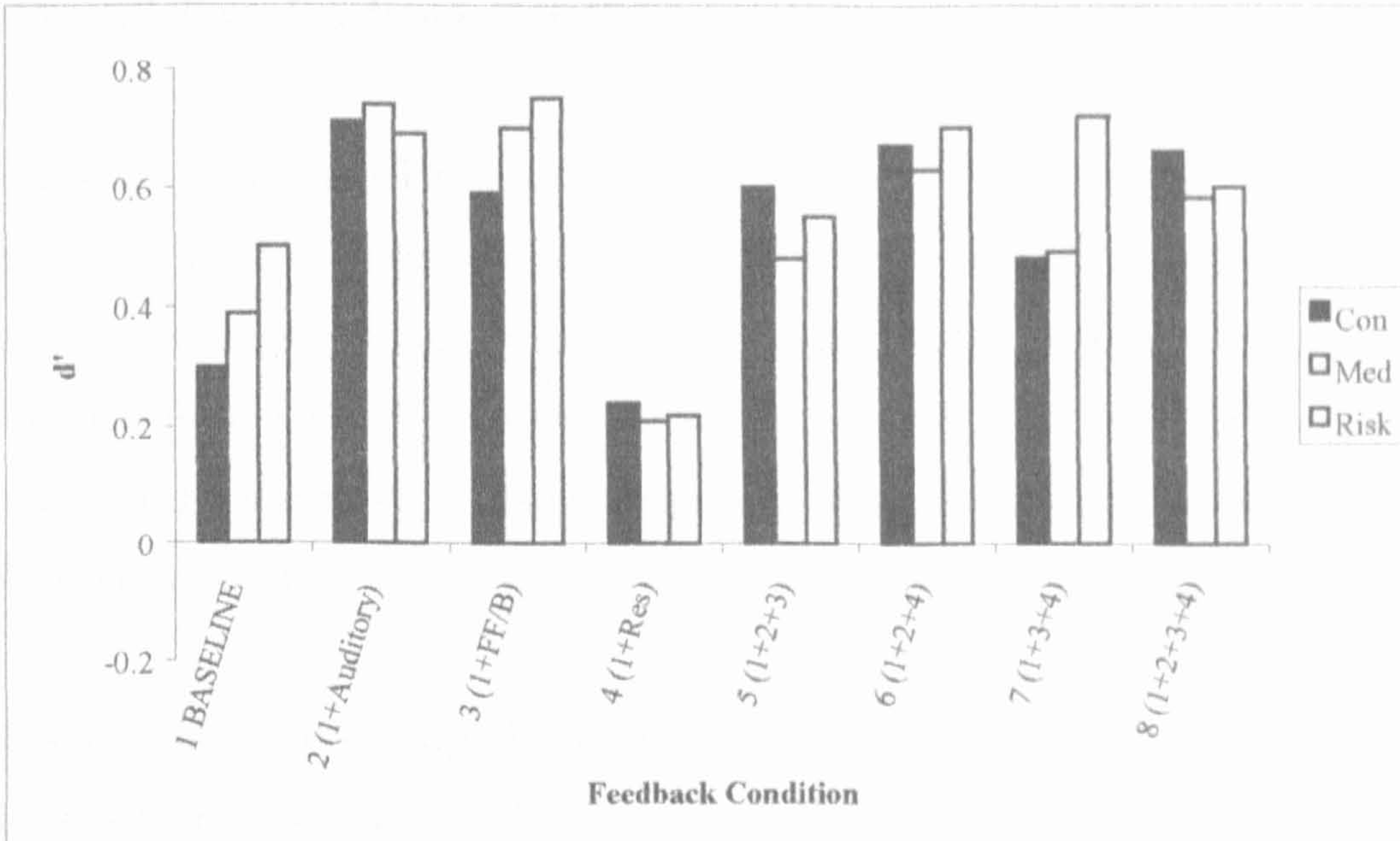
Overall mean d' values are *not* calculated by averaging the d' scores gained for each individual; instead, overall mean d' is gained from the mean sample z(H) and mean sample z(FA), and calculating d' thus (McNicol, 1972). Overall mean d' values are computed in this manner for the Conservative, Medium, and Risky decision criterion points. Evaluation of d' values could then proceed at the two levels of analyses. Firstly, at the overall level, d' was derived simply for each feedback condition *across* the seven probe items. This level of analysis is dealt with next. A more fine grained analyses used d' for every feedback condition *and* every one of the seven categories of probe item. This permitted comparisons of sensitivity contingent upon feedback *and* category of driving task enactment as specified in the HTAoD. This is covered later. The results for overall mean d' versus feedback condition are shown in figure 6.5 below.



	1 BASELINE	2	3	4	5	6	7	8
Con	0.3	0.71	0.59	0.24	0.6	0.67	0.48	0.66
Med	0.39	0.74	0.7	0.21	0.48	0.63	0.49	0.58
Risk	0.5	0.69	0.75	0.22	0.55	0.7	0.72	0.6

Figure 5.13 - Chart and data table showing conservative, medium, and risky criterion d' values versus feedback condition.

By visual inspection of the data alone it does appear that there are some marked changes in d' across the eight feedback conditions. It is also apparent that over and above the baseline of visual feedback; the additional contribution of feedback through other modalities in terms of d' is relatively modest, as anticipated by the fact that visual feedback is likely to specify the largest part of sensitivity. The largest calculated d' values are obtained during conditions of auditory, and steering force feedback. The smallest additional contributions to sensitivity are made by the under-seat resonators. Given that there are no similar studies, let alone similar studies that have employed SDT towards these experimental variables, it is therefore difficult to find a comparison in order to judge whether these changes are large or small; normal or unusual. Future work that employs SDT in this area will of course be readily comparable.



	1 BASELINE	2	3	4	5	6	7	8
Con	0.3	0.71	0.59	0.24	0.6	0.67	0.48	0.66
Med	0.39	0.74	0.7	0.21	0.48	0.63	0.49	0.58
Risk	0.5	0.69	0.75	0.22	0.55	0.7	0.72	0.6

Figure 5.13 - Chart and data table showing conservative, medium, and risky criterion d' values versus feedback condition.

By visual inspection of the data alone it does appear that there are some marked changes in d' across the eight feedback conditions. It is also apparent that over and above the baseline of visual feedback; the additional contribution of feedback through other modalities in terms of d' is relatively modest, as anticipated by the fact that visual feedback is likely to specify the largest part of sensitivity. The largest calculated d' values are obtained during conditions of auditory, and steering force feedback. The smallest additional contributions to sensitivity are made by the under-seat resonators. Given that there are no similar studies, let alone similar studies that have employed SDT towards these experimental variables, it is therefore difficult to find a comparison in order to judge whether these changes are large or small; normal or unusual. Future work that employs SDT in this area will of course be readily comparable.

5.4.4 Overall d' vs. Feedback Condition

5.4.4.1 Statistical Tests on d'

The next step in this analysis is to determine if there are any statistically significant differences between SA sensitivity (d') and vehicle feedback. This data, being continuous and collected from a healthy sample size would normally lend itself well to parametric procedures such as ANOVA. However, there are two main problems with using an ANOVA on this data.

Firstly is the presence of large between subjects variability. Normal practice in these situations is to remove outliers from the analysis (the presence of outliers reduces the probability of detecting a true effect, in other words it increases the likelihood of a type one error). Non-parametric procedures, using ranking, completely avoids this outlier problem, and enables the full data set to be used with only a small trade off in power efficiency.

Secondly, parametric tests on d' calculate the mean d' by averaging the individual d' values, this is incorrect (McNichol, 1972). Group d' needs to be calculated by obtaining the mean z(H) and z(FA) and performing the calculation for d' on these values. Not following this procedure places mean d' in error. Thus parametric procedures are not an accurate reflection of the central tendency of group d' data such as this. Using non-parametric procedures gets over this problem as well by transforming the d' data into ranks, and testing the difference based on this rather than a difference based on an erroneous mean d' value.

The non-parametric equivalent for a repeated measures ANOVA is a Friedman test, and this is the procedure that is used for hypothesis testing on d'. Significant differences were detected with respect to d' versus feedback using this procedure. These significant differences occurred within every response criterion group (Conservative criterion: Chi-Square = 22.78, df = 7, $p < 0.01$, Medium criterion: Chi-Square = 26.23, df = 7, $p < 0.01$, and Risky criterion: Chi-Square = 23.13, df = 7, $p < 0.01$). Having established that there are significant differences between the d' values gained within each vehicle feedback condition, it is required now to unearth between what feedback conditions these differences lie. The analysis falls into planned comparisons and unplanned comparisons. Planned comparisons involve comparing the respective feedback conditions with the baseline condition (condition one, visual feedback only). Unplanned comparisons analyse every other pairwise combination of feedback condition(s).

5.4.4.2 Planned Comparisons

Post hoc testing for the Friedman procedure involves finding the difference in mean ranks between the baseline and every other remaining condition. The following formula is used to derive a critical value, where:

k = the levels of the independent variable (8)

N = sample size (35)

alpha = the significance level (0.05)

Ri = the mean baseline value

Rv = the mean comparison value

q(alpha,# c) = a value referenced from data tables

$$\left[\bar{R}_i - \bar{R}_v\right] \geq q(\alpha,\#c)\sqrt{\frac{k(k+1)}{6N}}$$

A critical value is derived from this formula. When the baseline condition mean rank is subtracted from each of the other conditions, the absolute difference is compared to the critical value. If the difference value exceeds the critical value then the comparison is significantly different at the five percent level. Within the present Study the absolute value of the planned comparisons have to exceed the critical value of 1.52. Those pairwise comparisons that do achieve this are highlighted in table 5.2 below.

Table 5.2 – Results of planned feedback condition vs. d' analysis.

Baseline Comparison

Difference	**Conservative**	**Medium**	**Risky**
1 – 2	**-2.02**	**-1.64**	-0.99
1 – 3	-1.26	-1.42	-1.33
1 – 4	-0.20	0.31	0.53
1 – 5	-1.23	-0.62	-0.26
1 – 6	**-1.62**	**-1.89**	**-1.79**
1 – 7	-0.56	-0.82	-0.87
1 – 8	**-1.59**	-1.37	-0.90

The direction of all the significantly different comparisons is for the comparison value to be *greater* than the visual baseline condition. Remember also that the visual baseline condition is present within all the subsequent feedback conditions. From these results, in the strictest conservative criterion; auditory feedback, auditory feedback combined with under-seat resonators, and all these modalities combined again with steering force feedback are significantly different from the baseline. In the medium criterion once again auditory feedback is significantly different from the baseline, as is auditory feedback combined with under-seat resonators. Visual, auditory and under-seat resonators are the only combination of feedback modalities that yield a significant difference in sensitivity from the baseline in the risky decision criterion. In summary, tactile feedback through the seat appears to be useful regardless of decision criterion but *only* when combined with visual and auditory feedback. Auditory and visual feedback seems to be more powerfully implicated in increasing sensitivity, and therefore better driver SA

5.4.4.3 Unplanned Comparisons

A range of multiple comparisons will assist in exhaustively analysing the interrelationships between the available feedback conditions in terms of d'. A new formula is used to derive a critical value for unplanned comparisons, where:

k = the levels of the independent variable (8)

N = sample size (35)

alpha = the significance level (0.05)

Ru = the mean comparison value a

Rv = the mean comparison value b

Z alpha/k(k-1) = values referenced from data tables

$$\left|\bar{R}_u - \bar{R}_v\right| \geq Z_{\alpha / k(k-1)} \sqrt{\frac{k(k+1)}{6N}}$$

The formula for unplanned comparisons yields a critical value of 1.83. If the difference between pairwise comparisons of mean ranks exceeds this value then the relevant feedback conditions differ from each other significantly. Only statistically significant values are reported below in table 6.3.

Table 5.3 – Results of unplanned feedback condition vs. d' analysis.

Pairwise Comparison Difference	**Conservative**	**Medium**	**Risky**
4 < 2	**-1.82**	**-1.95**	**-1.86**
4 < 6		**-2.20**	**-2.32**

Here in table 5.3 it can be gathered that significantly lower levels of d' are experienced with visual feedback combined with under-seat resonators only; than when compared with auditory feedback, and a combination of auditory and under-seat resonators. It is possible to argue from this that the findings in respect of tactile feedback through the seat in condition six are due to the presence of auditory feedback. This is because under-seat resonators (combined with the visual baseline) appear not to make a contribution on their own. It is also worth mentioning that none of the other significant *baseline comparison* conditions possessed significant differences between themselves, so apart from the case above involving visual, auditory, and under-seat tactile feedback; conditions two and eight would appear to exert an equal difference (statistically) in terms of increasing d' and drivers SA; this is despite only two modalities being presented in condition two, and four in condition eight.

5.4.4.4 Summary of Overall d' Findings

Overall, feedback has been shown to positively influence d', and thus increase driver SA in addition to the SA contribution afforded by visual feedback only. Furthermore, the effect of auditory feedback seems to be the strongest. As evidence of this, not only was auditory feedback yielding significantly higher d' than the baseline in its own right, but every further condition that yielded a significant difference had auditory feedback combined within it (namely conditions six and eight). In terms of conditions six and eight then, it can be argued that the addition of either under-seat resonators, or steering force feedback, was yielding at best only minor additional contributions to that made by auditory feedback combined with visual feedback on its own.

5.4.5 HTAoD Behaviour Category Sensitivity Analysis

5.4.5.1 HTAoD Behaviour Categories

Having established that feedback significantly effects d', it is now time to perform a more fine grained analysis at the HTAoD level; to see within what categories of driving tasks these differences in SA sensitivity are originating from. This analysis proceeds by decomposing the probe item ratings into their constituent HTAoD categories. Seven SA probe items were completed by drivers during every simulation pause. It will be recalled that SA probes one to five are referring directly to the SA requirements of categories one to five of the HTAoD. These are as follows:

Behaviour Category 1: Basic Driving Tasks are concerned with fundamental physical vehicle control tasks performed by the driver.

Behavior Category 2: Core Driving Tasks are still basic physical operations applied within a basic contextual setting of controlling vehicle speed and trajectory.

Behavior Category 3: Specific Driving Tasks cover strategies and operations for coping with specific road environment situations, such as junctions or crossings.

Behavior Category 4: General Driving Tasks represent increasingly goal orientated, overarching strategies for adapting to different road types, or general procedures for dealing with other traffic.

Behavior Category 5: Global Driving Tasks are concerned with goal orientated operations related to high-level driving strategy, such as rule compliance or navigation.

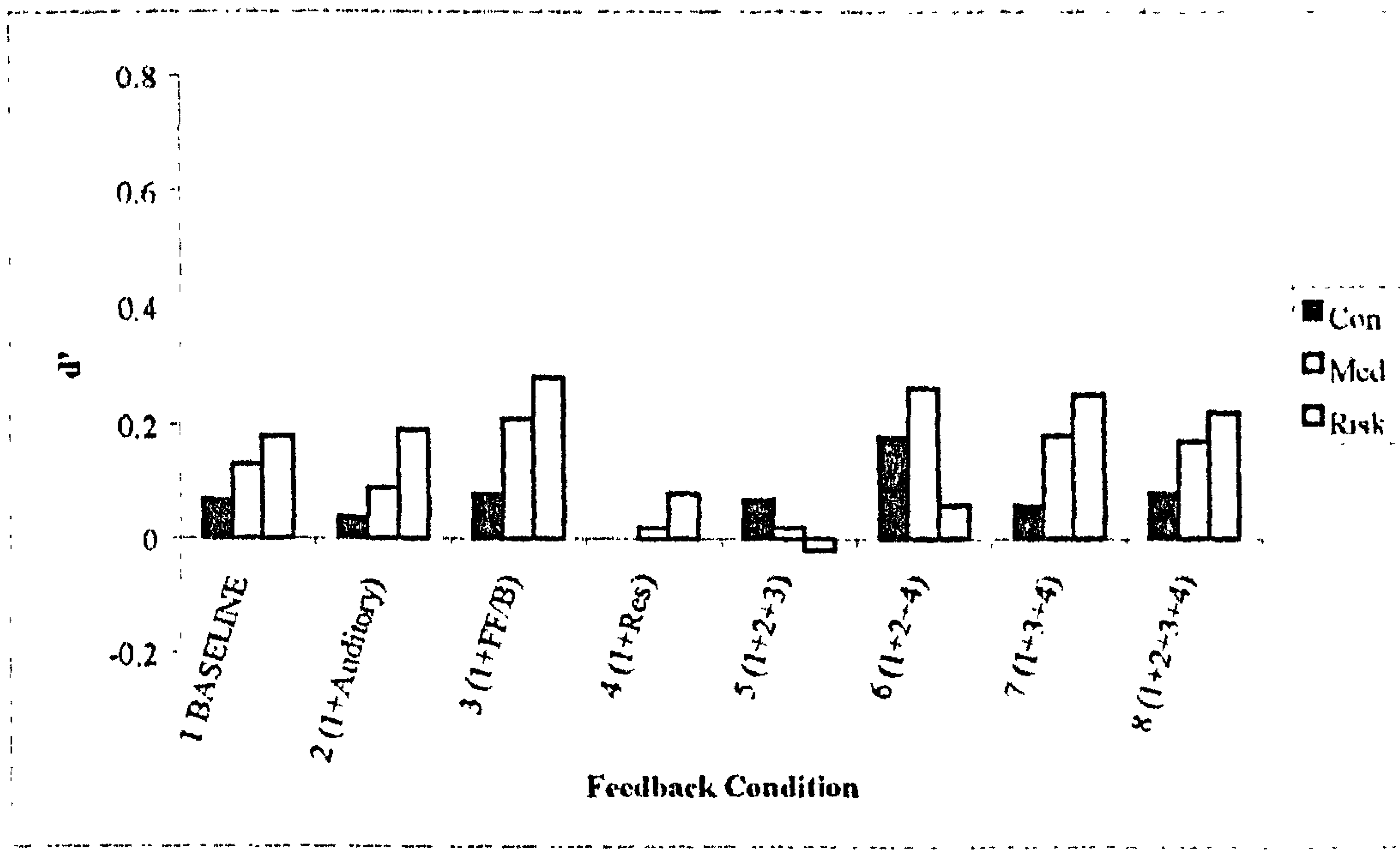
The remaining two out of the seven probes provided for any given simulation pause were not directly related to the HTA, but were situation specific probes of a random nature. The main point is that each of these driving goal categories can be analysed separately, using the Friedman procedure of overall testing, planned, and unplanned comparisons as employed above.

5.4.5.2 HTAoD Basic Driving Tasks; Sensitivity Analysis

No significant differences were detected between d' and feedback condition for probe items relating to category one of the HTAoD.

5.4.5.3 HTAoD Core Driving Tasks; Sensitivity Analysis

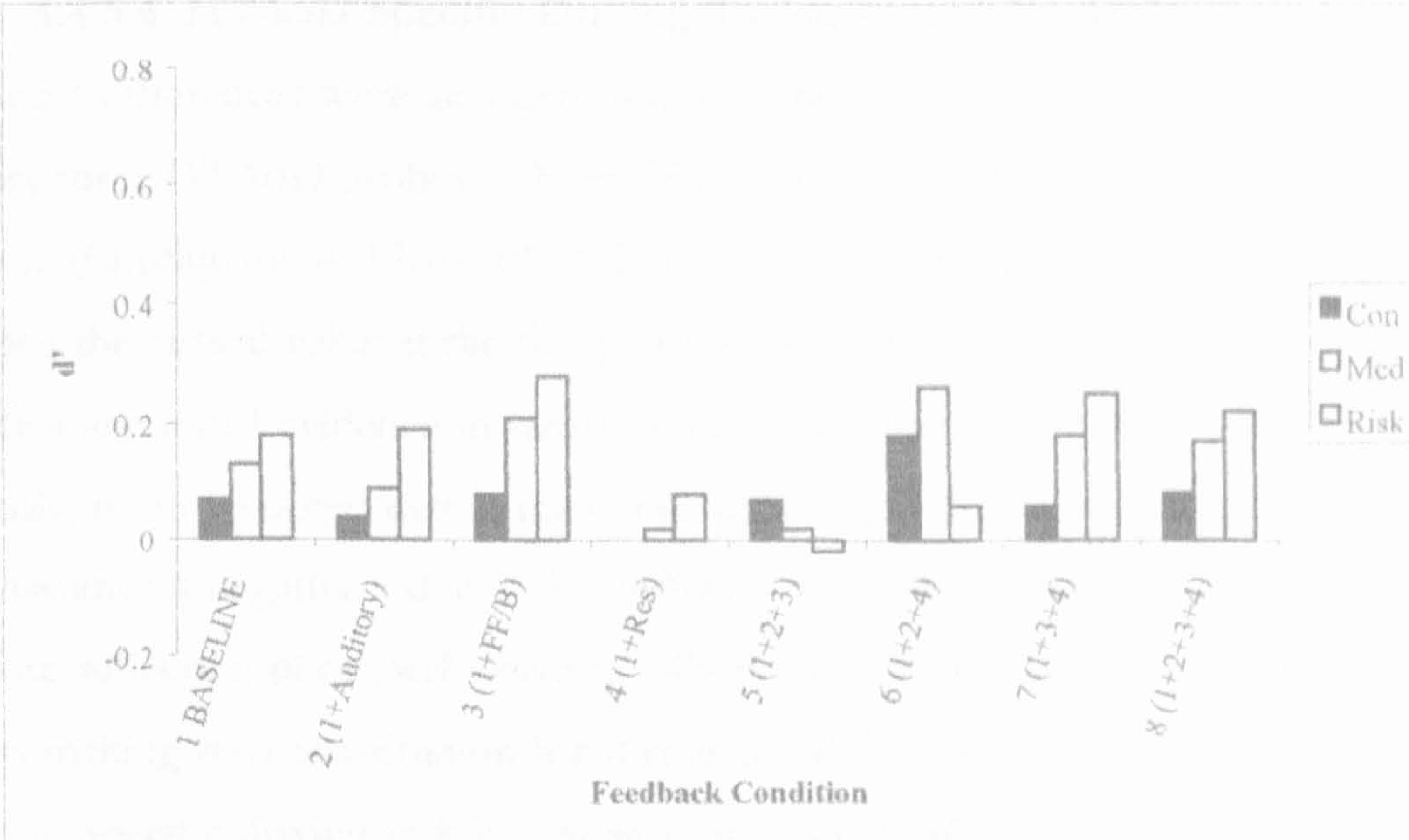
Significant differences were however detected between feedback and d' in category two HTAoD probes. These differences were in the risky response criterion (Chi-Square = 18.53, df = 7, $p < 0.01$), and the mean d' values for each feedback condition pertaining to category two HTAoD are shown in figure 6.6 below.



	1 BASELINE	2	3	4	5	6	7	8
Con	0.07	0.04	0.08	0	0.07	0.18	0.06	0.08
Med	0.13	0.09	0.21	0.02	0.02	0.26	0.18	0.17
Risk	0.18	0.19	0.28	0.08	-0.02	0.06	0.25	0.22

Figure 5.14 - Category two HTAoD probes; feedback condition versus d'.

No comparisons with the baseline exceeded the critical value, however, unplanned comparisons showed that condition four yielded consistently lower values of d' compared to conditions three, six, and seven. Therefore the under-seat resonators yielded poorer SA sensitivity performance than steering force feedback. Furthermore, the addition of auditory feedback combined with under-seat resonators (as in feedback condition six) shows that with the two modalities combined a bigger difference in sensitivity is realised then with the two modalities presented separately; the sum of the two modalities yielding greater sensitivity than the parts perhaps. For condition seven (that is made up of under-seat resonators and steering force feedback) it could on the other hand be argued that it is steering force feedback that is responsible for the increase in combined sensitivity, with little or no additional contribution being made by the resonators?



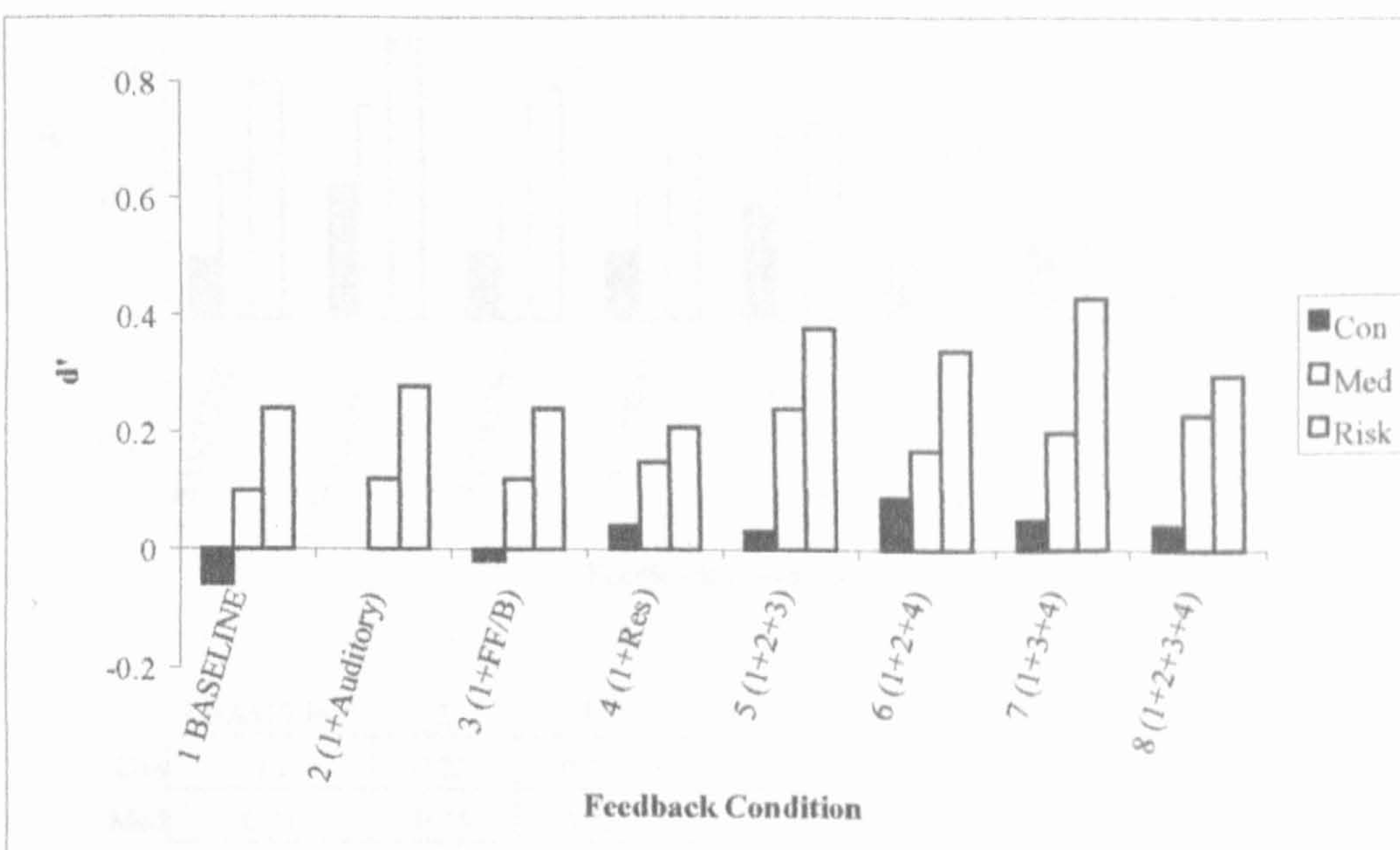
	1 BASELINE	2	3	4	5	6	7	8
Con	0.07	0.04	0.08	0	0.07	0.18	0.06	0.08
Med	0.13	0.09	0.21	0.02	0.02	0.26	0.18	0.17
Risk	0.18	0.19	0.28	0.08	-0.02	0.06	0.25	0.22

Figure 5.14 - Category two HTAoD probes; feedback condition versus d'.

No comparisons with the baseline exceeded the critical value, however, unplanned comparisons showed that condition four yielded consistently lower values of d' compared to conditions three, six, and seven. Therefore the under-seat resonators yielded poorer SA sensitivity performance than steering force feedback. Furthermore, the addition of auditory feedback combined with under-seat resonators (as in feedback condition six) shows that with the two modalities combined a bigger difference in sensitivity is realised then with the two modalities presented separately; the sum of the two modalities yielding greater sensitivity than the parts perhaps. For condition seven (that is made up of under-seat resonators and steering force feedback) it could on the other hand be argued that it is steering force feedback that is responsible for the increase in combined sensitivity, with little or no additional contribution being made by the resonators?

5.4.5.4 HTAoD Specific Driving Tasks; Sensitivity Analysis

Significant differences were also detected in respect to feedback modality and d' within category three HTAoD probes. These differences were detected within the conservative criterion (Chi-Square = 17.10, df = 7, $p < 0.05$), although no pairwise comparisons exceeded the critical value at the five percent level. Reference to figure 6.7 below might provide some initial evidence in terms of what direction these effects might be heading. Curiously, it can be noted that in the conservative criterion, for condition one, that the d' value assumes a negative value. This indicates that false alarms are exceeding hits, and therefore reflecting poor performance. To the extent, perhaps, that visual feedback is not just making zero contribution but it is in actual fact misleading in terms of SA probes related to specific driving tasks? Significant overall differences were detected for d' in the risky criterion, Chi-Square = 17.47, df = 7, $p < 0.05$.



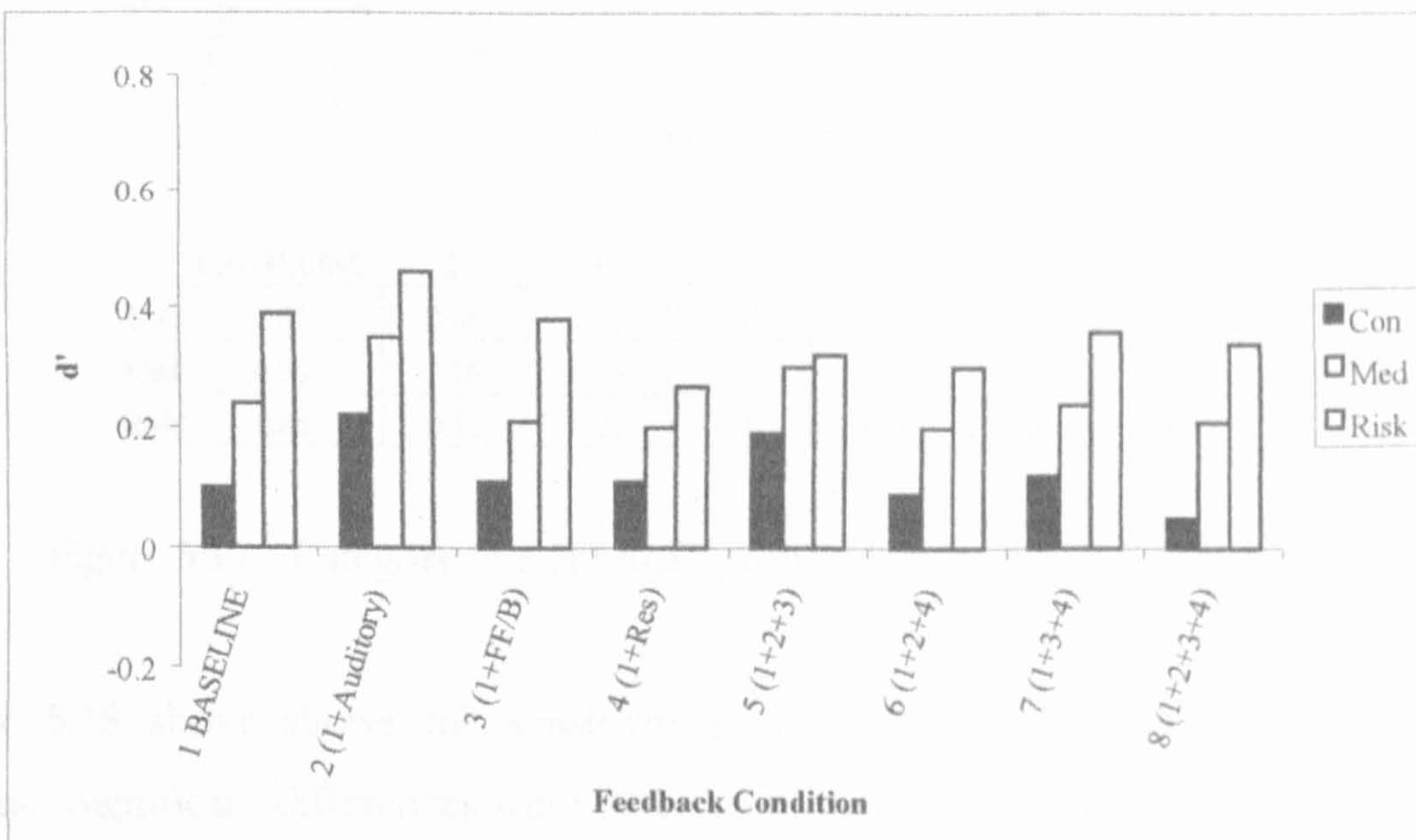
	1 BASELINE	2	3	4	5	6	7	8
Con	-0.06	0	-0.02	0.04	0.03	0.09	0.05	0.04
Med	0.1	0.12	0.12	0.15	0.24	0.17	0.2	0.23
Risk	0.24	0.28	0.24	0.21	0.38	0.34	0.43	0.3

Figure 5.15 - Category three HTAoD probes; feedback condition versus d'.

For the risky criterion, significant differences were detected between conditions four and seven once again. With four assuming the lower value, and suggesting that the addition of steering force feedback on top of the resonators yields a significant increase in sensitivity. Though neither condition on its own shows any significant effect, there seems to be some tentative evidence for the role of steering force feedback within specific driving tasks.

5.4.5.5 HTAoD General Driving Tasks; Sensitivity Analysis

Figure 5.17 below presents the sensitivity performance across feedback conditions where significant differences were detected in the conservative criterion (Chi-Square = 27.6, df = 7, $p < 0.01$), and the medium criterion (Chi-Square = 19.83, df = 7, $p < 0.01$) of category four HTAoD probes.

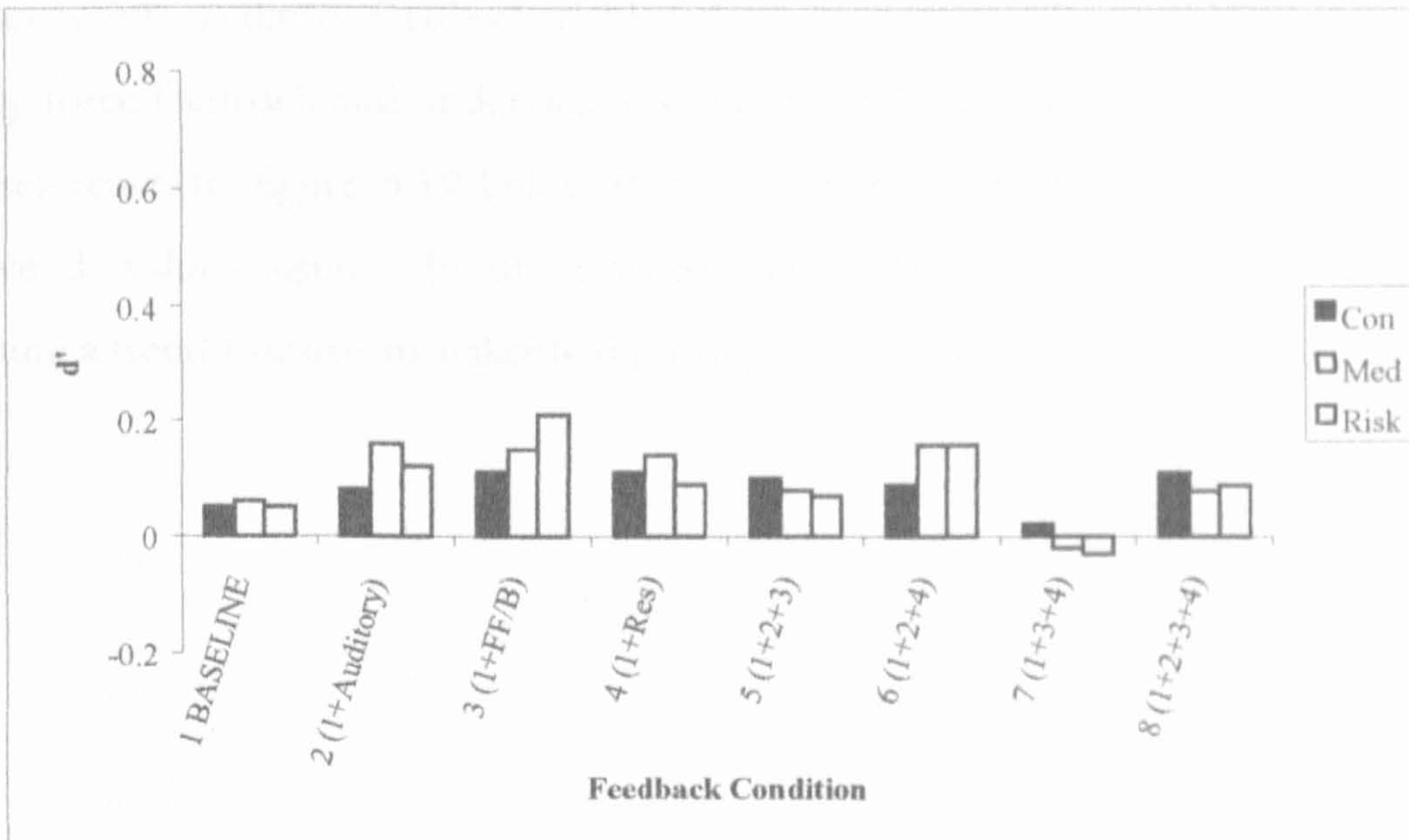


	1 BASELINE	2	3	4	5	6	7	8
Con	0.1	0.22	0.11	0.11	0.19	0.09	0.12	0.05
Med	0.24	0.35	0.21	0.2	0.3	0.2	0.24	0.21
Risk	0.39	0.46	0.38	0.27	0.32	0.3	0.36	0.34

Figure 5.16 - Category four HTAoD probes; feedback condition versus d'.

In the conservative criterion the baseline visual condition yielded significantly lower sensitivity than visual plus auditory, and this condition (number two) yielded higher sensitivity than condition eight. This is interesting as condition eight represents all of the available combinations of feedback. In the medium criterion, although significant differences were detected, no pairwise comparisons exceed the critical values at the five percent level.

5.4.5.6 HTAoD Global Driving Tasks; Sensitivity Analysis



	1 BASELINE	2	3	4	5	6	7	8
Con	0.05	0.08	0.11	0.11	0.1	0.09	0.02	0.11
Med	0.06	0.16	0.15	0.14	0.08	0.16	-0.02	0.08
Risk	0.05	0.12	0.21	0.09	0.07	0.16	-0.03	0.09

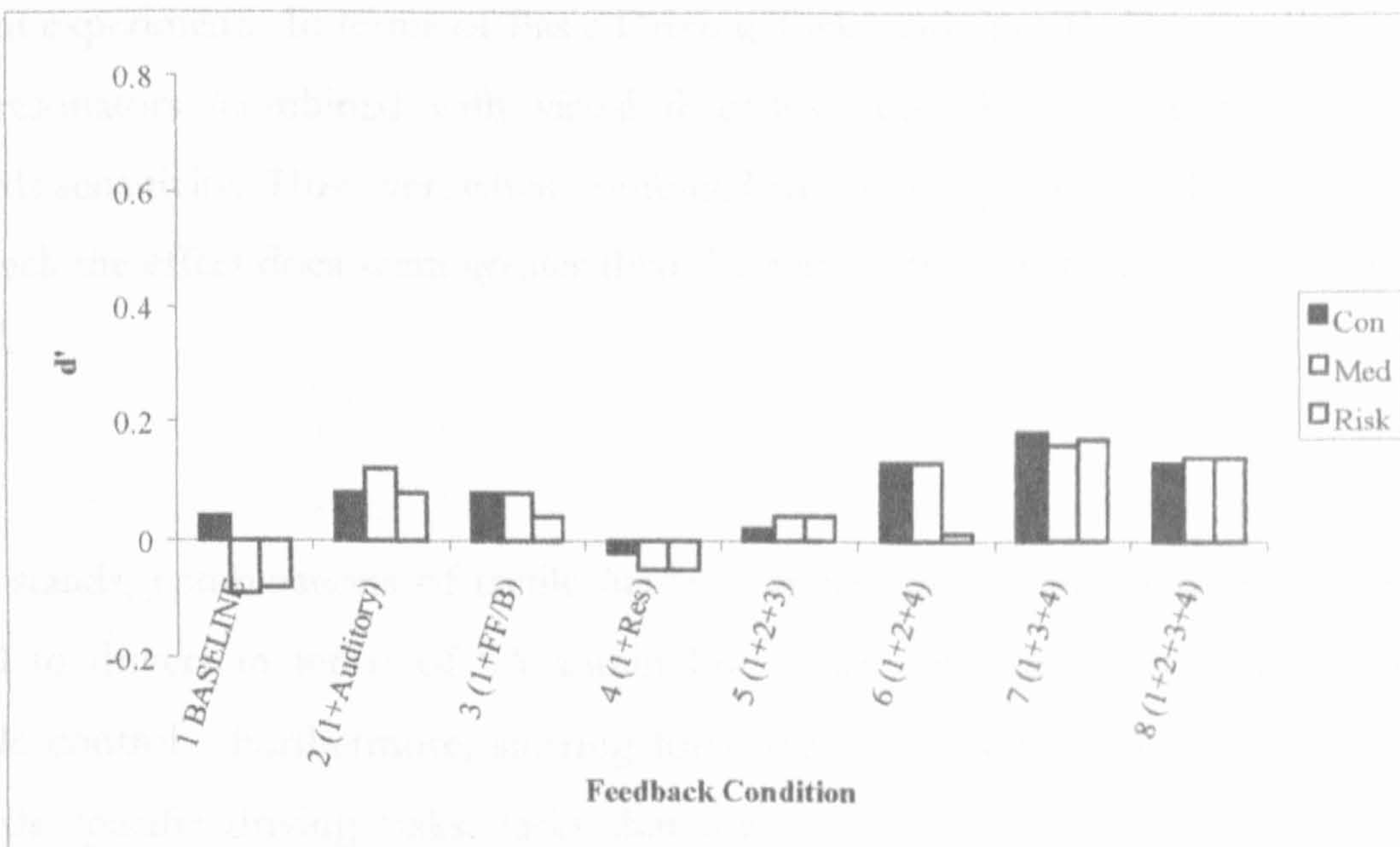
Figure 5.17 - Category five HTAoD probes; feedback condition versus d'.

Figure 5.18 above shows the sensitivity performance within category five HTAoD probes. Significant differences were detected in the conservative and medium response criterions (Chi-Square = 15.41 and 16.42 respectively, df = 7, $p < 0.05$), although no pairwise comparisons reached or exceeded the critical values. Reference to figure 6.9 above might be helpful in estimating the potential direction of the overall effect detected. In particular, consideration can be given to the large differences between feedback conditions three and seven. The difference between these two feedback conditions is the addition of under-seat resonators within condition seven. This appears to cause the largest *drop* in sensitivity consistent with that detected statistically within core driving tasks (category two, above).

5.4.5.7 Probe Items 6 and 7; Sensitivity Analysis

The two remaining probe items provided for each simulation pause were not directly related to the HTAoD categories. When probing general levels of awareness to specified stimuli, probe number seven revealed significant differences in sensitivity at the medium and risky response criteria respectively (Chi-Square = 16.75 and 16.62, df = 7, $p < 0.05$).

These differences were all related to the baseline condition one. Here it was found that condition one yielded significantly lower sensitivity than condition two, seven, and eight. In other words, auditory feedback yielded the same increase in sensitivity as combining steering force feedback and under-seat resonators, and presenting all available modalities. With reference to figure 5.19 below it can be gathered that condition one embodies negative d' values again. In other words, false alarms exceed hits in some cases, indicating a trend towards mistakenly reporting an event when it does not actually exist.



	1 BASELINE	2	3	4	5	6	7	8
Con	0.04	0.08	0.08	-0.02	0.02	0.13	0.18	0.13
Med	-0.09	0.12	0.08	-0.05	0.04	0.13	0.16	0.14
Risk	-0.08	0.08	0.04	-0.05	0.04	0.013	0.17	0.14

Figure 5.18 - Category seven HTAoD probes; feedback condition versus d'.

It is unusual that probe question six did not yield similar results to question seven. These probes were selected at random from an available pool of probe items, although the small d' values, and the reduced number of signal plus noise trials at this individual level of analysis may make statistical comparisons rather more delicate compared to the overall level of analysis.

5.4.5.8 HTAoD Categories; Sensitivity Analysis Summary

In summary, when distilling the analysis of sensitivity down to the level of HTAoD goals, systematic differences in sensitivity contingent upon feedback are derived from Basic Driving Tasks, Specific Driving Tasks, and General Driving Tasks. There is also some tentative evidence of experimental effects existing within Global Driving Tasks, but further work would be needed to ascertain precisely where these differences might lie. At the moment, absolute levels of d' are rather low, combined with a reduction in the quantity of signal and noise trials. Future work may want to bolster this aspect of the current experiment. In terms of Basic Driving Tasks and Specific Driving Tasks, under-seat resonators (combined with visual feedback only) do not appear to contribute towards sensitivity. However, when combined with steering force feedback and auditory feedback the effect does seem greater than the sum of the constituent feedback modality 'parts'.

As it stands, combinations of tactile (under-seat resonators) and auditory feedback are useful to drivers in terms of SA within lower task categories involving fundamental vehicle control. Furthermore, steering force feedback seems to be tentatively related towards specific driving tasks, tasks that are couched at the level of applying these fundamental driving behaviours within more defined traffic and road scenario's. On the other hand, driving tasks related to more overarching driving behaviours embodied under General driving tasks, (including navigation for example) implicate auditory feedback as having a significantly positive effect on driver SA. Interestingly, adding more feedback causes no further increase in sensitivity, and in fact reaches a point whereby sensitivity starts to fall again. Tentatively, this could be explained with reference to a possible plateau effect, whereby there is an upper limit of information processing and additional feedback presentation may exhaust these capabilities? Finally, for probe items related purely to the situation and not systematically to the HTAoD, the baseline condition is consistently the lowest performing in terms of d'. Again, auditory feedback, and combinations involving auditory and tactile feedback thereof lead to increases in SA.

Based on this analysis it would seem that lower category driving tasks benefit most from tactile and auditory feedback. On the other hand, driving tasks that are situated within higher task categories seem to benefit most from auditory feedback in terms of increasing driver SA. What is clear is that different categories of driving task require different types of feedback, and this Study has helped to identify and more clearly define this.

5.4.6 Statistical Power Analysis

5.4.6.1 Power Efficiency and Effect Size Calculations

This section on statistical power analysis helps to justify the experimental design and sample size used. First of all the power efficiency of the Friedman test is good. With k=8 (k being the number of feedback conditions) power efficiency is 84.2%. Or in other words, the Friedman test, like for like is 84.2% as efficient at detecting experimental effects as a repeated measures ANOVA (Siegel & Castellan, 1988). Given that the Friedman test ranks *all* data points, and that outliers would have had to be removed from the data set in order to prepare it for an ANOVA, this slight drop in power efficiency is not a big disadvantage, if at all.

The purpose of the earlier on-road studies (Chapter Three) was to explore the issue of vehicle feedback and its effect on driver cognition. This exploration now provides a very useful guide as to the anticipated effect sizes to be gained when vehicle feedback is manipulated and driver cognition measured. The experimental effect in that study, even under the exploratory experimental paradigm was strong. The exact effect size for the on-road studies covered in Chapter Three was determined using a computer program called GPOWER (Faul & Erdfelder, 1992). For the analysis categories that dealt with the three levels of situational awareness (the focus of interest in this particular Study), the average effect size (d) is 1.85; which by any standards is very large. This offers justification in using Cohen's (1988) effect size conventions for large effect sizes in our a-priori sample size calculations for the Friedman tests used in this simulator based Study.

5.4.6.2 Statistical Power Estimates

Unlike the on-road studies, the lab studies presented here are much more highly controlled and employ a within subjects paradigm. Both these factors help to increase the possibility of detecting a large or medium experimental effect should one actually exist (Cohen, 1990; 1994). A few computer based procedures for calculating statistical power are available, but none of these deal adequately with non-parametric tests, nor do they cope well with repeated measures designs. Using GPOWER again, set up to measure power for ANOVA tests, the guideline effect size of 0.4 (large) was selected. As this is a repeated measures design the experimental conditions were multiplied by the number of valid participants. This course grained procedure was performed in order to provide an *estimate* of the number of participants required to achieve a power figure of 0.8 or above. Or in other words, to state how many participants would be required to provide at least an 80% probability of detecting a true effect if one should exist. With these parameters set, it was determined that with N=30 power would be in excess of 0.8. As a Friedman test is 15% *less* power efficient than the ANOVA specified, 15% extra participants are required to maintain the desired power level, raising total N to 35. Substituting the non-parametric test for the parametric equivalent is normal within power calculations such as these (Howitt & Cramer, 1997). On the basis of these power estimates, the a-priori sample size was determined, and can be justified as 35.

Significant findings were detected using this sample size, thus successfully avoiding the expense in time and resources of collecting too much or too little data. Having collected the data from the initial sample of 35, determined a-priori from power estimates, the *actual* effect size observed in the experiment can now be calculated. For the Friedman test, this involves transforming the statistic into a correlation coefficient, which in this case is denoted by r_{phi}. This enables the relationship between feedback and sensitivity, or feedback and SA to be interpreted just like any other correlation (Howitt & Cramer, 1997).

At the overall level of analysis the effect size is found for the conservative criterion to be $r_{phi} = 0.80$, the medium criterion as $r_{phi} = 0.86$, and the risky criterion $r_{phi} = 0.81$. At the individual HTAoD category level of analysis, the mean effect size (where there was a statistically significant effect) was $r_{phi} = 0.72$. All of these values suggest a very strong positive association between feedback and SA; a relationship that the sample size of 35 was readily able to detect.

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5.5 RESULTS PART III SUBJECTIVELY RATED MENTAL WORKLOAD

5.5.1 Data Normality Checks

The reason for using non parametric tests in the SART analysis (Part I) was due to outliers causing a drop in power sufficient to make non-parametric measures *more* power efficient. Non-parametric tests were also employed in the analysis of SA sensitivity (d'), this was due to parametric measures not accurately reflecting the central tendency of the data (Part II). Set against this background, the normality of the MWL data was thoroughly checked and verified. The TLX scores are continuous combined with the healthy sample size of N=35, therefore providing that the normality assumptions are upheld, the data is very amenable to parametric procedures.

Histograms, normal Q-Q plots and boxplots provided visual indication of data normality, backed up by Shapiro-Wilk normality significance checks. With normality as the null hypothesis, the Shapiro-Wilk test statistic did not posit a significant result (that the data was in fact non-parametric). After removing three outliers from the Overall mental workload data set, as suggested by the boxplot shown in figure 5.20, this left a sample size of N=32.

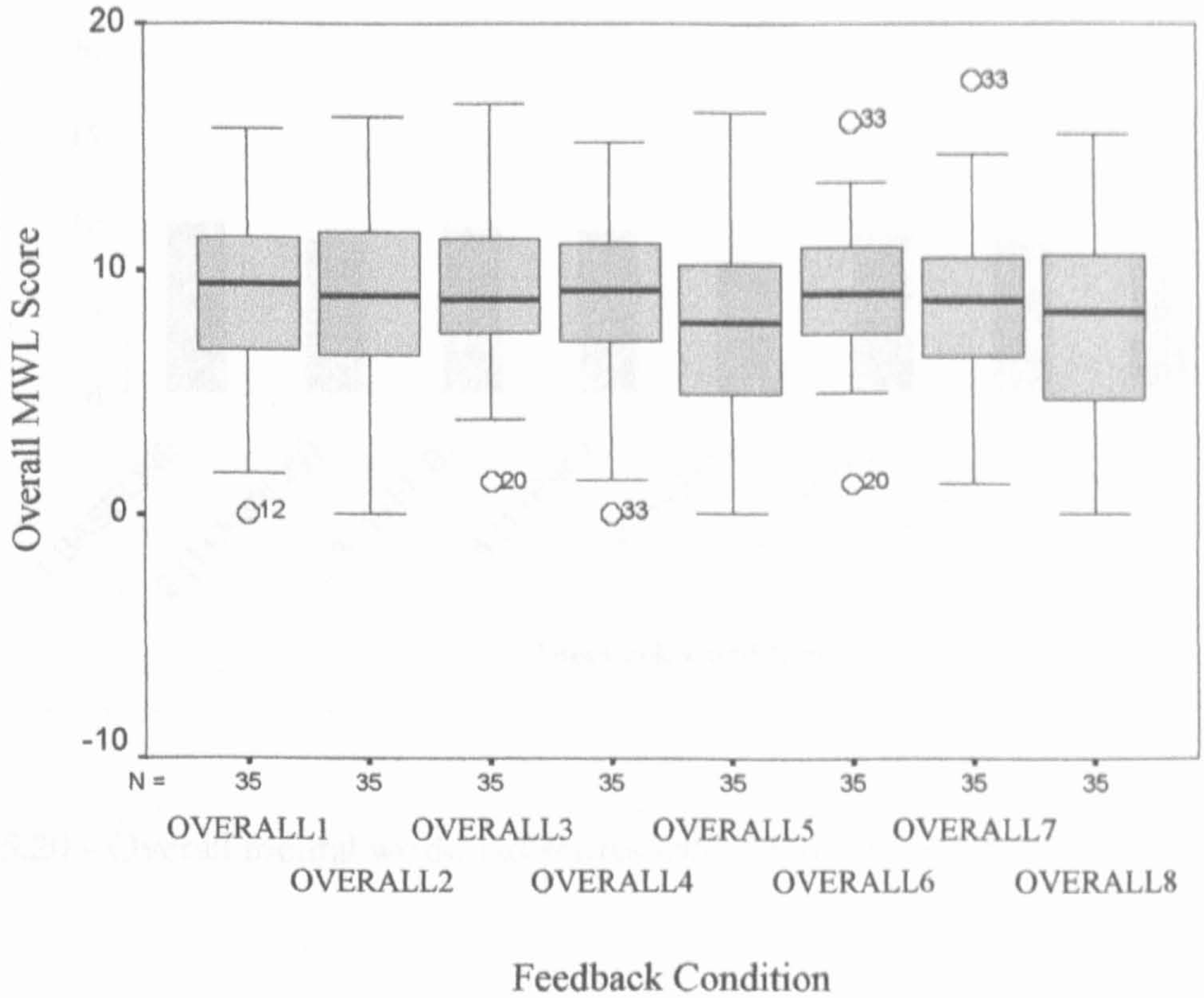

Figure 5.19 - Overall mental workload calculated from NASA TLX questionnaire showing sample distribution and outliers (removed) across the eight numbered feedback conditions.

In terms of power efficiency, despite removing these outliers the test is still more efficient than the non-parametric equivalent. Suitably reassured, it is possible to proceed with the analysis proper.

5.5.2 Analysis of Overall Mental Workload

Here the purpose is to seek to detect differences within subjects *across* the eight feedback conditions. Figure 5.21 presents the mean Overall mental workload score for each condition. The overall MWL score is calculated by taking the mean of all the six component TLX scales.

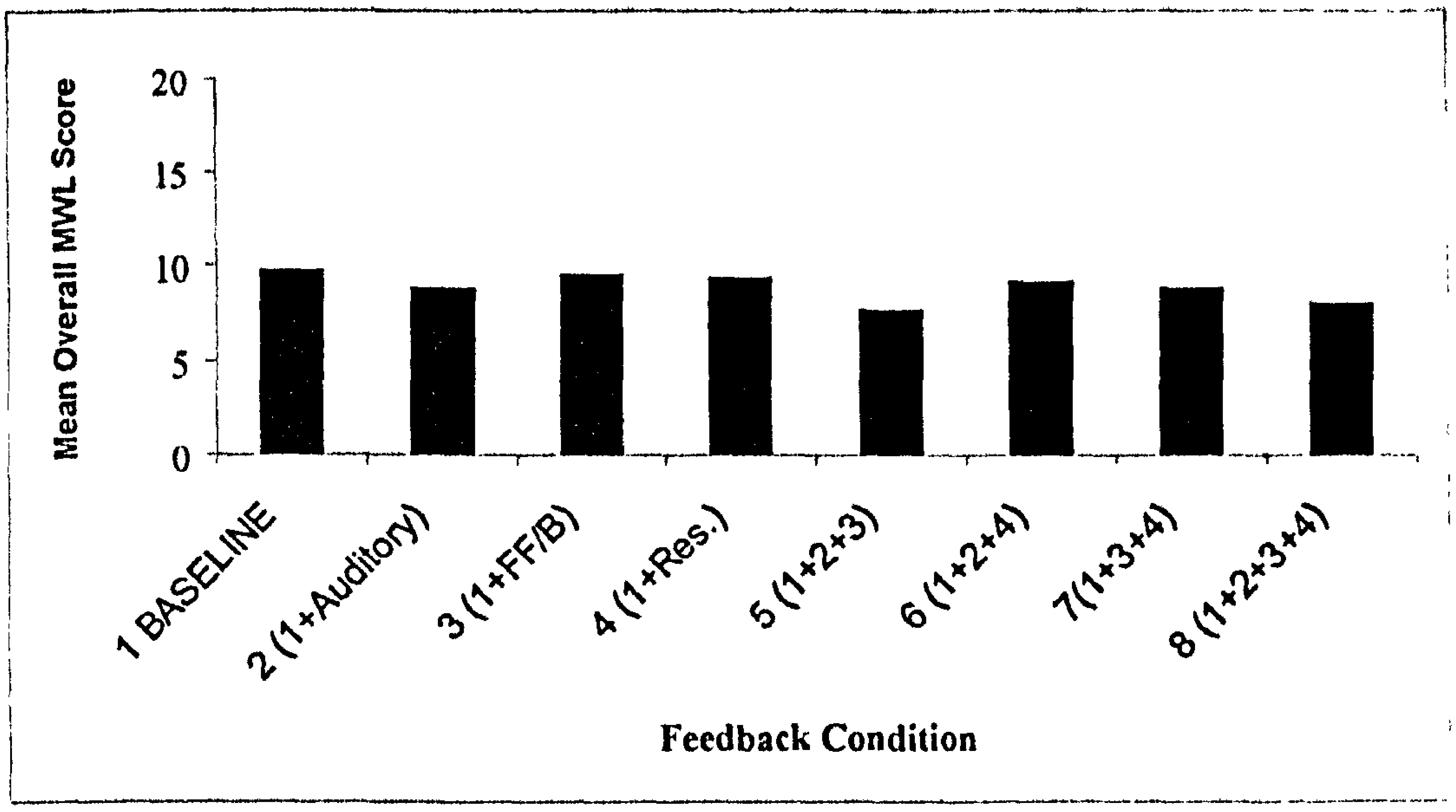

Figure 5.20 - Overall mental workload scores calculated for each feedback condition.

Taken as a whole mental workload whilst driving is neither particularly high nor particularly low (falling somewhere in the vicinity of the midpoint of the 20 point scale). This might suggest that demands in driving are generally modest, perhaps leaving drivers with around 50% spare capacity? However, absolute value comparisons of this nature do not benefit from an external anchor task, and should be interpreted with a degree of caution. After all, relative to other simple tasks, the task of driving may perhaps be given a much higher absolute rating than found here, although at present this cannot be gauged.

Condition one, visual feedback only, has the highest levels of overall MWL, whilst condition five (closely followed by condition eight) have the lowest levels of MWL. With visual feedback serving as the baseline, adding auditory feedback on its own seems to cause the largest singular drop in MWL. Also it would appear that the cumulative addition of feedback categories on top of vision causes an approximately linear drop in MWL scores. Adding auditory to visual feedback (moving from condition one to two) causes a reduction in MWL, adding steering force feedback (to make condition five) causes a further drop, although the addition of the under-seat resonators (to make condition five into condition eight) causes no further reductions. This could be due to the fidelity of this particular feedback modality within the simulation, or it could be due to a plateau effect whereby further increases in feedback do not provide any further reductions in workload. In summary the most interesting result is that mental workload appears to be highest in the visual feedback only, baseline condition. Adding feedback *reduces* mental workload, rather than increasing it.

To test whether these relative values of overall MWL are significantly different to each other a repeated measures ANOVA was performed using the SPSS General Linear Model procedure. For post-hoc multiple comparisons paired t-tests using a Bonferroni adjustment were carried out. Sharing the significance level among the eight levels of the independent variable of feedback means that to achieve significance at the 5% level, the significance must actually be smaller than 0.05/8.

5.5.3 Statistical Tests on Overall Mental Wokload

Highly significant main effects of feedback on Overall mental workload scores were detected, $F(3.61,111.82)=4.26$; $p<0.01$. Post-hoc multiple comparisons show where these differences lie. These are presented in table 5.4 below, and the critical difference to be compared using the Bonferroni adjustment is 0.05/8 = 0.0063.

Table 5.4 - Results of post-hoc multiple comparisons showing Overall mental workload and feedback condition.

Pairwise Comparisons of Feedback Condition	**t**	**df**	**Sig. 5% (p<0.0063)**
1>5	3.92	31	.000
1>8	3.76	31	.001
3>5	3.08	31	.004
4>5	3.38	31	.002

To a large extent the statistical tests bear out the visual inspection of the data. Condition one, the baseline condition, does indeed have significantly higher Overall mental workload associated with it compared to conditions five and eight. However, conditions five and eight are not significantly different from *each other.* Condition eight is condition five with the addition of under-seat resonators, and as such suggests that the addition of under-seat resonators does not significantly decrease (or otherwise change) MWL. The fact that conditions five and eight exert a more or less equal effect on MWL could be indicative of the plateau effect discussed above. Condition two, auditory feedback, despite causing the largest drop in MWL scores for a single feedback modality, was not seen to change MWL significantly. Interestingly, steering force feedback (condition three) has significantly higher overall MWL associated with it than condition five, and similarly, condition four is significantly higher than five. This could be indicative that these modalities on their own (combined with just the visual baseline) make only a minimal contribution towards changes in MWL scores. From an Overall MWL point of view, providing visual, auditory, and steering force feedback together has the biggest effect in terms of lowering MWL.

5.5.4 Within Subjects Analysis of NASA TLX Mental Workload Sub-Scales

Having established that there exist highly significant differences in Overall MWL scores it is of interest to establish where these differences emanate from. In order to achieve this more fine grained analysis the TLX sub-scales were analysed individually. In each case, the normality of the distributions were verified with boxplots and outliers removed where appropriate. Despite this procedure, power efficiency remained within acceptably high bounds.

5.5.4.1 Mental Demand

Mental demand probed *"how much mental and perceptual activity was required* [to complete the task] *(e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?"* (Hart & Staveland, 1988, p. 169). Mental demand is a scale that is related to the behaviour of the participant in terms of the effort needed to perform the task. Highly significant differences were detected in ratings of mental demand across the eight feedback conditions, $F(4.82,134.98) = 4.0$; $p<0.01$. Multiple comparisons using the Bonferroni adjustment revealed that condition one was associated with significantly higher mental demand than condition eight ($t = 3.03$, df =

28, $p<0.05$). The combination of all available feedback modalities in condition eight has favourable implications for mental demand, thinking, deciding, calculating etc., compared with the baseline condition one.

5.5.4.2 Physical Demand

Physical demand probed *"how much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?"* (Hart & Staveland, 1988, p. 169). Physical demand appears to be like an odd scale to have within a mental workload questionnaire, but nonetheless has been found empirically to provide a valuable independent source of information relating again to the task behaviour of the participant. No significant within subjects effect was detected for the TLX physical demand sub-scale, $F(4.42,150.13) = 1.10$; p=ns. This implies that differences were below the effect size threshold able to be detected by this experimental paradigm, and that such small effects as might exist in the population are small enough to be relatively meaningless in design terms. Therefore as it stands feedback does not seem to be associated with useful changes in ratings of physical demand. This is interesting, as with each cumulative increment of feedback the driver is supplied with a greater quantity of physical stimuli (steering force feedback is one prominent case in point).

5.5.4.3 Temporal Demand

Temporal demand refers to *"how much time pressure* [did the participant feel they experienced] *due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?"* (Hart & Staveland, 1988, p. 169). This scale refers to the objective task demands. Driving is an essentially self paced and dynamic activity and thus likely to embody widely varying degrees of time pressure (Fuller, 1984). Fortunately, within the simulator drivers were required to remain at a steady speed within a specified virtual road environment. Thus this factor can be controlled to a large extent, and manipulations of vehicle feedback measured with this potential temporal confound minimised. As a result, significant effects of vehicle feedback and temporal demand were detected ($F(4.48,152.33) = 2.63$; $p<0.05$). Multiple comparisons revealed that drivers experienced more time pressure in condition one than condition eight ($t = 3.28$, $df = 34$, $p<0.05$), and condition six compared to condition eight ($t = 3.28$, $df = 34$, $p<0.05$). The trend here being that auditory and under-seat resonators plus the baseline (condition six) lead to significant reductions in temporal demand, but not as much as maximum multi modal feedback as embodied in condition eight.

5.5.4.4 Performance

The performance sub-scale is particularly interesting from the point of view of its relation towards feedback. Here the scale is defined for the participant as *"how successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?"* (Hart & Staveland, 1988, p. 169). Feedback has been defined elsewhere as referring to knowledge of results (Annett & Kay, 1957). In other words, feedback relates strongly to knowledge of performance, and a number of significant differences were detected to that effect ($F(4.59,142.15) = 4.97$; $p<0.01$). For clarity table 5.5 presents the results of the multiple comparisons, and figure 5.22 presents the relative scores.

Table 5.5 - Multiple post-hoc comparisons of performance ratings versus feedback.

Pairwise Comparisons of Feedback Conditions	t	df	Sig. 5% (p<0.0063)
1>5	5.12	31	.000
1>7	3.16	31	.004
1>8	4.29	31	.000
3>5	3.14	31	.004
4>5	4.46	31	.000
5<6	-4.09	31	.000

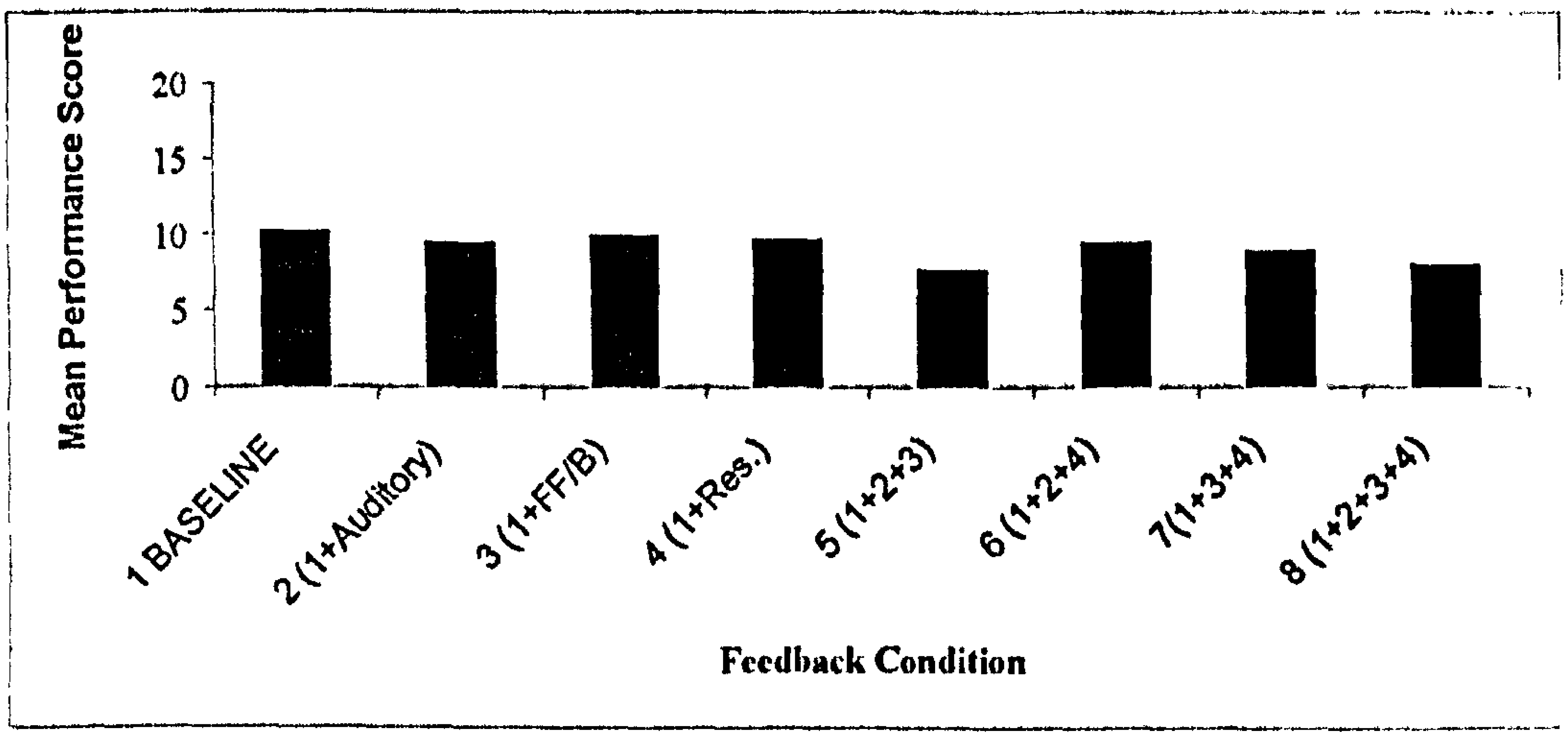

Figure 5.21 - Results of scores provided in the NASA TLX performance sub-scale.

With visual feedback only, driver's rate their performance as being the poorest. With increasing feedback performance is rated significantly higher. Additional differences were detected with condition five, this condition being associated with significantly better performance ratings than both conditions three and four (steering force feedback and resonators respectively). Furthermore, condition five was also associated with significantly better performance ratings compared to condition six (auditory feedback plus under-seat resonators). This positive effect of performance and feedback could be related to knowledge of results, in that a lack of feedback robs drivers of such knowledge. Greater feedback (to a point) creates a more accurate mental model of performance, actual task demands, and therefore perhaps greater self awareness of how well the drive is being accomplished.

5.5.4.5 Effort

The Effort sub-scale was defined for participants as *"how hard did you have to work (mentally and physically) to accomplish your level of performance?"* (Hart & Staveland, 1988, p. 169). Significant differences were detected with respect to ratings of effort supplied to the situation contingent upon feedback condition, $F(3.49,108.08) = 2.71$; $p<0.05$. These differences arose between conditions four and eight ($t = 2.95$, $df = 31$, $p<0.05$), with condition four (visual plus under-seat resonators) receiving the highest rating. In condition four therefore, more effort is supplied compared to condition eight where the driver experiences full multi-modal vehicle feedback. Tentative evidence at least that more feedback, through more modalities, is implicated in less effort being required on the part of the driver.

5.5.4.6 Frustration

The frustration scale homes in on the psychological impact of the task demands, and is defined as *"how insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?"* (Hart & Staveland, 1988, p. 169). Under this definition lower scores would indicate higher levels of driver satisfaction, and it is interesting to note that significant differences were detected between feedback conditions and this rating scale, $F(7,210) = 4.75$; $p<0.05$. These differences were between the feedback conditions presented in table 5.6 and figure 5.23 below.

Table 5.6 - Pairwise feedback comparisons of frustration sub-scale scores.

Pairwise Comparisons between Feedback Conditions	t	df	Sig. 5% (p<0.0063)
1>5	5.61	30	.000
2>5	3.22	30	.003
3>5	3.24	30	.003
4>5	4.36	30	.000
5<6	-3.11	30	.004
5<7	-3.29	30	.003

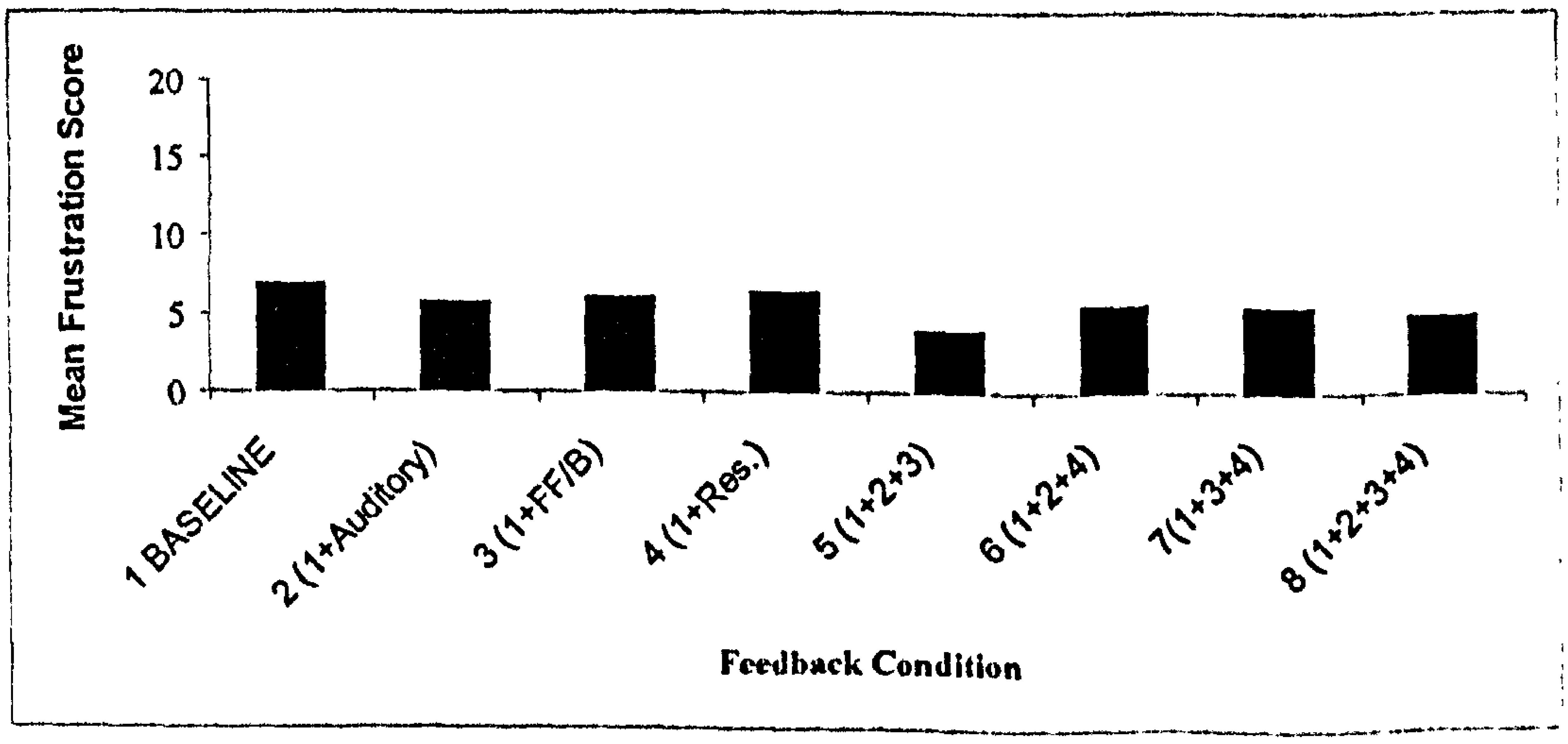

Figure 5.22 – Results of scores provided in the NASA TLX frustration sub-scale.

Based upon this analysis, condition five (visual plus auditory plus steering force feedback) appears to be implicated with the most driver satisfaction (i.e. it receives significantly lower ratings of frustration), and condition one, the baseline appears to be the most frustrating. The finding in respect to condition five in this frustration sub-scale is the same as that for overall MWL. Clearly a combination of visual, auditory, and steering force feedback exerts a consistent and noticeable effect on the dimension of driver enjoyment, as well as Overall MWL.

5.5.5 Power Analysis

The driving simulator laboratory studies presented in the current and previous Chapters are linked. It is still desired, however, to gain an estimate of statistical power, to determine with what probability an experimental effect is likely to be detected. In more detail, it is highly desirable to verify whether the participant pool employed here, numbering N=32, provides a sufficient probability of observing an experimental effect should one actually be present.

To achieve this the exploratory on-road study is once again referenced. Using the GPOWER (Faul & Erdfelder, 1992) power analysis program it is clear once again that the effect of vehicle feedback upon mental workload is large. Using this as a guide as to the anticipated effects of such a manipulation in the simulation lab, power analyses proceeds by determining whether N=32 is likely to enable such an effect to be observed with anything over 80% power. The alpha level was set at 0.05, and due to limitations in specifying within subjects experimental paradigms once again the number of participants was multiplied by the available feedback conditions. This provides an *estimate* of the power to be achieved with the current sample size. With N=32 there is in excess of an 80% probability that a large experimental effect will reveal itself should one actually exist. Therefore experimental power remains reassuringly high for the mental workload analyses.

5.5.6 Mental Workload Analysis Summary

There are highly significant differences between the Overall MWL score and the amount of vehicle feedback supplied to the driving simulator. Condition one is implicated with the highest Overall MWL scores, and conditions five and eight with the lowest Overall MWL. In other words, increases in multi-modal vehicle feedback lead to decreases in Overall MWL. However, no further reductions in workload were detected between conditions five and eight, and this could be due to a plateau effect, reflective of a hypothetical U shaped relationship between feedback and MWL. At this stage of analysis the data does fit in with this conception. A more fine grained analysis examined the six TLX subscales individually and discovered that every sub-scale, with the exception of Physical demand, showed significant differences in rating scores associated with differing levels of vehicle feedback. In summary, out of 20 significant differences discovered through multiple pairwise comparisons of feedback conditions, eight of these were related to condition one being the highest scoring condition, 10 being related to condition five receiving the lowest associated ratings, with condition eight accounting for five significant differences (being the lowest in all significant pairwise comparisons). Although conditions five and eight did not on the whole show significant differences between them, it is nonetheless fair to state that increasing feedback is implicated in lower driver mental workload, greater driver satisfaction, and higher, and perhaps more realistic ratings of driving performance.

5.6 CONCLUSIONS

5.6.1 Summary

Vehicle feedback yields and effect on SA and MWL. Manipulating vehicle feedback in the driving simulator causes changes in sensitivity to SA related probe stimuli. Specifically, feedback helps to *increase* driver SA. Perceived or subjective mental workload is also sensitive to manipulations of vehicle feedback. Evidence presents itself that as feedback is increased, mental workload is *decreased*. In driving one thing is immediately apparent, and that is the functional distinction between MWL and SA should be retained in the feedback framework, as it has been all along. The fact that SA and MWL seem to be functionally distinct is of important value to designers. If this is the case then there is no longer a trade-off; SA *and* MWL can both be optimised. Very much in its favour this Study offers an enhancement on the SAGAT method by relating it directly to the driver's task goals, whilst offering a much more objective means of measuring driver's SA abilities. This exercise is important, as drivers seem extremely poor at subjectively rating the state of their own SA. Furthermore, this Study does not stand alone, and in combination with earlier exploratory work contained in Chapter Three moves the central argument of this Thesis successfully from the survey and literature, to the exploratory, to the experimental. The findings remaining robust at all stages.

5.6.2 Situational Awareness Conclusions

Overall, there is evidence to suggest that with visual feedback serving as the baseline, auditory feedback causes significant increases in sensitivity, as does the cumulative addition of tactile feedback, and the further cumulative addition of steering force feedback. Auditory feedback appears to play a particularly prominent part in vehicle feedback over and above vision, and compares equally with further cumulative additions of other feedback modalities. These further cumulative additions of feedback, whilst remaining significantly higher in sensitivity terms than just visual feedback alone are not significantly higher than each other, or often not higher than vision plus auditory alone.

So is it possible to overwhelm drivers with feedback? This could provide one explanation for the lack of further increases in sensitivity despite the more modalities that were provided. At the overall level of analysis, conditions two, six, and eight all yielded significant sensitivity increases above the baseline. Condition two is a two feedback modality condition, six a three modality condition, and eight a four modality condition. No further increases in sensitivity were gained the more modalities were brought to bear over and above auditory feedback. This could be presented as at least tentative evidence in favour of the notion of feedback saturation. This situation could arise due to the information bandwidth of the driver, who is unable to process any further information through these feedback channels, in particular the skill based channel mentioned earlier in Chapter Three. However, findings in respect of feedback saturation have to be tempered of course to some degree by the available fidelity of the simulator, where subtle cues and the sheer realism of the driving task may, to a greater or lesser degree have been missing. Future studies will have to expand on this issue. However, these findings are suggestive of an interesting design challenge, as 'more modalities' may not necessarily mean higher feedback quality. Specifically, the challenge becomes not about the sheer number of feedback modalities, but also about the timing and content of feedback, something that Welford (1968) and Annett and Kay (1957), for example, hinted at some 30 years ago. In terms of feedback quality, this Study does indeed offer suggestions as to *what driving tasks need what modalities of feedback.* Or in other words, achieving a match between what information is required along what feedback modality channels.

Absolute levels of d' obtained during the Study were comparatively low; this was expected. By far the largest share of sensitivity towards SA stimuli is argued as being provided by vision, and the additional contribution made by other modalities is therefore *relatively* small, but by no means meaningless. For example, the difference between visual feedback and auditory feedback was a d' value of 0.51. In round figures this corresponds to around 30% extra responses being a Hit. Therefore, it can be reasonably stated that in some cases the addition of multi-modal feedback gives rise to 30% more Hits, and thus a worthwhile increase in SA than would otherwise have been the case. From this it would seem that multi-modal vehicle feedback has a significant contribution to make in alleviating potential sources of level 1 SA errors and leading to accurate mental models of system state.

Contrast these findings now with Part I and the subjective SA ratings of drivers, where it appears that they are singularly unaware of the state of their own SA, and more concerningly, are not even aware of any shortfall in their SA; despite being subject to overt changes in simulator vehicle feedback, repeatedly and interchangeably. This finding occurs within an experimental paradigm that in many instances went from presenting visual feedback only straight to three further modalities of feedback added on top of vision.

5.6.3 Mental Workload Conclusions

Within certain limits feedback appears to be *inversely* related to MWL. In contrast to the findings with respect to SA, where it was discovered that auditory feedback was a dominant determinant of SA performance, auditory *combined* with steering force feedback was found to be the most favourable feedback combination for lowering Overall MWL. Within the NASA TLX sub-scales the two most interesting findings are in relation to performance (highly related to knowledge of results), and frustration (or driver satisfaction). Richer, more accurate knowledge of results due to more vehicle feedback modalities gave rise to better ratings of performance. Under a risk homeostasis paradigm (Wilde, 1994; 1988) it would seem that feedback might have something to say towards perceived risk. Whether higher levels of feedback lead to performance overestimation, or that lower levels of feedback result in performance underestimation is unclear. What is interesting is that auditory feedback specifically has been shown empirically in prior work to improve driver's estimations of speed, thus perhaps individual estimations of performance as well (Horswill & McKenna, 1999; Matthews & Cousins, 1980; Evans, 1970). What feedback appears to be able to potentially do is alter the driver's perception of risk; that is if performance ratings can be taken as a metric for the self perception of safe and efficient driving accomplishment. This perception of performance/risk level may be in the direction of the driver's individual target risk level, and as such may have a role to play in moderating driver behaviour, thus helping to improve safety.

Greater vehicle feedback also seems to lead to greater satisfaction; or at least lower frustration. Driver enjoyment is another important contemporary vehicle design goal and is given in depth treatment in Chapter One. Suffice to say that based on this Study a combination of auditory and steering force feedback can be recommended to help achieve this particular design goal. This seems to run counter to much of prevailing automotive engineering design, whereby cars, if anything, are becoming quieter, more refined, with systems such as power assisted steering fitted almost as standard (Becker, et. al., 1996; Loasby, 1995). On the basis of the current findings vehicle feedback needs to be struck at an optimum level. This optimisation is likely to be highly dependent upon the specific context. For example, invigorating ride and control response characteristics may simply become tiring on a motorway compared to a country road. Although many different road types were used during the driving simulation, these were designed to offer an experimental control rather than an independent variable, therefore issues of context are within the domain of future work.

As a first insight this Study achieves its purpose of building upon prior research, moving the exploratory results gained in Chapter Three into the realm of experimental findings. This serves to provide additional detailed insights into substantive relationships between MWL and feedback. Future studies may want to build on this issue, perhaps bringing to bear a wider range of workload measures (in particular, primary task measurement using vehicle telemetry) that were not available for use in the present Study.

5.6.4 The Feedback Framework of Driving

Figure 5.24 shows the feedback framework of driving updated with the benefit of both the SA and MWL results gained in this Thesis. Under which it is possible to begin speculating with greater accuracy the processes of SA and MWL as they relate to feedback.

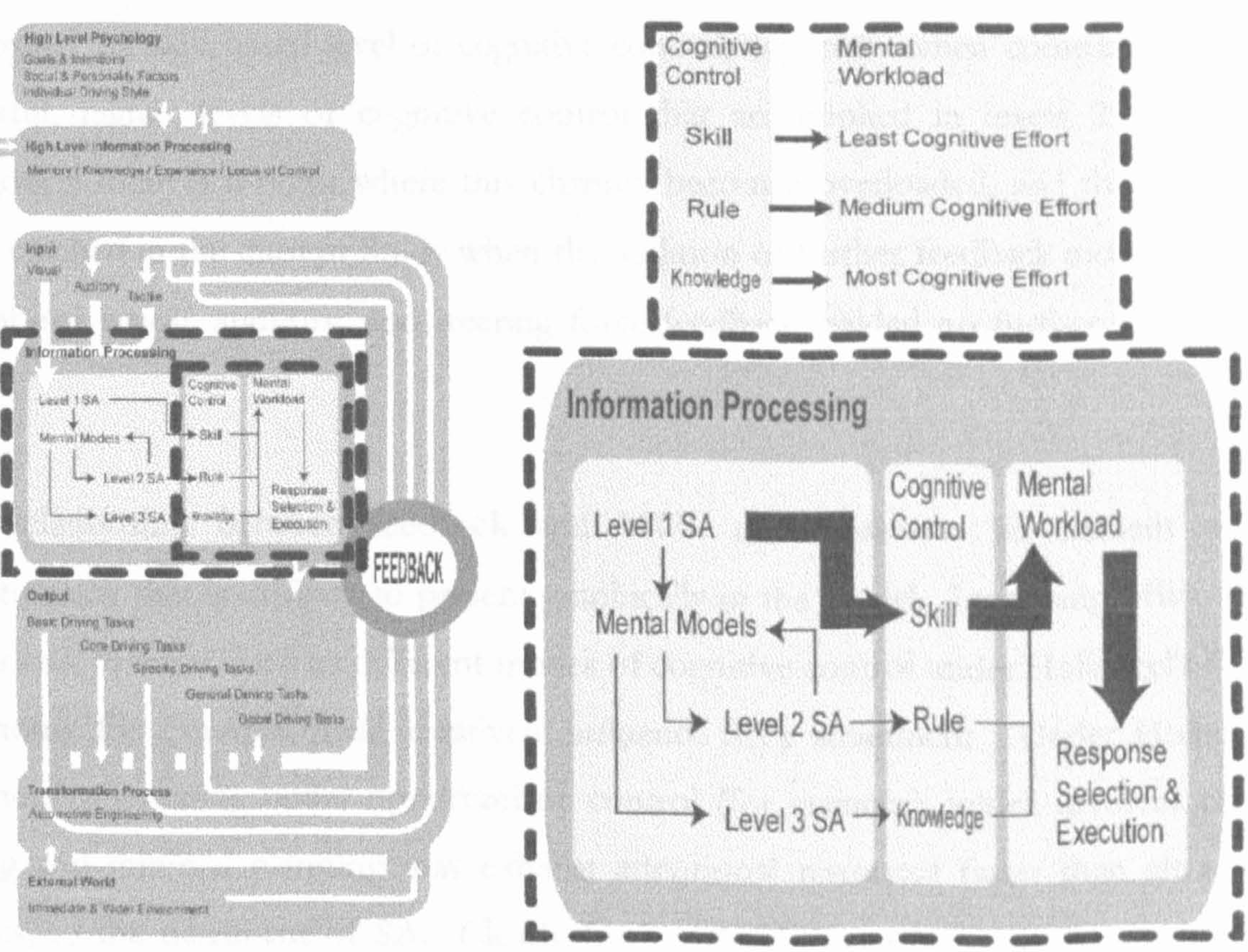

Figure 5.23 - Feedback model revised in light of mental workload findings.

According to the framework, for increased SA, and to some extent lower MWL, drivers require a combination of tactile and steering force feedback within lower HTAoD categories, and auditory feedback for higher HTAoD categories. These findings are derived directly from the individual probe item level of analysis. The feedback model enhancement presented above shows the pathways through which information is gained, and even, the pathways through which information in the future should be provided. As such, the feedback framework's ability to begin offering the vehicle designer future feedback solutions towards safer, more efficient and enjoyable driving performance is enhanced.

The reasons underlying the generally negative association between feedback and MWL are argued as being due to the provision of more feedback actively enhancing *level 1 SA*, as well as favourably influencing further SA levels. Level 1 SA is the first stage after perception of vehicle feedback has occurred, and is implicated in *skill based* cognitive control, the fastest and most efficient feedback channel through which decision making can proceed. The driving task, though highly complex, is also a highly skilled activity. Vehicle feedback can be argued as stimulating this channel in particular, as the large arrows in figure 5.24 emphasise. Mental workload can be reduced through fully deploying the skill based level of cognitive control, especially when compared to more effortful, higher levels of cognitive control that are implied in levels 2 and 3 SA. Obviously there is a point where this channel becomes overloaded, and this may have been reached in the current Study when the addition of further feedback modalities over and above vision, auditory, and steering force feedback yielded no further decreases in MWL.

The relationship between feedback and MWL also possesses an element of bi-directionality that is difficult to present graphically in the model. Increasing MWL *due to factors aside from SA*, such as different modes of cognitive control under Hollnagel's (1993) taxonomy for example, *could* negatively influence SA's attainment. Under Hollnagel's taxonomy, operating under opportunistic control (for instance), which involves chance taking and minimal planning may exhaust attentional resources faster than alternative modes, to the detriment of SA. Clearly from a design perspective, means have to be found of ensuring that these relevant cognitive control factors are set at an optimal level, and vehicle feedback may provide an especially useful mechanism to do so.

In summary, the issue of vehicle feedback has progressed from the level of the earlier survey and literature onwards to the exploratory level, and this knowledge can then be usefully combined in order to derive the final driving simulator experiment presented here. On the evidence of these findings, the type of information conveyed through the various feedback modalities plays a significant role in supporting particular sections of the driving task, and in optimising SA and MWL. This finding, in combination with the novel methodologies and use of the HTAoD, represent an interesting contribution to knowledge.

Chapter 6

Conclusions

6.1 SUMMARY

Technology is set to influence and change the nature of the driving task in a variety of profound ways. This thesis puts forward the role of feedback in helping to understand the effect that this is going to have on the psychology of the driver. According to a survey of motor industry professionals, it can be expected over the course of the next 15 years that many sections of the driving task will become automated, cars will possess many more secondary features, and that the vehicle's controls themselves will no longer be physically connected to the mechanical systems under control, they will be electronically connected. Safety, efficiency, and enjoyment are the key dimensions along which car manufacturers want to optimise their designs for future technology. Increased in-vehicle technology has so far brought many improvements on these dimensions, and has the potential to keep on bringing benefits. However, and this is the key point, work in human factors suggests a certain degree of caution as to the expected benefits of implementing such new technology into vehicles (e.g. Wilde, 1994), and although rightly representing a potential opportunity in terms of vehicle design, new technology also represents a potential threat.

At least in some measure, technology is no longer the problem because in many respects the interaction that the vehicle has with the road (as specified by automotive engineering) is well understood, and rapidly becoming optimised. The issue is shifting towards integrating a vehicle's physical abilities more appropriately with the psychology of the driver, and a consistent theme throughout the interviews with motor industry professionals is that new and imaginative ways of doing this are highly desired. This thesis defines feedback as one means by which the driver/vehicle interaction can be optimised, and one means by which the vehicle designer can take active steps to favourably manipulate this interaction. Although variously described within psychological literature, a definition relevant to the car driving domain posits a three dimension model of feedback.

Feedback represents information to the driver about the current situation. Feedback can be represented by the content of feedback (the quantity, nature and accuracy of the information), the source of feedback (be it directly from the environment or indirect feedback through the vehicle; reactive to driver outputs or passive to the vehicle's ongoing status in the environment; explicit or implicit in presentation, all of these ultimately being transmitted to the driver via their sensory modalities), and finally timing (the speed and sequence of feedback). Coming from the opposite direction, the information needs of drivers can be specified by the task analysis presented in Chapter Two, and when content, source, and timing of feedback matches the information requirements of a given section of the driving task, then feedback quality has been achieved. This is the sought after design end state.

Chapters One and Two conclude with a feedback framework. This reconciles key psychological variables with the vehicle, the road, and of course the central concept of feedback. The feedback framework of driving is useful to the design engineer in terms of mapping the complexity of the relationships between psychological states, and identifying the key psychological variables in car design. On its own this is a useful contribution to knowledge. The framework takes a systems perspective, and information flows between the system elements. The driver receives feedback from the vehicle and the environment. This information is used in dynamic decision making governed by higher psychological processes. The results of decision making are passed to the vehicle in the form of driving tasks, and thus the transformation process starts afresh with new feedback and decision making. The framework provides the backdrop from which exploratory on-road studies, and highly controlled simulator studies can proceed.

Feedback enjoys a central role in this work, and its role within the driving task would appear by the literature and analysis cited and performed in Chapters One and Two to be an important one. Before the issue can be properly explored in a simulator environment, the issue is put to the test in the context of an exploratory on-road study. With detailed reference to the underlying automotive engineering characteristics of the participating vehicles, it is possible to operationalise them into three groups contingent upon the feedback that they provide to the driver. This is achieved because the vehicle's interaction with the road is measurable, and can therefore be specified in relation to the feedback that is available to the driver to perceive. This operationalisation took into account all three stages of feedback; content, source, and timing of feedback.

Whilst fully recognising the exploratory nature of the study, and the use of a between subjects paradigm, it can be argued that changes in the feedback status of the vehicle lead to changes in the way in which driver's perceived and put feedback information to use within the driving task. The results of the concurrent verbal protocol suggest that levels 1 and 2 SA can be enhanced, that better quality feedback helps to increase verbalisations concerning the road environment as well as the vehicle's system and control dynamics. Interestingly, self awareness of SA, or any lack of self awareness of SA is poor. However, feedback does seem to interact with mental workload, with low feedback vehicles and motorcyclists scoring higher Overall MWL than high feedback car drivers. There is also some evidence to suggest that feedback also interacts with levels of self rated frustration, physical demand, and temporal demand. Studying feedback in the naturalistic driving context, though necessarily exploratory in nature, serves its purpose well by providing valuable insights into the effect of feedback, and insights into the future design of more highly controlled simulator studies.

The Brunel University Driving Simulator was constructed by the author for the specific purpose of examining vehicle feedback (Chapter 4). The simulator is fixed base, and capable of providing feedback through four modalities; visual, auditory, tactile steering force feedback, and tactile seat resonators. In doing this, feedback maintains all of its on-road temporal and content related properties, as well as all the functional characteristics of real life driving. However, it is the source of feedback that was manipulated in a binary fashion. The different modalities were presented (with a visual baseline) in different combinations. In effect, the modalities were turned off and on like a tap, and a simulation of the normal on-road feedback was then allowed to flow through each appropriate modality. According to the feedback definition, manipulating the modality of presentation represents a powerful independent feedback characteristic.

A novel experimental approach was also adopted in Chapter Five in order to provide an enhancement on SAGAT's inherent subjectivity. To this end Signal Detection Theory was employed to gauge the driver's sensitivity to the various items of feedback information. These items of information were probed using a freeze technique in the simulator, and the probes were related directly to the earlier HTAoD where specific information, or SA requirements were elicited. Under this experimental paradigm, changes in sensitivity did occur according to the modalities of feedback presented to drivers. Once again, increasing the number of modalities of feedback presentation is implicated in increasing driver's SA. The feedback framework can be further enhanced because lower HTAoD categories require tactile feedback information, in contrast to higher HTAoD categories requiring auditory feedback. As before though, self awareness of SA remains poor.

Changes in MWL are also observed contingent upon feedback modality. In general terms feedback is implicated in causing reductions in MWL, with a combination of visual, auditory, and steering force feedback being the most effective in order to achieve this. It can be speculated that these results derive from the interaction between feedback and the skill based level of cognitive control. In addition to this, feedback is once again implicated in increasing driver enjoyment (or at least reducing frustration), and is also reflected in changes in lower, perhaps more accurate ratings of performance.

The combination of work presented in this thesis represents a significant contribution to knowledge. Chapter One presents the direction that future vehicle technology is likely to take, Chapter Two presents, firstly, a feedback framework and the psychological processes that the vehicle designer needs to consider. Secondly is the HTAoD, this being inextricably bound up in the feedback requirements of the driving task alongside, thirdly, the dimensions of content, sources, and timing of feedback. This representing a definition of feedback in vehicles. Chapter Three takes the analysis into the exploratory domain, Chapter Four details the design and construction of a driving simulator specifically built to analyse feedback, while Chapter Five uses the simulator to take the exploratory findings further into the experimental level. These studies combine to highlight the very favourable role that feedback can play in designing future cars for human use.

6.2 DESIGN GUIDELINES

The survey, the HTAoD, the feedback framework, and the experimental studies all lend support to the role of feedback in user-centred vehicle design. Based on the work contained in this thesis, a number of design issues can be highlighted for the vehicle designer, helping to provide insights in to exactly how to achieve high quality feedback.

1. Reference to automotive engineering helps to define the feedback properties, and quality, embodied by various different vehicle designs. It is apparent that higher levels of feedback quality enhance driver's situational awareness, enabling them to increase their perception of relevant elements in the environment.

2. Secondary to vision, auditory feedback is a dominant modality within the task of driving, and applies more prominently towards high category general driving tasks/goals. General Driving goals include reacting appropriately to different road types, and dealing with road and traffic hazards.

3. Steering force feedback and tactile underseat feedback are beneficial to the SA requirements of Basic and Specific Driving Tasks. These task categories are at the level of negotiating corners and dealing with specific road features such as junctions, gradients and crossings. Steering force feedback needs to be combined with tactile feedback to yield an increase in SA as neither modality yields increased sensitivity on its own. For vehicle design this implies that suspension design, ride quality, and steering feel are interrelated. For example, an isolated ride quality with steering feedback will not be as likely to yield greater SA.

4. The most efficient means for reducing mental workload via feedback is to employ visual, auditory, and steering force feedback. No further significant increases are brought about in terms of workload by the addition of tactile feedback through the driver's seat.

5. Feedback causes increases in driver satisfaction or enjoyment, thereby enhancing the driving experience. From a human factors point of view, the trend in modern automotive design to make cars quieter and controls lighter might not be entirely valid.

6. Finally, greater feedback can make drivers rate their performance lower. Whether it is objectively lower, or subjectively felt to be lower is at this stage unclear. In whatever eventuality, this finding has potentially favourable design implications for increasing risk perception, and reducing risk taking.

6.3 DIRECTIONS FOR FUTURE WORK

The robustness of the feedback framework and the studies contained within this Thesis can be taken further and enhanced from a methodological standpoint. The on-road study can easily be extended to cover more participants, even to analyse feedback according to different road types. In addition, the simulator studies can easily be extended with even greater simulator fidelity combined with the ability to be able to measure and record driver inputs and vehicle performance as primary task measures. This could be an especially valuable further step for the mental workload simulator studies, as more targeted research could invoke the use of these additional measures. Clearly methodological constraints are to a large extent imposed by equipment, cost, and time limitations. The studies contained in this Thesis attempt a balance between these factors.

Moving away from methodological enhancements, there are also a number of future steps that can be taken to explore the construct of feedback in more detail. There are a total of nine dimensions under the combined headings of content, timing and source of feedback. Each of these nine dimensions can be examined separately. As an example of this, consider that the timing of feedback can be studied independently; instant versus delayed feedback perhaps, or else the content of feedback; large quantity versus small quantity of feedback. Many further subtle manipulations can also be examined from a *design* perspective, take for example changing implicit feedback to explicit feedback. In practical terms, this might mean a visual display of actual cornering forces compared to potential cornering forces. This would be a visual alternative/or joint source of feedback normally derived from implicit cues gained from tactile and kinaesthetic modalities. Crucially, these are all feedback possibilities well within the realm of future technology, and in themselves represent new and exciting future directions.

There can be little doubt that via the methodologies employed here, feedback reveals itself as a powerful independent variable, and therefore has important vehicle design implications. The feedback framework speaks towards defining the feedback and information needs of drivers; needs to which future technology is at least *potentially* able to *fully* support. In particular, for medium category driving tasks steering force feedback is heavily implicated in reducing driver frustration and workload and improving driver situational awareness. The designers of drive by wire systems can obviously benefit from this knowledge. Drive by wire systems, though capable of stripping the vehicle of *all* inherent feedback, also have the advantage of potentially being able to present to drivers their exact moment to moment feedback needs. This could represent in itself a very specific new area of targeted feedback application and research. In-vehicle devices couched at higher categories of driving task enactment, for example navigation systems, would seem to be implicated in the need to supply auditory feedback. Therefore, under this analysis navigation systems relying on voice synthesis rather than visual displays seem justified. And, so the examples can continue. It is of course difficult to specify and answer every possible design application of this knowledge, but the following hypothetical test drives present the design case more conclusively.

6.4 VEHICLE DESIGN IMPLICATIONS OF THE FEEDBACK MODEL OF DRIVING

6.4.1 An Optimistic 2017 Test Drive

Pulling out of the driveway, the handling management system rapidly detects via G-sensors and inputs from the active yaw system that the vehicle is travelling on challenging twisting roads. Neural networks within the drive by wire systems and engine management also detect that the driver is adopting a more 'sporting' driving style. These systems signal to the steer by wire and the active damping system to endow the chassis with greater, more responsive 'turn-in' characteristics at the expense of straight line stability. At the same time the engine management will revert to performance orientated fuel cell and traction motor maps, the combined effect of which serves to reduce response time lag, an important determinant of driver feedback quality. The soft instrument cluster also gives extra dominance to the rev counter and other engine parameters such as power consumption and temperature that befit the type of driving currently in progress. In essence, the vehicle intelligently adjusts its control and system dynamics in accordance with feedback model predictions, which in turn affects the driver's mental models of how the vehicle is responding to control inputs and the state of the vehicle within its environment. Careful human factors design at this stage ensures that vehicle feedback is optimal and characteristically sporty, such that the driver's mental models are accurate; therefore serving to enhance situational awareness and intrinsic risk appraisal.

As well as adjusting itself to the characteristics of the driver and their current driving style, the vehicle's embedded computers have been tailored to the sales market that this particular car was sold into. Identical cars sold into the German market have been biased towards a firm ride and vigorous high speed acceleration for autobahns, whereas the same car sold into the North American market has been biased towards a more compliant ride and energetic acceleration from lower speeds to cope with intersections and long distance driving. This ensures that its characteristics are well suited to the types of road environment that the vehicle is to be driven in. Furthermore, at the heart of the software running on the vehicle's embedded computing are a number of inviolable programs that define the vehicle's unmistakable, distinctive brand character or DNA. In this case the particular brand of vehicle is known for its very civilised ride characteristics coupled with lively performance. The embedded computing ensures that this is the overriding impression conveyed to the driver despite what other system or control dynamics it may be adjusting.

Upon joining a motorway the ACC automatically begins detecting other vehicles, and after monitoring control inputs detects, based on learned strategies, that the driver might be ready to pass control to the vehicle; it then offers support to the driver, as does the traffic information and GPS navigation system. Minor diversionary routes are busy with traffic avoiding a number of busy junctions ahead, and the route management system calculates that it will still be quicker to stay on the motorway; as navigation is a higher category driving task this information is passed to the driver via auditory feedback. This helps the driver to select routes that maximise the efficiency with which the road network can be used. Human factors ensures that not only is the transition from manual to automatic ACC control performed seamlessly, but that the automatic system interfaces with the driver effectively. It does this through monitoring mental workload by analysing control inputs, surrounding traffic, the driver's blink rate, and driver response times to navigation advice (a form of secondary task); thus ensuring that the transition to full ACC operation occurs with the driver fully in the loop and during conditions of optimum vehicle feedback. As such, the driver is constantly aware of the vehicle's status and mode, and mental workload is held at an optimal level. Behind the scenes the engine management is reverting to engine control maps that optimise fuel efficiency, and the soft instrument cluster gives prominence to the speedometer. Recognizing that sporty levels of feedback can increase mental workload, and are therefore inappropriate for motorway cruising, the steer by wire and active damping adjust the chassis for comfort and straight line stability.

The driver eventually joins a platoon of vehicles in the outside lane of the motorway, with all the vehicles in the convoy sensing each other via radar. The driver just has to steer the vehicle, and good progress is being made with minimal physical effort. In the platooning mode the chassis is gradually adjusted for a firmer ride (increasing tactile feedback through the seat), and engine noise is also adjusted slightly. This slight increase in vehicle feedback helps to sustain mental workload at a reasonable level, and provides an auditory cue as to how ACC is manipulating engine power and vehicle speed. The driver's response to automatic braking and the need to occasionally intervene is closely monitored, and the vehicle remains ready to relinquish control, and if required to do so will gradually ramp up driver feedback until the transition is complete. In the meantime an older vehicle in the middle lane has not noticed the vehicle in front of it slowing suddenly, and cuts sharply into the path of the car.

The car's 360 degree sensors detect a potential collision. The drive by wire sensors detect that the driver is not *quite* using the vehicle's abilities to the full, so the vehicle steps in to *assist* by initiating the ABS and cutting the vehicle's audio and communication system. The car now detects that the driver *is* responding with collision avoidance manoeuvres. The vehicle's drive by wire systems augment the feedback made available to the driver via the controls, which serves to encourage the driver to make full use of the vehicle's considerable road holding abilities. In particular, the steering torque gradient is maintained to a much higher level, as the dead-zone of steering response will cause the driver to think that grip is being lost before it actually has been (in normal driving the dead zone is somewhat lower to *implicitly* encourage the driver not to push the vehicle too hard). The driver is now taking vigorous evasive action, taking in inputs that the vehicle's collision avoidance system simply cannot see. The vehicle's computer architecture was designed with this in mind, and helps the driver as much as possible. To do this information is flowing between vehicle systems throughout the car via the OSEK architecture. The active yaw control and ABS are talking to the engine management so that the driven wheels are helping in skid control and collision avoidance. This causes the car to conform as closely as possible to the driver's inputs despite its 'on the limit' status. But just in case, the smart airbags already know that there are two occupants on board, an individual in the driver's seat who weighs 90Kg and a passenger in the front seat weighing 60Kg, and if required would deploy accordingly, as would seat belt pre-tensioners via powerful 42volt actuators. Fortunately the car, by helping and supporting the driver within a task in which they are generally very good, has enabled this brief incident to be successfully avoided, and the journey can resume as before.

6.4.2 A Pessimistic 2017 Test Drive

Pulling out of the driveway the driver accelerates hard whilst piloting the car along twisting country lanes. The car is certainly going where the driver is intending it to, but the feedback is a little confusing for the driver. The whole driving experience feels rather sterile, as though the controls are remote from the devices actually under control. It appears that even the most subtle inaccuracy in the timing of feedback cues made available to the driver through the primary controls gives rise to inaccurate mental models of the vehicle's state, and thus the driver's situational awareness (unbeknown to them) is actually quite poor. As a result of this the driver is not able to comprehend the fact that the road is rather uneven, and therefore driving performance and utility suffers; the vehicle leaves the uneven road section with a muted thump and gives a gentle weave towards the kerb as a consequence, which to the driver's mind is for no apparent reason. It looked excellent in the car showroom, but the dashboard now persists in altering its appearance and layout and the driver simply finds this distracting. Another thing that appeared good in the showroom was the dual fuel power train; its certainly powerful, but the transition between power modes is hesitant to say the least, and the throttle response is rather inconsistent.

Accelerating onto the motorway the autonomous ACC system automatically activates, braking the vehicle even though the driver is halfway through a lane change whilst filtering past traffic, admittedly at headways slightly less than the regulation 'safe' two seconds. The driver would actually prefer to remain in manual control for a while to settle down to a desirable cruise speed. The navigation system also attempts to be helpful, but the driver already knows exactly where they want to go. Besides which, the navigation system sent the driver along 15miles of externally speed restricted 30mph roads the other day, and they do not wish to repeat the experience. Unfortunately, the head-up route display is also rather distracting, as the visual channel is preoccupied enough, and the driver has difficulty in shutting the device down. Increasingly frustrated the driver sets the cruise speed to a belligerent 100mph (a local performance dealer is able to recalibrate the 70mph speed limiter using a chip intended for the German market) and therefore sets about picking their way through slower traffic. Misuse of one of the vehicle's automated systems means that there is no longer much need to use the vehicle's mirrors prior to indicating. This is because the driver, over time, has learnt to trust the collision warning system, and it generally warns the driver if there is a car alongside using a virtual camber that increases steering resistance in the direction of the potential collision. But to the driver's yet to be encountered surprise, a resident pathogen in the system means that it doesn't always detect motorbikes.

Five miles down the road the driver joins a platoon of ACC equipped cars cruising in convoy in the outside lane of the motorway. Although heavily frowned upon by the police, ACC allows the lead car to set their cruise speed to 70mph, which in terms of target risk is about the level at which most drivers seem willing to exceed the 50mph variable motorway speed limit by; the temporary speed limit is due to patchy fog. It is also implicitly assumed by other drivers that the lead vehicle is anticipating the road conditions further ahead on their behalf, and the following drivers, apart from steering the vehicle, tend to disengage with the driving task as mental underload takes effect. Cars are so quiet and refined it feels rather like floating down the road, and besides, in-vehicle devices such as MP3 players and in-car internet provide plenty of other things to do whilst cruising.

However, while passing a string of older vehicles in the middle lane the driver notices that brake lights are coming on, a valuable early warning cue that the collision avoidance system does not notice. As anticipated by the driver, a vehicle from the middle lane cuts across immediately in front of the car. The driver could see that the other vehicle, though very close indeed is trying to accelerate out of the way, so the driver is not expecting a collision. At the instant before the driver was about to shift into a small vacant gap in the adjacent lane the ABS cuts in violently. Whilst sustaining an unexpected one G of deceleration, the driver still tries to steer left to allow the other car to pass in front, but the collision avoidance system has other ideas. The steer by wire system, having relegated the steering wheel to being merely a transducer totally overrides the driver's steering inputs. In an almost comic fleeting instance the driver is furiously twirling the wheel with no discernable effect on vehicle trajectory. The collision avoidance system maintains the car in a straight ahead position because the physical model embedded in the vehicle's software architecture knows this to be the most efficacious for rapid braking. This failure to be able to exert control causes the driver to panic. Although the driver is still required to step into the control loop when in-vehicle automation cannot cope with unexpected situations, in this case the car had ultimate authority. The driver and passenger are suddenly recoiled back in their seats as the seat belt pre-tensioners activate, the driver's view is then totally obscured as the airbags deploy and a violent collision occurs at the front of the vehicle. Both occupants are shaken but otherwise completely unharmed. The technology proving to be especially efficient 'after the event'. Unfortunately, the other older vehicle and its occupants have not emerged from the collision with the newer car very well at all.

6.5 FINAL CONCLUSIONS

These two scenarios illustrate the role of feedback, the potential effects on driver behaviour, as well the psychological factors that need to be considered for current in-vehicle systems, and systems that have yet to enter vehicles. From a technical standpoint the two scenarios are identical, differing only in respect of the *implementation* of the technology. Scenario one is a technological and human factors utopia. It demonstrates how technology and embedded computing optimises the interaction that the vehicle has with the road, and how it can potentially enhance the interaction between the vehicle and the driver. The assumption in this case is that the implementation of vehicle technology has benefited from the insights embodied by the feedback framework to actively enhance feedback to the driver, leading to accurate mental models and good situational awareness. In addition, allocation of function is optimised (again using feedback) to smooth the integration and transition between the machine and human elements of the system, furthermore, the design of this automation loads attentional resources optimally. Conversely, scenario two presents a situation whereby the vehicle and its associated technology is interacting optimally with the road, but not with the psychology of the driver. This causes inaccurate mental models, poor situational awareness, sub-optimal mental workload, and poor risk perception. It also presents a view of the driver fighting for control with the vehicle systems. This view is not as far fetched as it may seem, as very similar types of incident have been reported in aviation where the pilot's inputs have been totally over-ridden by automation (Sarter & Woods, 1997). Frustration and misuse seem to be the inevitable consequences of this. What is relevant to both scenarios is the issue of partial integration, whereby the newer technology laden vehicle is sharing the road with older, less sophisticated vehicles, with a range of consequences especially for safety and efficiency.

By now it is evident that all vehicle technologies have consequences, some of them unanticipated, not only for the interaction that the vehicle has with the road, and other vehicles, but also for the interaction between the car and driver. What should be clear is that the whole issue is much more complex than merely putting yet more technology into vehicles. Increased in-vehicle technology presents an *opportunity* and a *threat* in terms of the consequences for feedback to the driver. As shown by the two scenarios above, the consequences for the driver could easily go either way. In order to ensure that future vehicle technologies are designed to maximise their potential benefits, on the evidence of this thesis there is still much that remains to be learnt. Part of this gap in knowledge is feedback. Feedback presents itself within this thesis as one means by which safety, efficiency, and enjoyment can be maximised by the designer, and one means by which novel and imaginative user-centred car design solutions can be achieved.

Chapter 6

Conclusions

6.1 SUMMARY

Technology is set to influence and change the nature of the driving task in a variety of profound ways. This thesis puts forward the role of feedback in helping to understand the effect that this is going to have on the psychology of the driver. According to a survey of motor industry professionals, it can be expected over the course of the next 15 years that many sections of the driving task will become automated, cars will possess many more secondary features, and that the vehicle's controls themselves will no longer be physically connected to the mechanical systems under control, they will be electronically connected. Safety, efficiency, and enjoyment are the key dimensions along which car manufacturers want to optimise their designs for future technology. Increased in-vehicle technology has so far brought many improvements on these dimensions, and has the potential to keep on bringing benefits. However, and this is the key point, work in human factors suggests a certain degree of caution as to the expected benefits of implementing such new technology into vehicles (e.g. Wilde, 1994), and although rightly representing a potential opportunity in terms of vehicle design, new technology also represents a potential threat.

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Feedback represents information to the driver about the current situation. Feedback can be represented by the content of feedback (the quantity, nature and accuracy of the information), the source of feedback (be it directly from the environment or indirect feedback through the vehicle; reactive to driver outputs or passive to the vehicle's ongoing status in the environment; explicit or implicit in presentation, all of these ultimately being transmitted to the driver via their sensory modalities), and finally timing (the speed and sequence of feedback). Coming from the opposite direction, the information needs of drivers can be specified by the task analysis presented in Chapter Two, and when content, source, and timing of feedback matches the information requirements of a given section of the driving task, then feedback quality has been achieved. This is the sought after design end state.

Chapters One and Two conclude with a feedback framework. This reconciles key psychological variables with the vehicle, the road, and of course the central concept of feedback. The feedback framework of driving is useful to the design engineer in terms of mapping the complexity of the relationships between psychological states, and identifying the key psychological variables in car design. On its own this is a useful contribution to knowledge. The framework takes a systems perspective, and information flows between the system elements. The driver receives feedback from the vehicle and the environment. This information is used in dynamic decision making governed by higher psychological processes. The results of decision making are passed to the vehicle in the form of driving tasks, and thus the transformation process starts afresh with new feedback and decision making. The framework provides the backdrop from which exploratory on-road studies, and highly controlled simulator studies can proceed.

Feedback enjoys a central role in this work, and its role within the driving task would appear by the literature and analysis cited and performed in Chapters One and Two to be an important one. Before the issue can be properly explored in a simulator environment, the issue is put to the test in the context of an exploratory on-road study. With detailed reference to the underlying automotive engineering characteristics of the participating vehicles, it is possible to operationalise them into three groups contingent upon the feedback that they provide to the driver. This is achieved because the vehicle's interaction with the road is measurable, and can therefore be specified in relation to the feedback that is available to the driver to perceive. This operationalisation took into account all three stages of feedback; content, source, and timing of feedback.

Whilst fully recognising the exploratory nature of the study, and the use of a between subjects paradigm, it can be argued that changes in the feedback status of the vehicle lead to changes in the way in which driver's perceived and put feedback information to use within the driving task. The results of the concurrent verbal protocol suggest that levels 1 and 2 SA can be enhanced, that better quality feedback helps to increase verbalisations concerning the road environment as well as the vehicle's system and control dynamics. Interestingly, self awareness of SA, or any lack of self awareness of SA is poor. However, feedback does seem to interact with mental workload, with low feedback vehicles and motorcyclists scoring higher Overall MWL than high feedback car drivers. There is also some evidence to suggest that feedback also interacts with levels of self rated frustration, physical demand, and temporal demand. Studying feedback in the naturalistic driving context, though necessarily exploratory in nature, serves its purpose well by providing valuable insights into the effect of feedback, and insights into the future design of more highly controlled simulator studies.

The Brunel University Driving Simulator was constructed by the author for the specific purpose of examining vehicle feedback (Chapter 4). The simulator is fixed base, and capable of providing feedback through four modalities; visual, auditory, tactile steering force feedback, and tactile seat resonators. In doing this, feedback maintains all of its on-road temporal and content related properties, as well as all the functional characteristics of real life driving. However, it is the source of feedback that was manipulated in a binary fashion. The different modalities were presented (with a visual baseline) in different combinations. In effect, the modalities were turned off and on like a tap, and a simulation of the normal on-road feedback was then allowed to flow through each appropriate modality. According to the feedback definition, manipulating the modality of presentation represents a powerful independent feedback characteristic.

A novel experimental approach was also adopted in Chapter Five in order to provide an enhancement on SAGAT's inherent subjectivity. To this end Signal Detection Theory was employed to gauge the driver's sensitivity to the various items of feedback information. These items of information were probed using a freeze technique in the simulator, and the probes were related directly to the earlier HTAoD where specific information, or SA requirements were elicited. Under this experimental paradigm, changes in sensitivity did occur according to the modalities of feedback presented to drivers. Once again, increasing the number of modalities of feedback presentation is implicated in increasing driver's SA. The feedback framework can be further enhanced because lower HTAoD categories require tactile feedback information, in contrast to higher HTAoD categories requiring auditory feedback. As before though, self awareness of SA remains poor.

Changes in MWL are also observed contingent upon feedback modality. In general terms feedback is implicated in causing reductions in MWL, with a combination of visual, auditory, and steering force feedback being the most effective in order to achieve this. It can be speculated that these results derive from the interaction between feedback and the skill based level of cognitive control. In addition to this, feedback is once again implicated in increasing driver enjoyment (or at least reducing frustration), and is also reflected in changes in lower, perhaps more accurate ratings of performance.

The combination of work presented in this thesis represents a significant contribution to knowledge. Chapter One presents the direction that future vehicle technology is likely to take, Chapter Two presents, firstly, a feedback framework and the psychological processes that the vehicle designer needs to consider. Secondly is the HTAoD, this being inextricably bound up in the feedback requirements of the driving task alongside, thirdly, the dimensions of content, sources, and timing of feedback. This representing a definition of feedback in vehicles. Chapter Three takes the analysis into the exploratory domain, Chapter Four details the design and construction of a driving simulator specifically built to analyse feedback, while Chapter Five uses the simulator to take the exploratory findings further into the experimental level. These studies combine to highlight the very favourable role that feedback can play in designing future cars for human use.

6.2 DESIGN GUIDELINES

The survey, the HTAoD, the feedback framework, and the experimental studies all lend support to the role of feedback in user-centred vehicle design. Based on the work contained in this thesis, a number of design issues can be highlighted for the vehicle designer, helping to provide insights in to exactly how to achieve high quality feedback.

1. Reference to automotive engineering helps to define the feedback properties, and quality, embodied by various different vehicle designs. It is apparent that higher levels of feedback quality enhance driver's situational awareness, enabling them to increase their perception of relevant elements in the environment.

2. Secondary to vision, auditory feedback is a dominant modality within the task of driving, and applies more prominently towards high category general driving tasks/goals. General Driving goals include reacting appropriately to different road types, and dealing with road and traffic hazards.

3. Steering force feedback and tactile underseat feedback are beneficial to the SA requirements of Basic and Specific Driving Tasks. These task categories are at the level of negotiating corners and dealing with specific road features such as junctions, gradients and crossings. Steering force feedback needs to be combined with tactile feedback to yield an increase in SA as neither modality yields increased sensitivity on its own. For vehicle design this implies that suspension design, ride quality, and steering feel are interrelated. For example, an isolated ride quality with steering feedback will not be as likely to yield greater SA.

4. The most efficient means for reducing mental workload via feedback is to employ visual, auditory, and steering force feedback. No further significant increases are brought about in terms of workload by the addition of tactile feedback through the driver's seat.

5. Feedback causes increases in driver satisfaction or enjoyment, thereby enhancing the driving experience. From a human factors point of view, the trend in modern automotive design to make cars quieter and controls lighter might not be entirely valid.

6. Finally, greater feedback can make drivers rate their performance lower. Whether it is objectively lower, or subjectively felt to be lower is at this stage unclear. In whatever eventuality, this finding has potentially favourable design implications for increasing risk perception, and reducing risk taking.

6.3 DIRECTIONS FOR FUTURE WORK

The robustness of the feedback framework and the studies contained within this Thesis can be taken further and enhanced from a methodological standpoint. The on-road study can easily be extended to cover more participants, even to analyse feedback according to different road types. In addition, the simulator studies can easily be extended with even greater simulator fidelity combined with the ability to be able to measure and record driver inputs and vehicle performance as primary task measures. This could be an especially valuable further step for the mental workload simulator studies, as more targeted research could invoke the use of these additional measures. Clearly methodological constraints are to a large extent imposed by equipment, cost, and time limitations. The studies contained in this Thesis attempt a balance between these factors.

Moving away from methodological enhancements, there are also a number of future steps that can be taken to explore the construct of feedback in more detail. There are a total of nine dimensions under the combined headings of content, timing and source of feedback. Each of these nine dimensions can be examined separately. As an example of this, consider that the timing of feedback can be studied independently; instant versus delayed feedback perhaps, or else the content of feedback; large quantity versus small quantity of feedback. Many further subtle manipulations can also be examined from a *design* perspective, take for example changing implicit feedback to explicit feedback. In practical terms, this might mean a visual display of actual cornering forces compared to potential cornering forces. This would be a visual alternative/or joint source of feedback normally derived from implicit cues gained from tactile and kinaesthetic modalities. Crucially, these are all feedback possibilities well within the realm of future technology, and in themselves represent new and exciting future directions.

There can be little doubt that via the methodologies employed here, feedback reveals itself as a powerful independent variable, and therefore has important vehicle design implications. The feedback framework speaks towards defining the feedback and information needs of drivers; needs to which future technology is at least *potentially* able to *fully* support. In particular, for medium category driving tasks steering force feedback is heavily implicated in reducing driver frustration and workload and improving driver situational awareness. The designers of drive by wire systems can obviously benefit from this knowledge. Drive by wire systems, though capable of stripping the vehicle of *all* inherent feedback, also have the advantage of potentially being able to present to drivers their exact moment to moment feedback needs. This could represent in itself a very specific new area of targeted feedback application and research. In-vehicle devices couched at higher categories of driving task enactment, for example navigation systems, would seem to be implicated in the need to supply auditory feedback. Therefore, under this analysis navigation systems relying on voice synthesis rather than visual displays seem justified. And, so the examples can continue. It is of course difficult to specify and answer every possible design application of this knowledge, but the following hypothetical test drives present the design case more conclusively.

6.4 VEHICLE DESIGN IMPLICATIONS OF THE FEEDBACK MODEL OF DRIVING

6.4.1 An Optimistic 2017 Test Drive

Pulling out of the driveway, the handling management system rapidly detects via G-sensors and inputs from the active yaw system that the vehicle is travelling on challenging twisting roads. Neural networks within the drive by wire systems and engine management also detect that the driver is adopting a more 'sporting' driving style. These systems signal to the steer by wire and the active damping system to endow the chassis with greater, more responsive 'turn-in' characteristics at the expense of straight line stability. At the same time the engine management will revert to performance orientated fuel cell and traction motor maps, the combined effect of which serves to reduce response time lag, an important determinant of driver feedback quality. The soft instrument cluster also gives extra dominance to the rev counter and other engine parameters such as power consumption and temperature that befit the type of driving currently in progress. In essence, the vehicle intelligently adjusts its control and system dynamics in accordance with feedback model predictions, which in turn affects the driver's mental models of how the vehicle is responding to control inputs and the state of the vehicle within its environment. Careful human factors design at this stage ensures that vehicle feedback is optimal and characteristically sporty, such that the driver's mental models are accurate; therefore serving to enhance situational awareness and intrinsic risk appraisal.

As well as adjusting itself to the characteristics of the driver and their current driving style, the vehicle's embedded computers have been tailored to the sales market that this particular car was sold into. Identical cars sold into the German market have been biased towards a firm ride and vigorous high speed acceleration for autobahns, whereas the same car sold into the North American market has been biased towards a more compliant ride and energetic acceleration from lower speeds to cope with intersections and long distance driving. This ensures that its characteristics are well suited to the types of road environment that the vehicle is to be driven in. Furthermore, at the heart of the software running on the vehicle's embedded computing are a number of inviolable programs that define the vehicle's unmistakable, distinctive brand character or DNA. In this case the particular brand of vehicle is known for its very civilised ride characteristics coupled with lively performance. The embedded computing ensures that this is the overriding impression conveyed to the driver despite what other system or control dynamics it may be adjusting.

Upon joining a motorway the ACC automatically begins detecting other vehicles, and after monitoring control inputs detects, based on learned strategies, that the driver might be ready to pass control to the vehicle; it then offers support to the driver, as does the traffic information and GPS navigation system. Minor diversionary routes are busy with traffic avoiding a number of busy junctions ahead, and the route management system calculates that it will still be quicker to stay on the motorway; as navigation is a higher category driving task this information is passed to the driver via auditory feedback. This helps the driver to select routes that maximise the efficiency with which the road network can be used. Human factors ensures that not only is the transition from manual to automatic ACC control performed seamlessly, but that the automatic system interfaces with the driver effectively. It does this through monitoring mental workload by analysing control inputs, surrounding traffic, the driver's blink rate, and driver response times to navigation advice (a form of secondary task); thus ensuring that the transition to full ACC operation occurs with the driver fully in the loop and during conditions of optimum vehicle feedback. As such, the driver is constantly aware of the vehicle's status and mode, and mental workload is held at an optimal level. Behind the scenes the engine management is reverting to engine control maps that optimise fuel efficiency, and the soft instrument cluster gives prominence to the speedometer. Recognizing that sporty levels of feedback can increase mental workload, and are therefore inappropriate for motorway cruising, the steer by wire and active damping adjust the chassis for comfort and straight line stability.

The driver eventually joins a platoon of vehicles in the outside lane of the motorway, with all the vehicles in the convoy sensing each other via radar. The driver just has to steer the vehicle, and good progress is being made with minimal physical effort. In the platooning mode the chassis is gradually adjusted for a firmer ride (increasing tactile feedback through the seat), and engine noise is also adjusted slightly. This slight increase in vehicle feedback helps to sustain mental workload at a reasonable level, and provides an auditory cue as to how ACC is manipulating engine power and vehicle speed. The driver's response to automatic braking and the need to occasionally intervene is closely monitored, and the vehicle remains ready to relinquish control, and if required to do so will gradually ramp up driver feedback until the transition is complete. In the meantime an older vehicle in the middle lane has not noticed the vehicle in front of it slowing suddenly, and cuts sharply into the path of the car.

The car's 360 degree sensors detect a potential collision. The drive by wire sensors detect that the driver is not *quite* using the vehicle's abilities to the full, so the vehicle steps in to *assist* by initiating the ABS and cutting the vehicle's audio and communication system. The car now detects that the driver *is* responding with collision avoidance manoeuvres. The vehicle's drive by wire systems augment the feedback made available to the driver via the controls, which serves to encourage the driver to make full use of the vehicle's considerable road holding abilities. In particular, the steering torque gradient is maintained to a much higher level, as the dead-zone of steering response will cause the driver to think that grip is being lost before it actually has been (in normal driving the dead zone is somewhat lower to *implicitly* encourage the driver not to push the vehicle too hard). The driver is now taking vigorous evasive action, taking in inputs that the vehicle's collision avoidance system simply cannot see. The vehicle's computer architecture was designed with this in mind, and helps the driver as much as possible. To do this information is flowing between vehicle systems throughout the car via the OSEK architecture. The active yaw control and ABS are talking to the engine management so that the driven wheels are helping in skid control and collision avoidance. This causes the car to conform as closely as possible to the driver's inputs despite its 'on the limit' status. But just in case, the smart airbags already know that there are two occupants on board, an individual in the driver's seat who weighs 90Kg and a passenger in the front seat weighing 60Kg, and if required would deploy accordingly, as would seat belt pre-tensioners via powerful 42volt actuators. Fortunately the car, by helping and supporting the driver within a task in which they are generally very good, has enabled this brief incident to be successfully avoided, and the journey can resume as before.

6.4.2 A Pessimistic 2017 Test Drive

Pulling out of the driveway the driver accelerates hard whilst piloting the car along twisting country lanes. The car is certainly going where the driver is intending it to, but the feedback is a little confusing for the driver. The whole driving experience feels rather sterile, as though the controls are remote from the devices actually under control. It appears that even the most subtle inaccuracy in the timing of feedback cues made available to the driver through the primary controls gives rise to inaccurate mental models of the vehicle's state, and thus the driver's situational awareness (unbeknown to them) is actually quite poor. As a result of this the driver is not able to comprehend the fact that the road is rather uneven, and therefore driving performance and utility suffers; the vehicle leaves the uneven road section with a muted thump and gives a gentle weave towards the kerb as a consequence, which to the driver's mind is for no apparent reason. It looked excellent in the car showroom, but the dashboard now persists in altering its appearance and layout and the driver simply finds this distracting. Another thing that appeared good in the showroom was the dual fuel power train; its certainly powerful, but the transition between power modes is hesitant to say the least, and the throttle response is rather inconsistent.

Accelerating onto the motorway the autonomous ACC system automatically activates, braking the vehicle even though the driver is halfway through a lane change whilst filtering past traffic, admittedly at headways slightly less than the regulation 'safe' two seconds. The driver would actually prefer to remain in manual control for a while to settle down to a desirable cruise speed. The navigation system also attempts to be helpful, but the driver already knows exactly where they want to go. Besides which, the navigation system sent the driver along 15miles of externally speed restricted 30mph roads the other day, and they do not wish to repeat the experience. Unfortunately, the head-up route display is also rather distracting, as the visual channel is preoccupied enough, and the driver has difficulty in shutting the device down. Increasingly frustrated the driver sets the cruise speed to a belligerent 100mph (a local performance dealer is able to recalibrate the 70mph speed limiter using a chip intended for the German market) and therefore sets about picking their way through slower traffic. Misuse of one of the vehicle's automated systems means that there is no longer much need to use the vehicle's mirrors prior to indicating. This is because the driver, over time, has learnt to trust the collision warning system, and it generally warns the driver if there is a car alongside using a virtual camber that increases steering resistance in the direction of the potential collision. But to the driver's yet to be encountered surprise, a resident pathogen in the system means that it doesn't always detect motorbikes.

Five miles down the road the driver joins a platoon of ACC equipped cars cruising in convoy in the outside lane of the motorway. Although heavily frowned upon by the police, ACC allows the lead car to set their cruise speed to 70mph, which in terms of target risk is about the level at which most drivers seem willing to exceed the 50mph variable motorway speed limit by; the temporary speed limit is due to patchy fog. It is also implicitly assumed by other drivers that the lead vehicle is anticipating the road conditions further ahead on their behalf, and the following drivers, apart from steering the vehicle, tend to disengage with the driving task as mental underload takes effect. Cars are so quiet and refined it feels rather like floating down the road, and besides, in-vehicle devices such as MP3 players and in-car internet provide plenty of other things to do whilst cruising.

However, while passing a string of older vehicles in the middle lane the driver notices that brake lights are coming on, a valuable early warning cue that the collision avoidance system does not notice. As anticipated by the driver, a vehicle from the middle lane cuts across immediately in front of the car. The driver could see that the other vehicle, though very close indeed is trying to accelerate out of the way, so the driver is not expecting a collision. At the instant before the driver was about to shift into a small vacant gap in the adjacent lane the ABS cuts in violently. Whilst sustaining an unexpected one G of deceleration, the driver still tries to steer left to allow the other car to pass in front, but the collision avoidance system has other ideas. The steer by wire system, having relegated the steering wheel to being merely a transducer totally overrides the driver's steering inputs. In an almost comic fleeting instance the driver is furiously twirling the wheel with no discernable effect on vehicle trajectory. The collision avoidance system maintains the car in a straight ahead position because the physical model embedded in the vehicle's software architecture knows this to be the most efficacious for rapid braking. This failure to be able to exert control causes the driver to panic. Although the driver is still required to step into the control loop when in-vehicle automation cannot cope with unexpected situations, in this case the car had ultimate authority. The driver and passenger are suddenly recoiled back in their seats as the seat belt pre-tensioners activate, the driver's view is then totally obscured as the airbags deploy and a violent collision occurs at the front of the vehicle. Both occupants are shaken but otherwise completely unharmed. The technology proving to be especially efficient 'after the event'. Unfortunately, the other older vehicle and its occupants have not emerged from the collision with the newer car very well at all.

6.5 FINAL CONCLUSIONS

These two scenarios illustrate the role of feedback, the potential effects on driver behaviour, as well the psychological factors that need to be considered for current in-vehicle systems, and systems that have yet to enter vehicles. From a technical standpoint the two scenarios are identical, differing only in respect of the *implementation* of the technology. Scenario one is a technological and human factors utopia. It demonstrates how technology and embedded computing optimises the interaction that the vehicle has with the road, and how it can potentially enhance the interaction between the vehicle and the driver. The assumption in this case is that the implementation of vehicle technology has benefited from the insights embodied by the feedback framework to actively enhance feedback to the driver, leading to accurate mental models and good situational awareness. In addition, allocation of function is optimised (again using feedback) to smooth the integration and transition between the machine and human elements of the system, furthermore, the design of this automation loads attentional resources optimally. Conversely, scenario two presents a situation whereby the vehicle and its associated technology is interacting optimally with the road, but not with the psychology of the driver. This causes inaccurate mental models, poor situational awareness, sub-optimal mental workload, and poor risk perception. It also presents a view of the driver fighting for control with the vehicle systems. This view is not as far fetched as it may seem, as very similar types of incident have been reported in aviation where the pilot's inputs have been totally over-ridden by automation (Sarter & Woods, 1997). Frustration and misuse seem to be the inevitable consequences of this. What is relevant to both scenarios is the issue of partial integration, whereby the newer technology laden vehicle is sharing the road with older, less sophisticated vehicles, with a range of consequences especially for safety and efficiency.

By now it is evident that all vehicle technologies have consequences, some of them unanticipated, not only for the interaction that the vehicle has with the road, and other vehicles, but also for the interaction between the car and driver. What should be clear is that the whole issue is much more complex than merely putting yet more technology into vehicles. Increased in-vehicle technology presents an *opportunity* and a *threat* in terms of the consequences for feedback to the driver. As shown by the two scenarios above, the consequences for the driver could easily go either way. In order to ensure that future vehicle technologies are designed to maximise their potential benefits, on the evidence of this thesis there is still much that remains to be learnt. Part of this gap in knowledge is feedback. Feedback presents itself within this thesis as one means by which safety, efficiency, and enjoyment can be maximised by the designer, and one means by which novel and imaginative user-centred car design solutions can be achieved.

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