UNIVERSITY OF SOUTHAMPTON
FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
Institute of Sound and Vibration Research

Driver Perception of Steady-State Steering Feel

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ABSTRACT

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DRIVER PERCEPTION OF STEADY-STATE STEERING FEEL

Anna Christina Newberry

Steering feel (the sensation experienced when interacting with the steering wheel) is a sought after attribute, and yet remains one of the most elusive for car manufacturers. Attempts to simulate and evaluate steering feel have been found wanting, and have led to a greater reliance on experience and trial and error than is desired by manufacturers in the development of new vehicles.

This thesis furthers knowledge by considering driver perception of mechanical properties at the steering wheel. An understanding of the relationship between actual and perceived steering system parameters allows engineers to determine how a steering system will feel from vehicle models.

Part 1 of this thesis gives a background to steering feel and reviews the literature, showing that force and angle are thought to be the main sensations responsible for steady-state steering feel.

Three psychophysical experiments were conducted in Part 2 to investigate the perception of steering wheel force and steering wheel angle. The first of these investigated participants' ability to match a reference on a wheel that did not move, and a reference on a wheel that was free to rotate. The results show that steering wheel force was more intuitive than steering wheel torque, and steering wheel angle was more intuitive than steering wheel displacement. The second experiment investigated difference thresholds (the smallest detectable change in a stimulus magnitude) for both steering wheel force and steering wheel angle. The results show that a 15% change in the steering wheel force was required in order to perceive a difference over the range 5.25 N to 21 N. A 14% difference was required in steering wheel angle over the range 4° to 18°. The third experiment examined perceptual scaling of steering wheel force and steering wheel angle, and found that neither property was perceived linearly (e.g. a doubling of force or angle was not perceived as a doubling of force or angle). The perception of steering wheel force grew at a faster rate than the actual force, and the perception of steering wheel angle grew at a slower rate than the actual angle.

Part 3 of the thesis investigates the perception of steering wheel stiffness with four studies. The first of these investigated the difference threshold (or smallest detectible change) of steering wheel stiffness, and found that a 20% change in the mechanical work done (force integrated over displacement) was required to perceive a difference between stimuli. The second study found that the scaling functions for steering wheel force and steering wheel angle determined in Part 2 could be combined to predict a stiffness profile that would feel linear (so that the forces and angles at the steering wheel would grow in magnitude in a linear way). The third study investigated preferred steering feel, and found that linear and preferred steering wheel stiffness are different. The last study in Part 3 investigated the use of a power law function to describe real vehicle data for steady-state steering feel from a Jaguar XK, Jaguar S-Type, Land Rover Freelander, Ford S-Max, Ford Focus, Ford Fiesta, and BMW 520i, and found that a power law approximates the data.

This thesis shows how quantification of driver perception can be used to investigate steering feel. The studies are limited to descriptions of sensations of sequential turns of the steering wheel, and further work is recommended to describe other steering wheel movements, and the perception of dynamic movements of the steering wheel.

Contents

List of Tables

List of Figures

To Alex, Doreen, and Steve

Glossary

Afferent	The conduction of nerve impulses from the sense organs to the central nervous system
Cutaneous receptors	Sensory receptors in or near the skin surface
Efferent	The conduction of nerve impulses from the central nervous system towards the peripheral nervous system (e.g. to the muscles)
Glabrous skin	Smooth skin, such as on the palm of the hand
Golgi tendon organ	A proprioceptive sensory nerve ending embedded among the fibers of a tendon
Handling	The responsiveness of the vehicle to driver input at the steering wheel
Haptic	Of or relating to the sense of touch
Isometric control	A control that can be operated by isometric contractions of the muscles. The control does not move but responds to applied force, or torque
Isotonic control	A control that can be operated by isotonic contraction of the muscles. The control moves but offers the same resistance to the applied force, or torque, at all positions
Kinaesthetic	The feeling of motion, especially from the muscles, tendons, and joints
Neuron	A specialized, impulse-conducting cell that is the functional unit of the nervous system
Ogive	A distribution curve where the frequencies are cumulative
Physiology	The science of the normal functions and phenomena of living things
Proprioception	The perception of information about the position, orientation, and movement of the body and its parts.
Psychophysics	The scientific study of the relationship between stimulus and perceived sensation
Psychophysiology	The branch of physiology dealing with the relationship between physiological processes and thoughts, emotions, and behaviour.
Sensorimotor	Relating to the neural circuit from a receptor to the central nervous system and back to a muscle.
Somatosensory	The combination of the cutaneous, kinaesthetic, and visceral sensory systems
Viscera	The soft internal organs of the body, especially those contained in the abdominal and thoracic cavitie

PART 1: INTRODUCTION

Chapter 1 Introduction to steering system engineering

Chapter 2 Review of human perception of steering feel

Chapter 3 Experimental apparatus

Part one provides an introduction to steering feel, and comprises three chapters. In Chapter 1 steering system technology and current practice for steering system development are described. Chapter 2 reviews the literature associated with steering feel, covering vehicle dynamics assessment, the physiology of perceiving movements through the hands, psychophysics, and a review of psychophysical studies associated with the perception of objects manipulated with the hands. Chapter 3 details the experimental apparatus used to test driver perception of steering wheel properties. Further details regarding the experiments can be found in Parts 2 and 3 of this thesis.

Chapter 1. Introduction to steering system engineering

1.1 A background to the industrial sponsor: Jaguar Cars Ltd

Jaguar Cars is a UK based luxury car manufacturer, with manufacturing plants in the West Midlands and Liverpool. Products include the sports coupe/convertible XK, the luxury XJ saloon, S-Type (soon to be XF), and X-Type sports saloons with large markets for these products at home in the UK, Europe and America.

Jaguar Cars is currently owned by Ford Motor Company, and amongst the various brands that Ford own across the world there has been a concerted effort to create a global synergy so that the individual brands that make up Ford's portfolio can leverage the resources of the whole organisation, whether that be in Ford North America, Ford of Europe, Volvo, Jaguar, Land Rover or any other Ford brand.

Globally, Ford's Research activities are divided among the brands, allowing development of expertise whilst minimising overlap of research activities. Jaguar Research is just one part of a large global research effort, specialising in refinement, comfort, and developing leading edge technology.

Ford's Global Product Development System (GPDS) is used at Jaguar for new car development, and incorporates all stages of the development process from product conception to Job #1 (production). Research activities at Jaguar can be classified into two broad categories: technology development specifically to production ready solutions, and 'blue sky' or 'big bang' projects that investigate the feasibility of new technologies.

Jaguars Research department is based at the Whitley engineering centre, Coventry, with additional facilities at Gaydon engineering centre and proving ground in Warwickshire.

This thesis represents a four-year collaboration between Jaguar Cars, and the Human Factors Research Unit, University of Southampton.

Jaguar Cars were interested in developing steer-by-wire technology as both an enabler for other technologies, and to close the technology gap with other manufacturers who were doing research in the same area.

Steer-by-wire technologies had been investigated previously at Jaguar Cars in the form of a test vehicle fitted with a motor and clutch arrangement on the steering column to provide tuneable feedback to the driver. This work, subsequent work with speed proportional steering assist, and active front steering highlighted gaps in knowledge to engineers at Jaguar about human perception of steering feel.

Steering feel, and more broadly vehicle dynamics, have a strong influence on the perception of a brand and so it is important for a luxury Jaguar car to have Jaguar 'feel'. To capture the essence of this 'feel' more needs to be known about the driver – steering wheel interface.

The initial brief from Jaguar was very broad, perhaps acknowledging the lack of knowledge in this area, and after initial contact with the engineers at Jaguar, the scope of the project was narrowed down through regular quarterly meetings with the project mentors.

1.2 Steering system technologies

The steering systems marketplace is dominated by hydraulic power steering systems, and has been for the last ten years. In that time, engineers have become skilled in the selection and tuning of hydraulic power steering systems for steering feel. Despite this, there are a number of market drivers that are encouraging vehicle manufacturers to consider different steering technologies.

This section looks at the main steering systems technologies available to vehicle manufacturers, and the market drivers associated with them.

1.2.1 Hydraulic power steering

Hydraulic power steering currently enjoys market leader status in Europe and North America. A basic hydraulic power steering system uses a mechanical steering system (usually either a rack-and-pinion or recirculating ball screw steering system) alongside a hydraulic system that provides additional assist by supplying hydraulic pressure to either end of the steering rack, making the steering lighter for the driver. The hydraulic pump is used to supply the necessary hydraulic pressure, and is belt driven from the engine.

The move away from hydraulic power steering systems to newer technologies is likely to be gradual as hydraulic power steering still achieves the best steering feel. Years of development also mean that hydraulic power steering has become low cost and would be expected to get even cheaper as hydraulic power steering market shares dwindle and steering system suppliers try to retain vehicle manufacturer business.

1.2.2 Electro hydraulic power steering

Electro hydraulic power steering uses a mechanical steering system with additional hydraulics much like hydraulic power steering, but the hydraulic pump is powered by an electric motor powered from the battery rather than directly from the engine.

Electro hydraulic power steering is an on demand system. This means that the electric pump runs at a low standby speed for straight ahead driving, and only ramps up to higher speeds (which are associated with higher current draw from the pump) for high speed steering inputs. This is more efficient than hydraulic power steering systems where the pump runs at high speeds all the time.

The benefits of electro hydraulic power steering over hydraulic power steering are better fuel economy, and as the hydraulic pump is driven electrically, there is the opportunity to change the steering assist depending on other vehicle parameters, such as vehicle speed.

Electro hydraulic power steering is seen as a short-term solution to get some of the benefits that electric power steering systems offer (such as improved fuel efficiency, and possible chassis integration), whilst avoiding the architectural issues involved with the higher electrical demands that electric power steering places on the vehicle. Once higher voltage architecture begins to appear on vehicles, it is expected that electro hydraulic power steering systems will be replaced by electric power steering, to obtain better fuel efficiency, and also save time on the production line (as there would be no need for hydraulic steering fluid on the production line). The cost of electro hydraulic power steering systems is also expected to come down over time.

1.2.3 Electric power steering

Electric power steering is the next step from electro hydraulic power steering. Here the hydraulics are dispensed with and all of the assist comes from an electric motor. There are three main types of electric power steering: column electric power steering, pinion electric power steering, and rack electric power steering depending on where the motor assist is packaged.

Electric power steering systems offer fuel efficiency benefits over both hydraulic and electro hydraulic power steering systems as it is a completely on demand system. For straight ahead driving the electric pump may be switched off completely.

Electric power steering systems can also be integrated with other chassis components to provide new safety features such as electronic stability programs.

The main drawback to electric power steering systems is the high electrical load required to allow the motor to work and maintain dynamic steering performance. There are limitations to implementing an electric power steering system on the current 12 volt architecture that most passenger vehicles use, which restricts the implementation of electric power steering systems to smaller vehicles until the 42 volt architecture becomes available. For instance, Smart, Fiat, Citroen, and Renault currently use electric power steering systems in their small segment vehicles.

Depending on the specific electric power steering system chosen, there can also be packaging and safety benefits.

1.2.4 Active steering

Active front steer can be applied to hydraulic power steering, electro hydraulic power steering, or an electric power steering system as a base. Here assist is given as an input to a planetary gear set, with the other inputs coming from either side of the steering column (the upper half being connected to the steering wheel, and the bottom half to the steering rack). This allows variable steering angle to be implemented depending on the assist given to the planetary gear by the electric motor.

This extra functionality provides vehicle manufacturers with the ability to improve driver comfort and driving agility.

Active front steer is currently available on some BMW vehicles as a premium option.

1.2.5 Steer-by-wire

Steer-by-wire replaces the conventional mechanical link entirely by using separate electric motors to drive the steering column and the steering rack separately.

Steer-by-wire was previously prohibited due to the requirement to have a mechanical link between the road wheels and steering wheel in European legislation (ECE Regulation 79). This rule was amended on April 21st 2005 making steer-by-wire a possibility (ECE R 79 r2).

Steer-by-wire systems offer energy efficiency savings like electric power steering and electro hydraulic power steering systems, but could also offer huge benefits for driver experience, packaging, and safety.

The feedback signal to the driver will be completely adjustable allowing full manipulation of the steering characteristics (subject to hardware limitations).

The removal of the steering column would allow the package of the vehicle to be optimised without the fixed steering wheel constraint. The wheel and motor can be packaged anywhere the designer sees fit. The removal of the steering column is also a benefit for safety because the steering column has always been a major risk to the driver in crash situations.

However, whilst steer-by-wire offers safety benefits, there is the potential for safety problems such as fail-safe operation of the steering system if one or several components fail. In all other steering system technologies, failure of the power assist is always fail-safe as the mechanical link will still allow the vehicle to be steered, although at increased steering efforts. One possible solution to this problem is to build in redundant components and systems similar to fly-by-wire systems in the aircraft industry, but this would impact on the cost and viability of steer-by-wire systems.

1.2.6 Customer demand and future developments

Fuel efficiency is the main driver for change from traditional hydraulic power steering systems to electric systems, and is driven by customer expectations.

Customers are becoming increasingly concerned about fuel efficiency after recent petrol price increases and fluctuations, and vehicle manufacturers have recognised that increasing petrol prices are a risk to business and they are spending more research and development time on fuel efficient solutions.

One solution is to develop hybrid vehicles that use a conventional internal combustion engine with a motor/generator and battery. Regenerative braking provides energy to the battery, which can then be used instead of the internal combustion engine, or to supplement it. If vehicle manufacturers use this type of technology, the steering system simply cannot be hydraulic because there will be no assist when the vehicle is running on the battery alone.

One of the main problems with electric power steering is the degradation of steering feel, and whilst electric power steering systems should be more tuneable than hydraulic power steering systems (and completely tuneable in the case of steer-by-wire), there can be issues with perceptible motor cogging, and specification of the motor can be difficult. For this engineers need to understand what makes good steering feel.

These market drivers are pushing vehicle manufacturers to consider new technologies in steering systems, but it is vital that steering feel is maintained. Expertise with hydraulic power steering systems over the years means that engineers know that they can tune the vehicle to have excellent steering feel. What is less certain is whether engineers will be able to tune electric power steering, active steering, and steer-by-wire systems to at least maintain steering feel at its current level, or improve on it.

1.3 Jaguar's current practice in the assessment vehicle dynamics and steering feel:

Vehicle dynamics assessment techniques used by vehicle manufacturers today borrow heavily from dynamics work in the aircraft industry.

Driven by military needs in the middle of the 20th Century, aircraft testing and aircraft handling qualities assessments were developed to ensure good aircraft handling.

Aircraft handling qualities are evaluated by test pilots who are required to rate an aircraft on a rating scale such as the Cooper-Harper rating scale (Cooper and Harper (1969)), while test engineers record the aircraft's control inputs and response. Gilruth (1943) was one of the first to use correlations of pilot opinion with flight recordings in order to evaluate handling qualities, and his method is considered routine in the aircraft industry today.

Focus on the handling dynamics of road vehicles is much more recent. In industry, vehicle manufacturers typically use three approaches in vehicle dynamics development:

1. Objective testing of real vehicles,
2. Subjective evaluation of real vehicles, and
3. Objective testing of virtual vehicles through simulation.

Metrics are gathered from objective and subjective real vehicle testing, and are used to set targets for new vehicles.

1.3.1 Objective vehicle testing

The aim of objective vehicle testing is to determine how the vehicle responds to a given input. Typically a test driver or steering robot completes a set manoeuvre whilst the vehicle is instrumented to record the vehicle response.

Various vehicle-level, open-loop test procedures are outlined in various International and British Standards including the constant radius tests, constant speed tests, step input tests, sinusoidal input, weave, and random input tests to determine the steady-state and transient response of the vehicle (British Standards Institution (2006), British Standards Institution (2002), British Standards Institution (2003), International Organization for Standardization (1988), and International Organization for Standardization (1988)).

Along with these standardised tests, vehicle manufacturers have their own test procedures to provide additional manoeuvres.

1.3.2 Subjective evaluation

There are two types of subjective evaluation used in vehicle dynamics assessment: the first is to evaluate the vehicle subjectively for the manoeuvres conducted in objective tests, and the second is to subjectively evaluate the whole range of vehicle operation.

1.3.2.1. Subjective evaluation of test manoeuvres

A simple rating system is used to collect the subjective assessment of a vehicle in a given manoeuvre for qualities such as vehicle performance, and satisfaction.

Both experts and customer representatives are used to assess the vehicle subjectively, although customers are expected to provide high-level emotional responses, and experts are expected to provide lower-level objective responses of specific properties.

1.3.2.2. Subjective evaluation of the whole range of vehicle operation

Subjective evaluation also allows the entire operating range of the vehicle to be tested. The assessor becomes a measurement device and is used to identify problems with the system for conditions outside the set manoeuvres conducted in objective vehicle testing.

Again both experts and customer representatives are used, and whilst the representative might be able to identify that it feels wrong, the expert tester is used to try to identify the specific component at fault.

1.3.3 Simulation

Computer aided engineering techniques allow complex models of the vehicle to be constructed, and also tested for the same manoeuvres that a real vehicle undertakes in objective vehicle testing.

Computer aided engineering models can either be built up from the component level by describing all the components in the system and their relation to one another, or by using objective data from rig tests on real vehicles. The model can then be put through a variety of test manoeuvres to simulate the vehicle response.

The major advantage of simulation is that it enables development of the vehicle before a prototype even exists. In reality, computer aided engineering models have to be validated against real vehicle data to ensure accuracy, so whilst the aim is to be able to model a vehicle before a prototype exists, it might not be possible to validate a simulated model until a prototype exists.

1.3.4 Metrics

Metrics are used to describe vehicle dynamics characteristics by correlating objective vehicle measurements with subjective ratings.

Objective test data is recorded from vehicle tests (as described in Section 1.3.1) and are assessed for correlation with the subjective ratings from expert testers (as described in Section 1.3.2.1).

The characteristics that are highly correlated with subjective ratings are used to describe the character of the vehicle in a metric.

Metrics can be used to set targets for a development vehicle, to compare competitor vehicles, and to check consistency with other vehicles in the same brand.

If issues are found in the vehicle from subjective testing of the whole range of vehicle operation, then metrics may help to identify where the problem originates.

Simulation engineers can also use these metrics to define a good and bad vehicle from the simulation data, as they are unable to 'drive' the model and validate it subjectively.

1.4 The need for better techniques to assess steering feel

Current vehicle dynamics techniques are limited in their ability to assess how the steering system feels to a customer. This section details two issues that require a better assessment of steering feel (as well as other handling characteristics): the first is the drive for a shorter development process, and the second is how metrics determined from subjective and objective correlation apply to new technology.

1.4.1 Shorter development processes

The drive to get new products to market faster has put pressure on development processes. Ideally vehicle manufacturers want to get products right first time, straight from the drawing board rather than wasting time and money on prototypes.

This has led to a greater emphasis on predictive engineering, largely based on computer models. However, simulated vehicle dynamics work relies on the subjective and objective correlations provided in the metrics in order to determine a good or bad vehicle set up, but metrics do not fully describe the dynamics of a vehicle, or the subjective impression. It is possible to have a vehicle that hits all the metric targets, but still has errors present when the vehicle is subjectively assessed.

1.4.2 New steering system technology

The use of correlation analysis can provide a problematic link between objective vehicle data and subjective ratings, as the metric correlations are conducted on a specific set of vehicles. Jaguar engineers have found problems with the metrics when dealing with their speed sensitive steering systems, as speed sensitive steering systems were never utilised when the metrics were developed. There is no way to assess whether the metric is still relevant for the new technology other than redoing the subjective and objective testing procedures and applying the correlation again. This is a time consuming and expensive process.

1.5 Thesis objectives and contributions

The objective of this research is to assess driver perception of the steady-state stimuli present at the steering wheel. In the context of this research steady-state means slow movements of the steering wheel from straight ahead to an away from centre position.

This thesis makes use of laboratory based experiments to investigate the drivers perception of haptic steering feel without the presence of other vehicle based stimuli.

It is hoped that this research will help engineers and experts to analyse objective steering data and associate the way the steering feels with the data. It is also hoped that specifying the limitations of human perception will allow engineers and experts to recognise when the steering system is appropriate from objective data.

1.6 Thesis overview

The remainder of Part 1 includes a further two chapters. Chapter 2 is introductory and provides a review of the relevant literature in the study of steering feel, whilst also outlining psychophysical methods used for studying perception. Chapter 3 describes the two experimental steering rigs used in the experiments. Part 2 contains chapters relevant to the perception of steering wheel force and steering wheel angle and includes Chapter 4, Chapter 5, and Chapter 6. Part 3 contains chapters relevant to the perception of steering wheel stiffness profiles, and includes Chapter 7, Chapter 8, and Chapter 9. Chapter 10 relates the perception studies to real objective vehicle data.

Chapter 11 presents the main results and conclusions of Sections 1, 2, and 3 and also recommends further work.

Chapter 2. Review of human perception of steering feel

Driving a car exposes the driver's body to a large number of stimuli, including visual, auditory, and somatosensory feedback. All of these feedback paths can give the driver useful information about the state of the car.

The most important feedback for steering feel comes through the hands in the form of haptic feedback. Haptics is the general study of the sense of touch, and has been developed by the fields of telemanipulation, haptic interface technology, and fundamental research into the processes involved in haptic perception.

This chapter reviews the state of the art for steering feel. There are five sections in this chapter. Section 2.1 introduces current approaches and research into steering feel and vehicle dynamics. Section 2.2 provides an introduction to the biological functions and processes involved in haptic sensation and perception. Section 2.3 deals with psychophysics, which is an area of scientific study that looks at the relationship between stimulus and sensation. Section 2.4 provides a review of the relevant literature from haptic perception, and Section 2.5 provides a summary.

The general conclusion for this chapter is that when considering only the haptic properties of the steering system, the forces, positions and movements on the steering wheel are the most important for defining how the steering system feels.

2.1 Approaches to steering feel and vehicle dynamics in the literature

2.1.1 Approaches to vehicle dynamics assessment

The objective-subjective correlations introduced in Section 1.3 are widespread throughout industry as a method to quantify the handling of a vehicle, and has been used by Bergman (1969), Bergman (1973), Weir and Di Marco (1978), Matsushita et al. (1980), Champagne (2000), and Data and Frigerio (2002). However, the use of objective-subjective correlations can be problematic. Sharp (2000) suggests that variability between participants and the influence of extraneous factors make objective-subjective correlations expensive to conduct so experimental designs often end up being a compromise between what is desirable and what is affordable. Sharp (2000) also highlights a problem with the use of manoeuvre time histories, as they often do not lend themselves to simple numerical descriptions which are needed in order to conduct the correlation analysis. Often a single point from the manoeuvre time history, or a gradient from specific point is arbitrarily chosen for the correlation analysis. Another method that has been used to capture the requirements for a subjectively 'good' vehicle is to build a variable stability vehicle and use it to create the appropriate conditions that are subjectively excellent. Segel (1964) and Sweatman and Joubert (1974) have done just this. Their approach can be extended to generate a set of rules that seem to create a good vehicle, but their approach does not explain why a specific set up is good.

Driving simulators can be used to assess vehicle dynamics instead of a real vehicle, and researchers including Lincke et al. (1973), Richter (1974), and Sugasawa et al. (1992), have done so. The simulator must accurately simulate a real vehicle for the results to be trusted, and as a result there has been lots of effort spent creating better and more realistic simulators rather than obtaining vehicle dynamics results.

Sharp (2000) provides a good overview of current vehicle dynamics practice, and problems associated with them.

2.1.2 Approaches to steering feel assessment

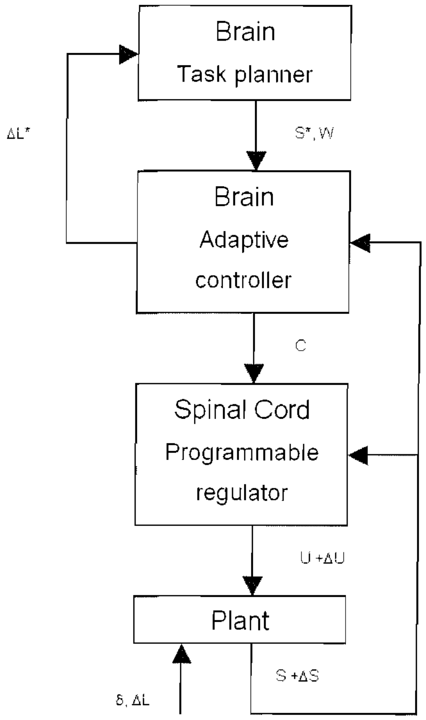
While vehicle dynamic subjective assessment covers the feel of the whole vehicle, if we limit our focus to steering feel, there is much less information available, perhaps rightly so as the steering system is never 'felt' in isolation when driving a car.

Setright (1999) suggests that 'steering feel' is the aligning torque generated by the tyre. Shimomura et al. (1991) suggest that the steering wheel torque versus steering wheel angle characteristic is the most important parameter that affects steering 'feel'. This is supported by the view of aircraft engineers. While stick force per g is considered the most important characteristic in defining handling quality (Gibson and Hess (1997)). A' Harrah (1964) found that pilot acceptance of stick pitch feel characteristics was determined by the stick force-displacement constant, with acceptable stiffness ranging from 3 to 25 pounds per inch for level 1 (i.e. the highest) handling quality.

2.2 An introduction to haptic sensation and perception

The term 'haptics' comes from the Greek meaning 'to touch', and was first introduced by Revesz (1950). Gibson (1966) described the haptic system as "The sensibility of the individual to the world adjacent to his body by use of his body" which recognises the interaction between sensory and motor organs in the perception of haptic stimuli. This interaction is further clarified by distinguishing between 'active' and 'passive' touch. Passive touch provides only sensory information, whereas 'active' touch can provide much more information, drawing from both motor and sensory information, for instance when a human manipulates an object. The haptic sense is unique in this respect, as no other sense can act on the stimulus in order to change the way it is perceived.

Manipulations of objects or the environment involves conscious effort and planning from the brain in order to control the movements required in the manipulation. Loeb et al. (1999) suggest a useful framework to consider the interactions between sensory and motor information in the control of movements by considering a hierarchical model for sensorimotor control (shown in Figure 2.1).



The adaptive controller sends changes in the estimated load (ΔL^*) to the task planner.
The task planner calculates the expected sensory feedback (S^*) and applies a weighting factor (W) to these sensations.

The adaptive controller sends the command (C) to the programmable regulator.
The adaptive controller also receives sensory feedback from the plant to allow it to calculate the error in its command.

The programmable regulator sends command motorneuron activity (U), and some motorneuron reflex response (ΔU) to the Plant.
The programmable regulator also receives sensory feedback from the plant to allow it to convert the command into motorneuron activity.

The plant receives command inputs through motorneuron activity ($U+\Delta U$), and also from the external environment through random mechanical inputs (δ), and load changes (ΔL).
The plant provides sensory feedback ($S+\Delta S$) to the higher orders.

Figure 2.1: Hierarchical model of sensorimotor control Loeb, Brown et al. (1999)

Both upward and downward flow is shown in the model, with the downward flow representing the descending motor commands, and the upward flow representing the ascending sensory feedback. Successful performance in the motor task depends on the interaction of the descending commands from the brain with the properties of the lower levels of the sensorimotor system (which includes the dynamic mechanical properties of the muscle, the somatosensory receptors, interneuronal circuitry of the spinal cord, and the noise in these elements).
The role played by each of the three major contributors of the model will be looked at in turn: the brain, neural transmission in the spinal cord, and the somatic sensory receptors.

2.2.1 The brain

The topography of the brain can be studied using techniques such as Positron Emission Tomography (PET) or Functional Magnetic Resonance Imaging (fMRI). Areas of the cerebral cortex involved in sensorimotor control have been mapped according to the areas of the brain that respond when perceiving a stimuli, or when the brain sends a motor command.
Figure 2.2 shows a cross section of the brain for both sensory stimuli (left hand side) and motor control (right hand side).
The sensory homunculus (on the left) shows the space in the cerebral cortex that the sensations of our body parts occupy. The lips, hands, feet and sex organs are much more

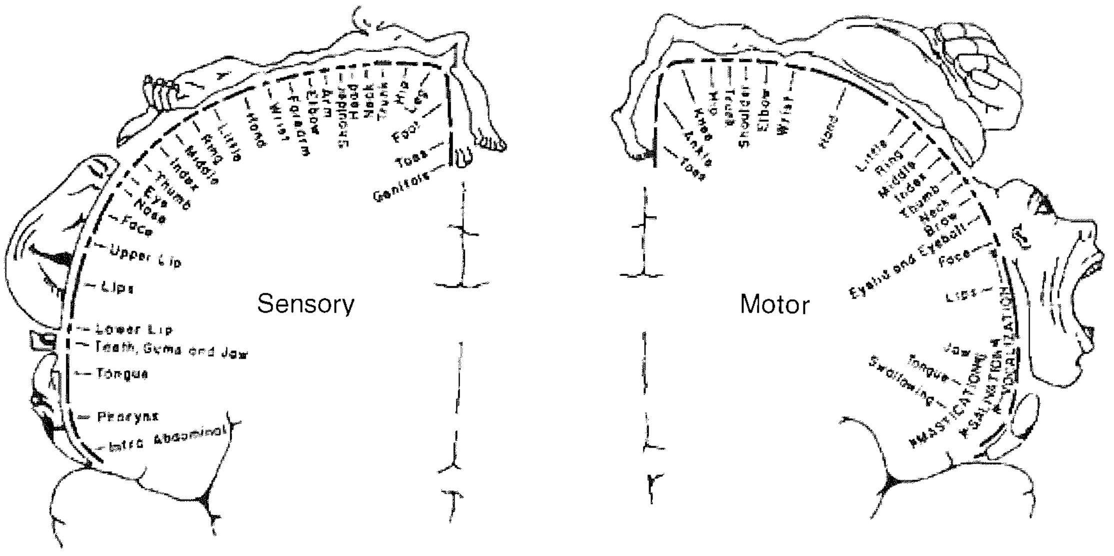


Figure 2.2: Cross sections of the cortex showing the sensory areas for the skin of various parts of the body and motor areas for movement (Reprinted from Penfield and Rasmussen (1950)).

sensitive than other parts of the body, and this is reflected in the proportions assigned to these areas in the cerebral cortex.

The motor homunculus (on the right) shows the space in the cerebral cortex that is dedicated to controlling the voluntary movement of body parts. Here the thumb is given a large representation on the cerebral cortex due to its everyday use in many complex tasks.

The exact forms of functions that the brain carries out on incoming neural information, and the processing to create motor commands are not fully understood.

2.2.2 Neural transmission in the spinal cord

The spinal cord and nervous system allow the transmission of neural information from the sensory receptors to the brain.

A neuron (or nerve cell) is the basic element of the nervous system and serves to transmit information around the human body. Some neurons act as receptor cells of the sensory organs, turning certain forms of physical energy into nerve impulses, which are then sent to other neurons and on to the brain. Neurons that send information from sensory receptors to the brain are called sensory neurons, whilst neurons that send information from the brain to the muscles are called motor neurons, and interneurons transmit information between neurons.

Neurons send information around the body through impulses. A neuron in an inactive state has a small negative charge called a 'resting potential', but once stimulated the resting potential in the neuron changes for a fraction of a second (this activity is called an action potential), sending an electric charge along its axis before returning to its resting potential.

A neural impulse may 'fire' or transmit impulses to adjacent neurons, but only if the electric charge exceeds a threshold level.

The number of action potentials and the time interval between them (i.e. the frequency of firing) represents the magnitude of the sensory stimulus. A stronger stimulus will increase the firing frequency of action potentials.

Another interesting characteristic of receptor cells is the ability to adapt. When adaptation occurs, receptors become less sensitive, which allows us to 'tune' out background noise in any sense modality. The ability to adapt depends on the nerve, some being fast adapting like pressure and touch, whereas others are slow adapting – such as muscle stretch and the sense of pain. Sensations of slow adapting nerves last a long time.

2.2.3 Somatic sensory receptors

Whilst there are a large number of sensory receptors located throughout the body that respond to many varied stimuli, we will focus on the receptors involved in touch and movement. A term sometimes used to encompass the large number of receptors involved in the sense of touch is somatic sensation, and is used to acknowledge that more than one sensation is involved in the more general sense of touch. Rather than just one sensation, the sense of touch consists of sensory receptors that trigger experiences of touch, pressure, temperature, pain, and the sensations of muscle movement and joint position.

In the study of steering feel, the sensations of interest are those of muscle movement and joint position, which are collectively termed proprioception or kinaesthesia.

Somatosensory receptors implicated in proprioception and kinaesthesia are classified in three groups of sensory receptors (Jones (1994), Proske et al. (2000)): cutaneous (skin) receptors, joint receptors, and muscle receptors.

- Cutaneous receptors: Cutaneous receptors are mechanoreceptors in the skin that can be stimulated to create sensation. In glabrous (hairless) skin, there are four different cutaneous mechanoreceptive afferent neuron types: Merkel cells (thought to be responsible for perception of pressure, Goldstein (2002)), Meissner corpuscles (flutter), Pacinian corpuscles (vibration), and Ruffini corpuscles (stretching).
- Joint receptors: Joint receptors are specialized mechanoreceptors positioned within the joints of the body, and are thought to signal the angle of the joint. They are implicated in the sense of bodily position and movement.
- Muscle receptors: Muscles are used in both sensory (afferent) and motor (efferent) functions. There are two important receptors in the muscle: muscles spindles (change in position of a limb), and Golgi tendon organs (sensitive to variations in contractile force).

2.2.4 Psychophysiology

Numerous psychophysical studies have been conducted in order to determine more about the underlying biological mechanisms involved in our perception of mechanical stimuli. By testing humans with psychophysical methods under different conditions it is possible to investigate the various signals that contribute to a specific perception, and how those signals combine. This area of research is sometimes referred to as psychophysiology to acknowledge the psychological and physiological nature of this research.

The rest of this section will look at the neural information thought to be useful for the brain in perceiving a variety of mechanical stimuli.

2.2.4.1. Origin of neural information used by the brain in the perception of force

The perception of force, weight and mass has been studied as far back as the experiments of Ernst Weber (1834) who was interested in whether weight perception depended more on touch, or on the 'muscular sense'.

The perception of force is a more complicated sensation than others, as force stimuli can both be created, and perceived by a participant. The brain can send commands to the muscles that generate force, as well as perceive sensory information that is transmitted back to the brain from the various receptors. A 'sense of force' can be derived from both the corollary discharges from the brain (an efferent signal caused by the generation of stimulus in the brain), and also from the Golgi tendon organ receptors (an afferent signal generated by sensation of a stimulus). It is generally accepted that there are both peripheral and central components that contribute to force perception (McCloskey et al. (1974), McCloskey (1978), McCloskey (1981), Gandevia (1996)).

Specific terminology is used to distinguish between the peripheral and central components: the peripheral component is associated with the 'sense of tension' in the muscles, and the central component is associated with a 'sense of effort'.

There is a lot of evidence to support the centrally derived 'sense of effort' as a contributor to force perception. Numerous studies have required participants to estimate force with a fatigued or paralysed muscle so that in order that the muscle still maintains a certain level of force the centrally driven activation rates of motor neurones must increase. The judgement errors made by participants indicate that the increase in the sense of effort led to a higher force perception.

A recent study by Toffin et al. (2003) required participants to control the force and direction of a joystick. They concluded that in a force direction task, human participants do not directly control forces or joint torques. Instead, force appears to be specified with control signals that modify the equilibrium position of the limb regardless of the impedance of the interaction with the environment. This supports the 'sense of effort' rather than the 'sense of tension' hypothesis.

The contribution of the 'sense of tension' from the peripheral receptors as a contributor to force perception is less clear, but it has been shown that the information from the Golgi tendon organs reaches the cerebral cortex (McIntyre et al. (1984)) and that the sense of tension can be used for force estimation (Roland and Ladegaard-Pedersen (1977)). Van Doren (1998) has also shown that when participants are given different instructions (either to concentrate on the sensations in the hand or arm and to ignore the differences in effort required, or to ignore peripheral sensations and match effort or motor commands) different matching behaviours are observed in participants.

Several recent studies have reported the perturbation of force estimates after eccentric exercise (Saxton et al. (1995), Brockett et al. (1997)), where eccentric exercise is the development of muscle tension while the muscle is being lengthened. These studies partly attribute errors to peripheral causes. Gregory et al. (2002) has further tested the hypothesis that some errors in force perception are caused by peripheral errors after eccentric exercise, but found that the Golgi tendon organs are extremely reliable in signalling whole muscle tension, even after fatigue or eccentric exercise, so the errors must be due to the centrally derived 'sense of effort'.

To what extent the peripheral 'sense of tension' contributes to force perception under various conditions is speculative, as although the peripheral signal seems to be accurate, errors in force perception are still made.

Under normal conditions when the muscle is not fatigued, the information provided by the efferent 'sense of effort' from the brain, and the afferent 'sense of tension' from the Golgi tendon organs is highly correlated with the force exerted (Jones and Hunter (1982)). This means that if the participant is not fatigued, either the sense of effort or the sense of tension will provide much the same information to the brain.

2.2.4.2. Origin of neural information used by the brain in the perception of limb position and movement

Slowly adapting joint receptors were thought to be the main group of receptors responsible for the sense of limb position and movement (kinaesthesia) for much of the 20th century (Skoglund (1973)). However, Goodwin et al. (1972) showed that muscle vibration could affect kinaesthesia and so implicated the muscle spindles in the conscious sensation of position and movement. It is now thought that the primary endings of muscle spindles are responsible for the sense of position and movement of our limbs, and that secondary endings of spindles contribute to the sense of position while tendon organs provide a sense of tension. At distal joints additional information can be obtained from skin and joint afferents (Gandevia (1996)).

Winter et al. (2005) have shown that the centrally derived 'sense of effort' also seems to be used in the perception of limb position and movement in a study requiring participants to equalise the effort required to hold a limb position in a matching task. When additional weights were added to the 'reference' arm, participants made errors in the matching arm consistent with an increase in the effort signal.

Jones et al. (1999) have shown that the ability to detect limb movement depends on factors including the particular joint used, if the muscles are contracting during the movement, and

Table 2.1: Neural inputs involved in proprioception of the hand Jones (1994)

Sensory event	Possible neural inputs
Perception of limb movement	Muscle spindle receptors Cutaneous mechanoreceptors Joint receptors
Perception of limb position	Muscle spindle receptors Cutaneous mechanoreceptors
Perception of force	Corollary discharges (efferent) Tendon organ receptors

the velocity of the movement. The proximal joints such at the shoulder or hip having lower differential thresholds for movement than distal joints such as the fingers or toes.

There is evidence that there is a separate static position and dynamic position sense. When a limb is moved so slowly so as not to be perceived (<2 °/min) (Cordo et al. (2000)), the position of the limb is still perceived. Absolute position sense to remember a joint location is not dependent on the velocity of the movement (Jones (1997)), although position sense when only using static position sense is less accurate than dynamic position sense (Proske, Wise et al. (2000)).

2.2.4.3. Origin of neural information used by the brain in the perception of other mechanical properties

The majority of sensory studies on the proprioceptive system have focused on the perception of force, positions and movements as outlined above. Much less attention has been paid to the neural information available for the perception of other mechanical stimuli such as stiffness and viscosity.

Jones and Hunter (1990) have studied the perception of stiffness and conclude that there is a reliance on both force and displacement cues in matching stiffness, as reliance on only one signal would cause a matching error, which was not observed in their experiments.

In another study, Jones and Hunter (1993) studied the perception of viscosity, and concluded that there is a reliance on force and movement velocity in order to perceive the viscosity of a mechanical system and can assume that the brain must be capable of integrating the force and movement information.

This suggests that force and position are the basic components that are sensed by the receptors in the body. In order for properties such as stiffness, viscosity and inertia to be perceived requires integration of these properties over time in the brain.

A summary of the neural inputs and their roles in perception are outlined in Table 2.1.

2.3 Psychophysics

Psychophysics is a branch of psychology that studies the scientific relationship between the stimulus in the physical domain, and sensation in the psychological domain (see Figure 2.3). Its history can be traced back as far as the 17th Century to scientists such as Weber and

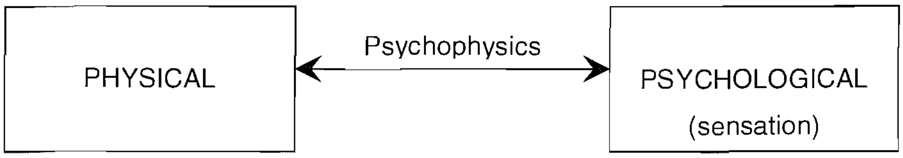


Figure 2.3: The role of psychophysics in identifying relations between physical and psychological stimuli

Fechner (Fechner is sometimes cited as the 'father of modern psychophysics'), whilst there are traces of psychophysical thinking far earlier than that.

The aim of psychophysical study is to relate the physical to the psychological. Whilst physical properties can be described in Newtonian physics with measurement devices of known accuracy in a robust way, it is problematic to measure the psychological continuum in the same way.

As shown in Section 2.2, various environmental stimuli stimulate neural signals via different receptors that are transmitted to the brain where we cognitively perceive our external world. Whilst direct access to neural signals in the spinal cord and brain may further our understanding of the way in which we perceive external stimuli, access to observe these signals is extremely difficult, and often invasive to the participant. Even if access were easier, it is often very difficult to understand how individual neural responses combine in the brain to generate our perception of external stimuli.

Instead psychophysical techniques are used to study perception based on the behaviour and judgements of the human participant by relating the stimulus to the judgement or response of participants in psychophysical experiments. Whilst psychophysical methods provide a non-invasive method to study human perception of stimuli, it is limited by the use of the human as the measuring device, and also can call into question whether human judgements can be used as a direct measurement of sensation, whether discrete sensations exist in the mind, and if a separate psychological realm exists (e.g.Gibson (1966), Savage (1970), Laming (1997)). Others have argued that judgements are not proportional to sensation magnitude (Anderson (1970), Shepard (1981), Birnbaum (1982)). Shepard (1981) instead theorised that in observing human behaviour or judgement, psychophysical techniques describe the relationship between stimulus and a convolution of a psychophysical function and a stimulus response function (see Figure 2.4). They argue that sensation itself is never directly observable, so you have to make assumptions about the form the psychophysical law and the response function take in order to estimate sensation from psychophysical judgements.

The problems imposed by the description of the response function depend on the use of the psychophysical experiment. There are two main uses of psychophysical methods: analytical psychophysics and descriptive psychophysics.

Analytic psychophysics uses the human behaviour or judgements as observed in psychophysical experiments to research the underlying biological processes between the receptors and the brain such as the studies in Section 2.2.4 on psychophysiology. These

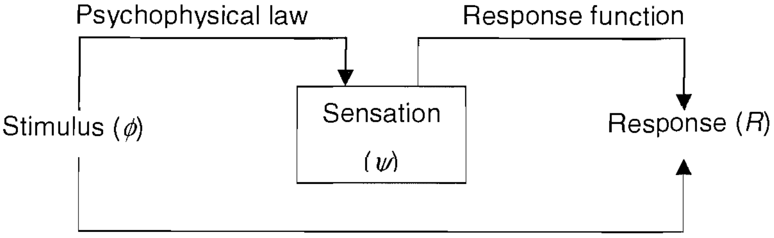


Figure 2.4: Relations among the psychophysical law, the response function, and the empirically determined stimulus-response function. From Gescheider (1997)

researchers are not interested in the cognitive transformation of sensation into a response, they are instead interested in the relationship between the stimulus and sensation. In order to investigate this from psychophysical techniques, the researchers must make assumptions about the response function (i.e. the relationship between sensation and response), or design the experiment to avoid any possible changes to the response function.

Descriptive psychophysics uses the human behaviour or judgements observed in psychophysical experiments to study and design human environments according to their perception of the stimulus. In descriptive psychophysics, whilst the response function may introduce a large inter-subject variability in results, this cognitive transformation from sensation to response (which is thought to differ across the population) is actually of interest to study. In descriptive psychophysics the inclusion of the response function in psychophysical measurement is less problematic than analytic psychophysics.

There are two main constructs in psychophysics: sensitivity (both absolute and differential sensitivity) and psychophysical scaling.

2.3.1 Psychophysical sensitivity

The sensitivity of any instrument is an important measure of accuracy, be it a piece of laboratory equipment, or a human. Psychophysical judgements use humans as the measurement device. Judgements are used to determine the sensitivity of participants to environmental stimuli, which can help to design better environments and tools for human use.

2.3.1.1. Absolute and differential sensitivity

There are two types of sensitivity measurement, absolute sensitivity, which is concerned with the specification of the smallest amount of stimulus energy that humans can perceive, and differential sensitivity, which is concerned with the difference required between two stimuli in order that two stimuli can be differentiated.

2.3.1.1.1. Absolute sensitivity

The absolute threshold is defined as the 'smallest amount of stimulus energy required to produce a sensation', and may be used to measure absolute sensitivity.

Taking measurements of the absolute threshold while changing the properties of the stimulus can reveal the factors that the threshold depend on, but also determine more about the underlying mechanisms involved in perception.

For instance, the absolute sensitivity of touch is known to vary across frequency, which researchers have hypothesised to be due to different receptors in the skin responding at different frequencies. Other factors known to affect the absolute threshold of touch include the area exposed to motion, which is thought to be due to the ability of the human to 'spatially summate' vibration exposure across receptors, and type of skin exposed to vibration, which is thought to be due to differing receptors and receptor densities in different types of skin.

2.3.1.1.2. Differential sensitivity

The difference threshold is defined as the 'amount of change in a stimulus required to produce a just noticeable difference in sensation', and may be used to measure differential sensitivity. As with absolute threshold measurement, difference threshold measurements can vary with properties of the stimulus, such as frequency, intensity level, or adaptation time.

E. H. Weber worked mainly on the discriminations of weights, and found that two heavy weights must differ by a greater amount than two lighter weights in order for one of the weights to be judged as heavier than the other or in other words the stimulus intensity affects the difference threshold (Weber (1834)). Moreover, Weber found that the ratio of the difference threshold to the magnitude of the stimulus was constant. This ratio is called the Weber fraction, and the linear relationship between difference threshold of a stimulus and the intensity of the stimulus seemed to be valid for many different sense modalities, although the value of the fraction may change. Weber's Law describes the relationship:

$$\Delta\phi = c\phi \tag{2.1}$$

where $\Delta\phi$ is the change in stimulus intensity that can just be discriminated (i.e. the just noticeable difference), c is the Weber fraction, and ϕ is the starting intensity of the stimulus.

Weber's law holds for many different sense modalities, and has proved to be a useful tool in providing an index of sensory discrimination, which can be compared across conditions and modalities.

Weber's law has been found to hold across a broad range of stimuli intensities, except at very low stimulus intensities near the absolute threshold where the Weber fraction tends to increase (see Figure 2.5).

A modification of Weber's law that can sometimes better describe the empirical data in these situations is:

$$\Delta\phi = c(\phi + a) \tag{2.2}$$

where a is a small constant offset. The significance of a has not been determined, but it seems to be related to the operation of sensory systems near threshold.

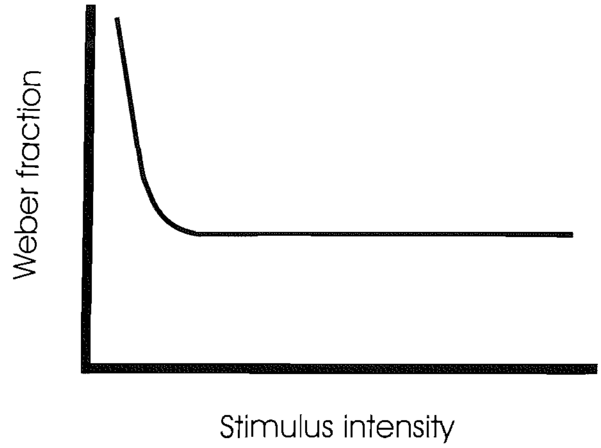


Figure 2.5: Weber fraction constant throughout range except near zero

2.3.1.2. Classical threshold measurement methods

Classical techniques can be used to determine absolute or difference thresholds, including the method of constant stimuli, the method of limits, and the method of adjustment. These methods are outlined in Appendix A.

Classical threshold techniques determine the absolute threshold as the value of the stimulus that is perceptible in 50% of trials (i.e. $p = 0.5$). The difference threshold is determined at 25% ($p = 0.25$) and 75% ($p = 0.75$) probability of detection where the reference stimulus is at $p = 0.5$.

It is clear from our discussion of analytical and descriptive psychophysics in the introduction of this chapter that classical threshold measurement methods measure response rather than sensation directly. Classical thresholds provide a measurement of the stimuli intensity change required to produce a change in the response of the participant. Analytical psychophysicists take these descriptive measurements further by proposing theories about the underlying mechanisms of sensory thresholds (and assume a response function), whereas descriptive psychophysicists may be satisfied with the results in the form these methods provide.

Classical threshold measurements report the threshold at a probability of 50% for absolute thresholds, and at 25% and 75% for difference thresholds, regardless of the experimental conditions.

2.3.1.3. Theory of signal detection: sensitivity measurement

One problem that is sometimes encountered in experiments designed with classical threshold measurement methods occurs when the participant reports a signal when there is none, and failing to report a signal when there is. Detecting a signal when there is none is called a 'false alarm', and the failure to report a signal when there is one is called a 'miss'.

Experiments have shown that participant expectancy and payoff can have a dramatic influence over detection behaviour, which leads to these false alarm and misses. This discovery has had profound implications on the classical measurement of thresholds, as the results may be so polluted by expectancy and payoff effects that the threshold measurement

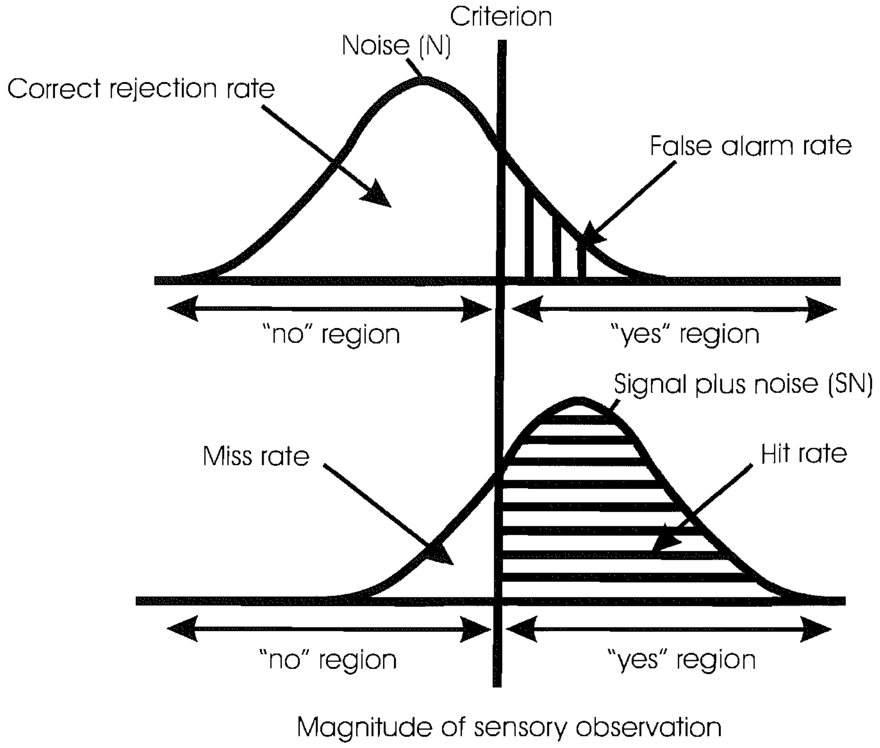


Figure 2.6: Theoretical frequency distributions of noise and signal plus noise. The location of the participant's criterion determines whether a particular sensory observation, *x*, results in a 'no' or a 'yes' response (from Gescheider (1997))

may be worthless if the participant changes their criterion during the measurement, especially for the analytical psychophysicist.

In order to try and model the effects expectation and payoff have on the threshold, a new theoretical conception of the detection situation has been devised called the theory of signal detection, and is formulated from statistical decision theory and electronic engineering. Instead of measuring a 'threshold' as in the classical methods, the theory of signal detection assumes that the participant has an adjustable 'criterion' when they make their judgement that is affected by expectancy and payoff.

The statistical nature of the theory of signal detection states that on each trial a sensory observation can be a random sample of either a noise distribution or a signal plus noise distribution. Based on the magnitude of an observation, the participant decides whether it is from the noise or the signal plus noise distribution based on their criterion (see Figure 2.6). Rather than the threshold concept advocated in classical threshold measurement methods, a fundamental assumption of the theory of signal detection is that signals or stimuli are always presented against a background of activity or noise where the noise is assumed to vary randomly and have a normal distribution with equal variance. When the signal is presented on top of this noise, the distributions may overlap. If the means of the distributions are far apart, and the variance is small so the distributions overlap only a little, participants should be fairly unequivocal whether the signal was present or not. If the means are very close, so that the

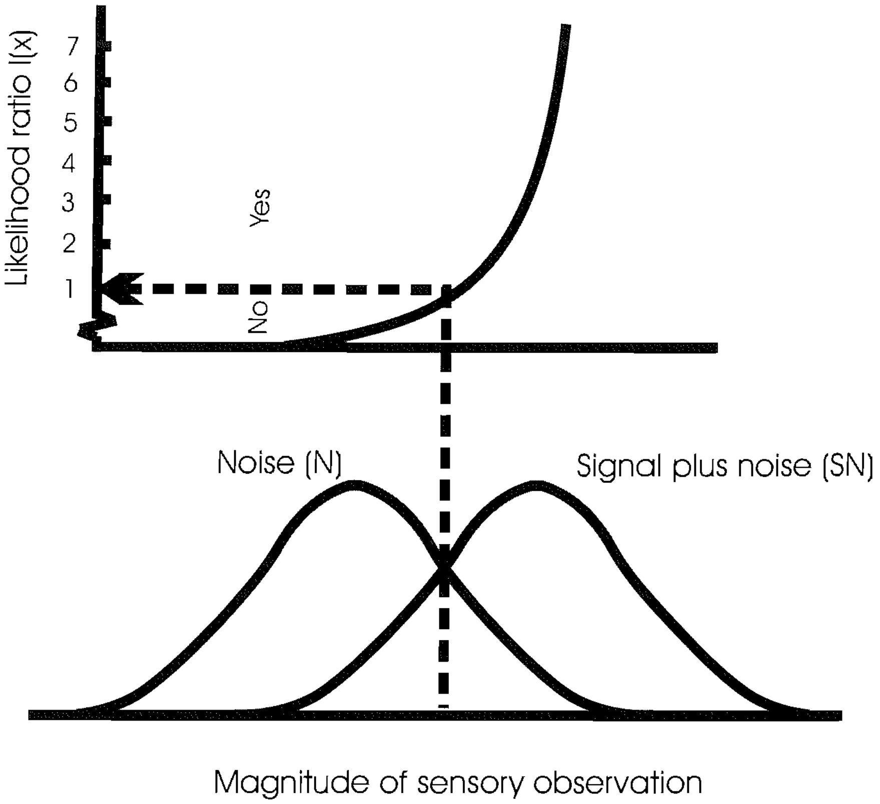


Figure 2.7: Change of likelihood ratio as a function of the value of *x*

distributions lie almost on top of each other, it will be difficult for the participant to determine if a given observation came from the noise distribution or the signal plus noise distribution.

The theory of signal detection assumes that a participant sets a particular criterion value, so that if a given observation is above this criterion, a signal will be reported, and below the criterion no signal will be reported.

The location of this criterion could be at magnitude of stimulus intensity and may be affected by expectation and payoff conditions. For instance, if the participant is told that the signal will appear with a probability of 0.3, they should give more 'no' answers than if the signal appears with a probability of 0.7, or if participants are awarded £1 for every correct response, but fined £5 for every false alarm, there may be more 'yes' responses.

In order to describe the location of this criterion, the 'likelihood ratio' (i.e. the likelihood of a specific stimuli magnitude when a signal is presented) may be calculated:

$$l(x) = \frac{ordinateofSN}{ordinateofN} \tag{2.3}$$

The theory of signal detection assumes that the participant establishes a decision rule based on some criterion, β. If a sensory stimuli has a likelihood ($l(x)$) value that is less than the criterion, β, then the participant will choose the noise distribution. If the likelihood is equal or greater than the criterion, then the participant will choose the signal plus noise distribution (see Figure 2.7).

It might seem that the best performance will be obtained when β is set to 1, where the distribution of the noise and signal plus noise cross (i.e. the point at which it is equally likely for the stimuli to have originated from the noise and signal plus noise distribution which will maximise the ratio of hits to false alarms), but optimal conditions depend on the expectation and payoff conditions.

Using the theory of signal detection techniques to determine the probabilities of p(no|N), p(yes|N), p(no|SN), and p(yes|N), and with knowledge of the costs and values assigned to various decision outcomes, you can calculate the optimum criterion point to maximise performance or earnings:

$$\beta_{opt} = \frac{p(N)}{p(SN)} x \frac{value(correctrejection) - \cos t(falsealarm)}{value(hit) - \cos t(miss)} \qquad (2.4)$$

Given a set of values and costs, it is usually found that participants do fairly well in maximising their winnings.

2.3.1.3.1. Methods of the theory of signal detection

Procedures that have been designed to give response proportions that can easily be converted into theoretical constructs of sensitivity, criterion, distribution variation, and distribution shape, and are detailed in Appendix B.

There are both classical methods and adaptive methods that can be used to determine the threshold. Adaptive techniques are the most widespread as they ensure a successful threshold measurement from every experiment.

2.3.1.4. Summary

This section has outlined psychophysical sensitivity measurement techniques used to quantify absolute and differential sensitivity to stimuli, with measurement methods outlined in Appendix A and Appendix B. The choice of method depends very much on the type of measurement required, experimental limitations (equipment, stimuli and time), and it is up to the experimenter to choose the appropriate method.

2.3.2 Psychophysical scaling

The vast majority of work in psychophysics is focused on the measurement of absolute and differential sensitivity of various sense modalities under various stimulus conditions. However, this does not provide a complete picture of the sensory system. Thresholds provide interesting measurements about the input (stimuli), but not how the input (stimuli) and output (sensation or response) are related. Psychophysical scaling seeks to provide this relationship by scaling sensation changes to stimuli changes.

The methods for constructing psychological scales can be classified into three types:

2.3.2.1. Confusion scaling

This type of scale is constructed by requiring participants to make discriminative responses between stimuli that are slightly different physically. Sensory magnitudes are inferred from the measures of stimulus discriminability. Confusion scaling leads to an interval scale (as the data

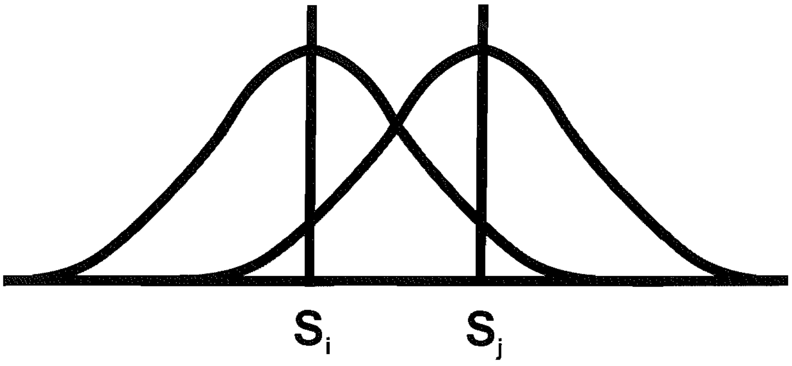


Figure 2.8: Stimuli distance on the psychological scale assuming Thurstone's case V.

only provides information about the differences among sensation magnitudes). These scales are sometimes known as discrimination scales.

Examples include the difference limen scale, and paired comparison scales.

2.3.2.1.1. Difference limen scale:

Fechner's law (see Section 2.3.2.4, Fechner (1860)) is constructed using Weber's law, or by starting at the absolute threshold, and measuring the difference limen to set the next stimulus level. A fundamental assumption is that each stimulus step required to produce a just noticeable difference is an equal change in sensation.

If such an assumption was correct, then the difference threshold must have some relation to the slope of the sensation magnitude function. This has been found to be untrue in some cases with several experiments finding the difference threshold is independent of the slope.

2.3.2.1.2. Paired comparison scales:

Similar to the difference limen scale, participants are required to discriminate between stimuli. The scale construction with this method is rather more elaborate than the difference limen scale.

Paired comparison scales assume that if similar stimuli are presented, they are more likely to be confused ($p = 0.5$), whereas if the two stimuli to be compared are very different then there should be perfect discrimination (i.e. $p = 1$). To analyse judgements, probability (p) scores are transformed into z scores where the z score is considered as the number of psychological scale units separating perceptual judgements. Various assumptions can be made about the distribution, and discriminal dispersions in order to place stimuli along the perceptual continuum, the broadest assumption being made in Thurstone's case V (Thurstone (1927)) where the distributions are assumed normal, and the dispersions are considered equal (see Figure 2.8). In this case, the z scores are taken as the distance between the signal means, and therefore the distance on the psychological scale where:

$$s_i - s_j = \sqrt{2}x_{ij} \tag{2.6}$$

where s_i and s_j are the two signals, and x_{ij} is the distance apart on the psychological scale.

2.3.2.2. Partition scales

These scales are obtained by direct scaling procedures where the participant makes direct judgements on the psychological differences between stimuli. From these judgements, interval scales can be constructed.
Examples include equisection scales, and category scales.

2.3.2.2.1. Equisection scales:

A bisection scale is constructed by presenting the participant with two stimuli, and asking them to adjust a third stimuli so that the two end stimuli are exactly divided in half. An equisection scale is similar, but requires the participant to place several intervals between the two end stimuli. An alternative way to produce a scale with more than one point is to repeat the bisection method several times.

2.3.2.2.2. Category scales:

Another division of partition scales is the category scale. Here the participant is required to place stimuli into categories by labelling them '1', '2', '3' etc. This procedure requires a vast number of trials, and the average (mean or median) category value is assigned to the stimulus.
It is also possible to construct verbally labelled category scales, such as Borg's perceived exertion scale RPE (ratings of perceived exertion) (Borg (2001)). Once tested, the experimenter can assign a number to each of the descriptive labels, you can then plot the number against the stimulus magnitude.

2.3.2.3. Ratio scaling

This scaling technique is a direct procedure and relies on the ability of the participant to make direct judgements of the ratio relationships between the magnitudes of sensations. The judgements can be used to make a ratio scale between the stimulus intensity and sensation. The actual units of the sensation and stimulus are arbitrary as long as the ratios between scale values are maintained.
There are four main methods in ratio scaling: ratio production, ratio estimation, magnitude production, and magnitude estimation.

2.3.2.3.1. Ratio production:

Two sensations are adjusted to a prescribed ratio. The participant is asked to adjust a test stimulus relative to a reference stimulus so that it is at a prescribed ratio of the reference. The method or constant stimuli, method or adjustment can be used to determine the ratio against a reference stimulus.

2.3.2.3.2. Ratio estimation:

Here, instead of adjusting two stimuli so that the sensations are of a prescribed ratio, the participants are asked to respond to two stimuli by estimating the apparent ratio between them.

Judgements in ratio production and ratio estimation can be affected by stimulus context affects such as the stimulus range.

2.3.2.3.3. Magnitude estimation:

This is the most often used psychophysical scaling method. The participant makes direct numerical estimations of sensory magnitudes.

You can undertake magnitude estimation tasks with or without a modulus. With a modulus, a standard stimulus is presented and assigned a number. Without a modulus, no standard or reference is presented.

2.3.2.3.4. Magnitude production:

This is the inverse of magnitude estimation. Here the experimenter gives the participant a numerical value, and the participant has to adjust the stimulus to represent that number. The stimulus must be continuously variable. Again these tests can be conducted with or without a modulus.

2.3.2.4. The psychophysical law

There have been two main attempts at a psychophysical law, one by Fechner with his logarithmic law that was widely accepted until the 1950's, and the other by Stevens with his power law.

Fechner (Fechner (1860), following on from Weber's law (see Section 2.3.1.1.2, Weber (1834)) proposed that the next logical step was to extend Weber's law into a scale by applying the assumption that each 'just noticeable difference' is an equal increment on the psychological scale. Successive measurements of the difference threshold can be plotted against the linear steps of sensation. The consequence of this formulation is a logarithmic law:

$$\psi = k\log\phi \qquad (2.7)$$

where ψ is the sensation magnitude, ϕ is the stimulus magnitude, and k is constant.

This is a type of indirect measurement and is valid only if the assumption of equal psychological increments holds – this has never been proven one way or another.

This law was generally accepted for 100 years, not necessarily because of its validity (as some proved that data did sometimes fail to fit Fechner's prediction), but because no one came up with a more satisfactory formula, and most data fitted the prediction well.

It was Stevens (2000) who challenged Fechner's logarithmic law in the 1950's when he discovered that the psychophysical magnitude function for brightness and loudness did not resemble logarithmic functions, and through many experiments, found that psychophysical judgements of both brightness and loudness were exponential functions of the energy of the stimulus.

Stevens' power law can be described as:

$$\psi = k\phi^n \qquad (2.8)$$

where ψ is the sensation magnitude, ϕ is the stimulus magnitude, k is constant determining the scale unit, and n is the value for the exponent which depends on the sensory modality and the stimulus conditions.

If Fechner's logarithmic law assumes that each difference threshold is an equal increment on the psychological scale, then Stevens' Power law assumes that there is an analogue to Weber's law in the psychological domain. This law is referred to as Ekman's law, based on Ekman's principle (Ekman (1956), Ekman (1959)), and states that the change in sensation required to be just noticed increases with sensation intensity:

$$\Delta\psi = c\psi \qquad (2.9)$$

where $\Delta\psi$ is the change in sensation that can just be discriminated, c is a constant, and ψ is the sensation magnitude.

2.4 Haptic literature review

Along with the psychophysiological studies discussed in Section 2.2.4, numerous psychophysical studies have been conducted in order to determine how physical stimuli are perceived, which are reviewed here.

2.4.1 Perception of force (weight)

Difference thresholds for lifted weights have been reported in Laming (1986) based on an experiment by Fechner (1860) using weights from 300 to 3000 g, resulting in a Weber fraction of 0.059 (5.9%). Oberlin (1936) measured difference thresholds for lifted weights from 50 to 550 g, giving a Weber fraction of 0.043 (4.3%). However it has been found that illusions can occur when lifting everyday objects to assess weight. Mass and volume of a lifted object seem to have complex effects on the perception of weight and heaviness, and other variables are also thought to affect weight perception.

Weight perception will not be looked into in any more detail because of the various influences that exist that can pollute or contaminate perception. The use of a steering wheel removes the human from directly manipulating weights, and so the size weight illusion is not relevant in this case, although the underlying biological mechanisms involved in perception are likely to be the same.

As outlined in the psychophysiology Section (2.2.4), the perception of force is thought to have contributions from the centrally derived 'sense of effort', and the peripheral 'sense of tension' in the muscles. How much each contributes to force perception is not known.

The perception of force has been studied by Jones (1989) who reports the difference threshold as a Weber fraction of 0.07 (7%) for forces generated at the elbow flexor muscles. Pang et al. (1991) reported difference threshold of force as 0.06 (6%) when the resisting a fixed plate, but the difference threshold increased to 0.14 (14%) Tan et al. (1995) when there was some movement of the plate.

Perceptual scales for weights and force have also been studied. Using the methods of magnitude estimation and production, power function exponents have been reported varied by as much as 0.8 to 2 (Bernyer (1957), Stevens and Mack (1959), Eisler (1962), Eisler (1965), Stevens (1973), Jones (1986)). These variations reflect the range of experimental procedures used in the studies (previous studies have used lifted weights, handgrip dynamometers, joysticks, all having contractions of various differing muscles). There have been no studies that have used a steering wheel, and so determining a suitable exponent to compare with the present study is difficult. The majority of the apparent force studies give a magnitude of apparent force that grows as the 1.7 power of the force exerted.

2.4.2 Perception of position and movement

Differential thresholds for limb movement has been reported as 8%, whilst differential thresholds for limb position have been reported as 9% by Jones et al. (1992).

Haptic discrimination of finger span with widths varying from 17.7 to 100 mm have been reported as 0.021 (2.1%) by Gaydos (1958). Discrimination of elbow movement are reported as 8% by Jones, Hunter et al. (1992) , while discrimination of sine wave movements of the finger studied by Rinker et al. (1998) produced difference thresholds that ranged from 10% to 18%.

A study of the haptic sensation of finger span by Stevens and Stone (1959) using widths of 2.3 to 63.7 mm reported an exponent of 1.33 using magnitude estimation.

2.4.3 Perception of stiffness (compliance), viscosity (damping), and inertia:

The perception of stiffness (or its inverse, compliance) has been investigated in various ways over the years. Jones and Hunter (1990) investigated difference thresholds and reported a just noticeable difference of 23%. Tan, Durlach et al. (1995) measured compliance discrimination for an active pinch grasp with 3 experimental set ups. In the first, the spring started unloaded, and the total displacement for each trial was the same. This gave compliance just noticeable difference as 8%. In the second test, the springs started unloaded, but the total displacement varied from trail to trial, which resulted in a just noticeable difference of 22%. In the 3rd test, the springs were preloaded at the start of the motion and the total displacement was held constant over the trials, which resulted in just noticeable differences of between 15% and 99%. The results suggested that the terminal force cues where very important in compliance discrimination, as when the total displacement varied the just noticeable difference got larger.

Maher and Adams (1995) report a difference threshold of 11% for elastic stiffness, Nicholson et al. (1997) report 7.7% for a pure elastic stiffness, and Nicholson et al. (2003) report a difference threshold of 14.7% for viscous stiffness.

Psychophysical scaling experiments have also been conducted with different stiffness, with Harper and Stevens (1964) reporting a power law exponent of 0.8 for the hardness of rubber samples, and Nicholson et al. (2000) report an exponent of 1.65.

The perception of viscosity has also received some attention. Jones and Hunter (1993) report the difference threshold of viscosity as 34%, and Scott-Blair and Coppen (1939)report the threshold as 30%.

Kreifeldt and Chuang (1979) and Ross and Benson (1986) report the just noticeable differences for moment of inertia between 28% and 113%.

2.5 Summary

Section 2.1 shows that evidence from aircraft and vehicle dynamics handling research points to the force-displacement or torque-angle characteristic as being important for 'feel' qualities.

Section 2.2 shows that neurophysiology has discovered cutaneous receptors, joint receptors, and muscle receptors which along with the descending efferent motor commands from the brain are thought to be responsible for human perception of limb position and movement, and the human perception of force.

Section 2.3 introduces some of the fundamental psychophysical methods which are used to acquire participants judgements of stimuli in a robust way where the judgement is not influenced by experimental conditions, and Section 2.4 details several psychophysical studies showing that the difference thresholds for the perception of force and the perception of limb movement and position are all fairly low and of the same magnitude, whereas perception of stiffness, viscosity and inertia, whilst still possible to discriminate, tend to be much less accurate. Researchers speculate that this degradation in difference threshold is due to the need for the human to integrate combinations of force, position, and movement sensations in order to discriminate stiffness, viscosity and inertia as there are not thought to be any specific receptors in the human body for these variables.

Chapter 3. Experimental apparatus

3.1 *Introduction*

This chapter describes the two steering rigs used to investigate the human perception of steering wheel properties.

A static rig allowed steering wheel force perception, and steering wheel angle perception to be investigated. A motor rig was developed from an existing rig at the Research department at Jaguar Cars, and allowed the driver perception of different stiffness profiles to be investigated. The experimental apparatus is relatively simple due to the one-degree of freedom nature of the steering system control task, with the driver only able to rotate the steering wheel about a column.

In all perception experiments, participants were required to provide a movement or force at the steering wheel, much as you would when driving a car. The static steering rig has two configurations with either a fixed column, or a free moving wheel. The motor steering rig creates various force demands based on the angle of the steering wheel. The motor was controlled by computer and could be programmed to produce numerous stiffness profiles. The two rigs are described in Section 3.2 and 3.3.

3.2 *Static rig for steering wheel force and steering wheel angle perception studies*

The static steering rig was a steering wheel mounted to a column that could either be clamped (isometric) or left to move freely (isotonic) in bearings, and is shown in Figure 3.1.

3.2.1 Mechanical and computer hardware

The steering wheel on the static rig was directly mounted to a two-piece column. The upper column attaches the steering wheel to the column, which runs through two rotary bearings allowing the column to rotate about the column. An optical encoder was mounted to the bottom of the upper column. The detachable lower column allows a torque cell to be mounted to the steering column. The lower column can be clamped with two screws for isometric control. A schematic of the static rig is shown in Figure 3.2. The components of the rig are described below.

3.2.1.1. Optical encoder

A rotary optical incremental encoder (Agilent Technologies: code wheel HEDM-6120#U09, encoder HEDS-9000#U00)) was mounted to the bottom of the upper column. The output from the encoder was a pulse train corresponding to the rotation of the graduated marks on the code wheel. The pulse count per revolution was 2048 for this code wheel. Further electronics increase the resolution from 2048 to 8192 counts per revolution by counting the edges of the pulse train. The pulse train was converted to a voltage that acts as an analogue input to the

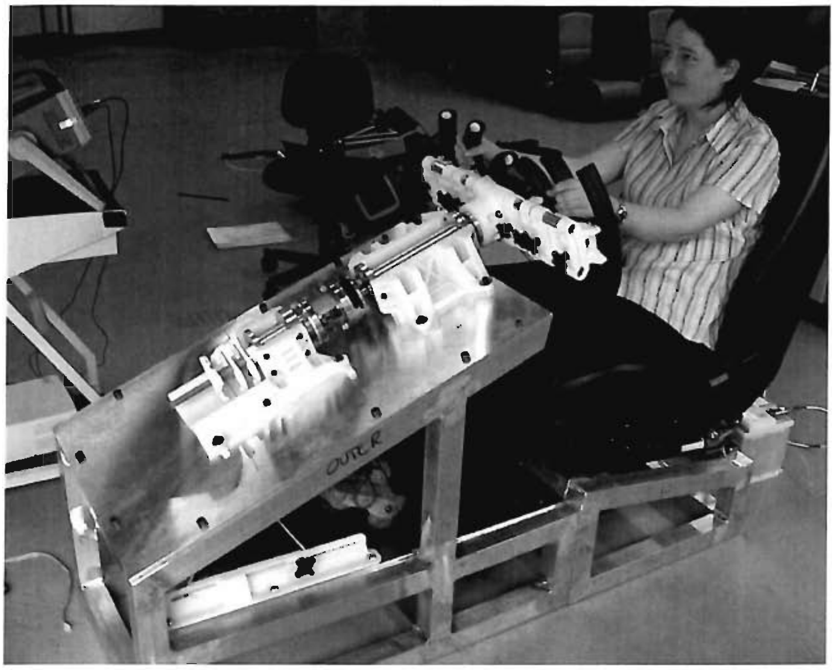


Figure 3.1: Static Rig

computer, where voltage was proportional to the angle. 8192 counts per revolution provide a 0.044 degree resolution.

3.2.1.2. Torque transducer

A strain gauge type torque transducer with flange mounting points (SensorData Technologies Inc. model T150-107-5K) was housed in the detachable lower column so that for isotonic conditions the inertia of the wheel was kept to a minimum. The output from the strain gauge was in microvolts, and was amplified (Mantracourt Electronics model SGA/A 10000206687) before processing. The typical accuracy of the torque cell was 0.01N·m.

3.2.1.3. Computer and interface boards

A computer was used to log the data from the optical encoder and the torque cell. A basic PCI data acquisition card with analogue inputs (National Instruments, model PCI-6014) was used, and was interfaced to from a technical computing program (Mathworks, Matlab Version 6.1 Release 13) on the PC. Data was collected and stored for analysis.

3.2.2 Ergonomics

The static rig was designed to simulate a Jaguar S-Type driving position.

The steering wheel, seat track, and heel point were used to dimension the rig framework. The seat was fully functioning allowing participants to move the seat to a comfortable position. However, the steering wheel did not have the same adjustability that is available in the S-Type.

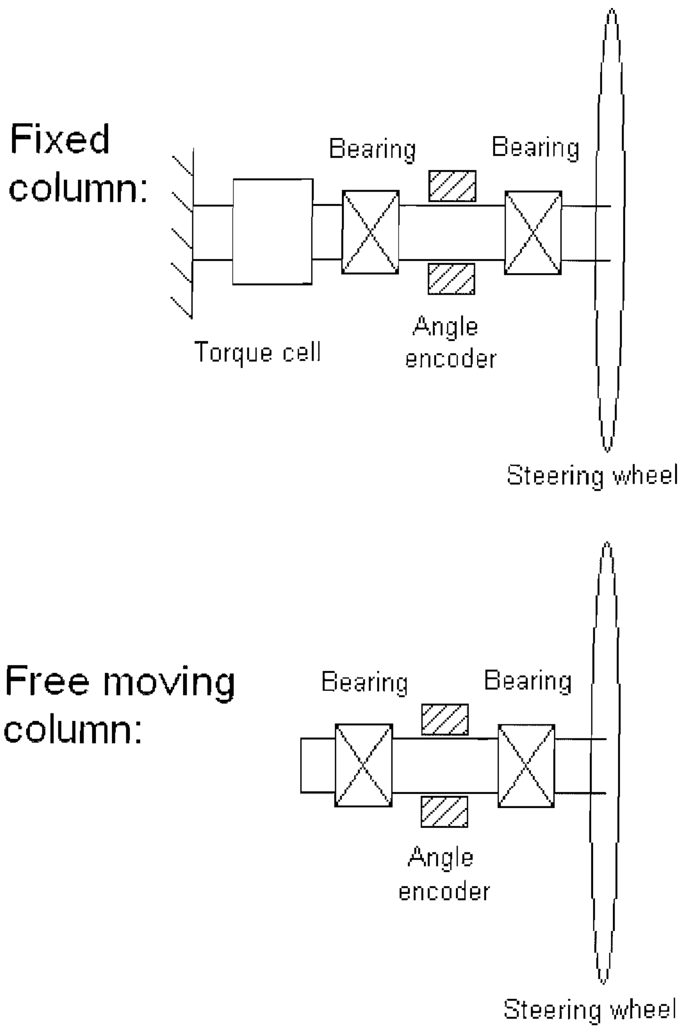


Figure 3.2: Schematic of the static rig showing the fixed and free moving column configurations.

The steering wheel was made from a rapid prototype polymer with the same cross section as a Jaguar S-Type, and was covered in leather that was glued and stitched on. The design of the steering wheel helped to make the participants hold the wheel at the '10 to 2' position, so moving hands around the wheel is taken out of the visual scene.

3.3 Motor rig for stiffness profile perception studies

A standalone motor rig has been available to Jaguar Research for over ten years, which was first used in a Steer-by-wire development vehicle at Jaguar Cars. When the vehicle was replaced, the motor for the steering column was removed and housed in a metal framework in order to conduct simulator and perception studies (see Figure 3.3).

Although the motor rig has all the main control interfaces available in a Jaguar car: steering wheel, brake, accelerator, J-gate gearbox, and instrument cluster, only the steering wheel is of interest in this project.

Figure 3.3: Motor Rig

3.3.1 Mechanical and computer hardware

The motor rig consists of a steering wheel mounted directly to the rotor of a DC brushless motor. In order to observe the torque generated by the motor, a torque cell is rigidly mounted to the column between the steering wheel and motor. The angle of the rotor is also observed from an angle encoder mounted to the shaft. A schematic of the rig is shown in Figure 3.4.

3.3.1.1. Motor

The motor used was a brushless DC motor. The stator has a 3 phase winding, with a permanent magnet rotor.

It is possible to control the speed of a brushless DC motor by manipulating the electrical voltage (see Equation 3.2), and motor current can be manipulated to control the torque generated by the motor (see Equation 3.1).

Motor torque is proportional to current: $T(t) = K_m i(t)$ (3.1)

Motor speed is proportional to voltage: $v_{emf}(t) = K_b \omega(t)$ (3.2)

For our application we were interested in developing torque with the motor rather than speed. In order to control the torque we must also consider the inertia on the rig:

Considering a simple inertial load: $\Sigma T = -K_f \omega(t) + K_m i(t)$ (3.3)

However, current control is not directly accessible on the rig, so instead, we use Ohm's law to achieve current control whilst manipulating the voltage:

Ohms law states that: $v = iR$ (3.4)

so: $\Sigma T = -K_f \omega(t) + K_m \dfrac{v(t)}{R}$ (3.5)

Several experiments conducted in this thesis require that the torque generated by the motor be based on angle feedback in a power law form:

$$T = k\theta^n \quad (3.6)$$

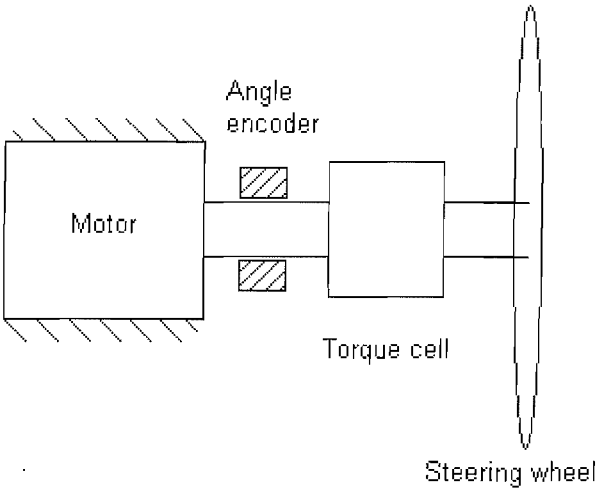


Figure 3.4: Schematic of the motor rig

so:

$$k\theta(t)^{n} = -K_{f}\omega(t) + K_{m}\frac{v(t)}{R} \tag{3.7}$$

$$v(t) = \frac{R}{K_{m}}K_{f}\omega(t) + \frac{R}{K_{m}}k\theta(t)^{n} \tag{3.8}$$

$$v(t) = a\omega(t) + b\theta(t)^{n} \tag{3.9}$$

So voltage is required to produce torque on the basis of the angle and angular rate of the steering wheel.

This voltage must be divided between the phases of the motor in order to generate torque:

$$v_{1} = v_{\max}.\sin(\theta_{electrical})$$

$$v_{2} = v_{\max}.\sin(\theta_{electrical} - 120)$$

$$v_{3} = v_{\max}.\sin(\theta_{electrical} - 240) \tag{3.10}$$

3.3.1.2. Angle encoder

As the motor came from a development vehicle, the steering sensor provides angle information using CAN signals.

Unfortunately, being a legacy component, the exact specifications of the angle encoder provided on the motor rig are not known, although the resolution has been estimated as 0.1 degree through testing.

The angle encoder also provides a velocity signal by differentiating the angle information over time. The velocity signal was used in to cancel out the back electro motive force of the motor.

3.3.1.3. Torque transducer

The torque transducer is the same one used in the static rig. See Section 3.2.1.2 for details.

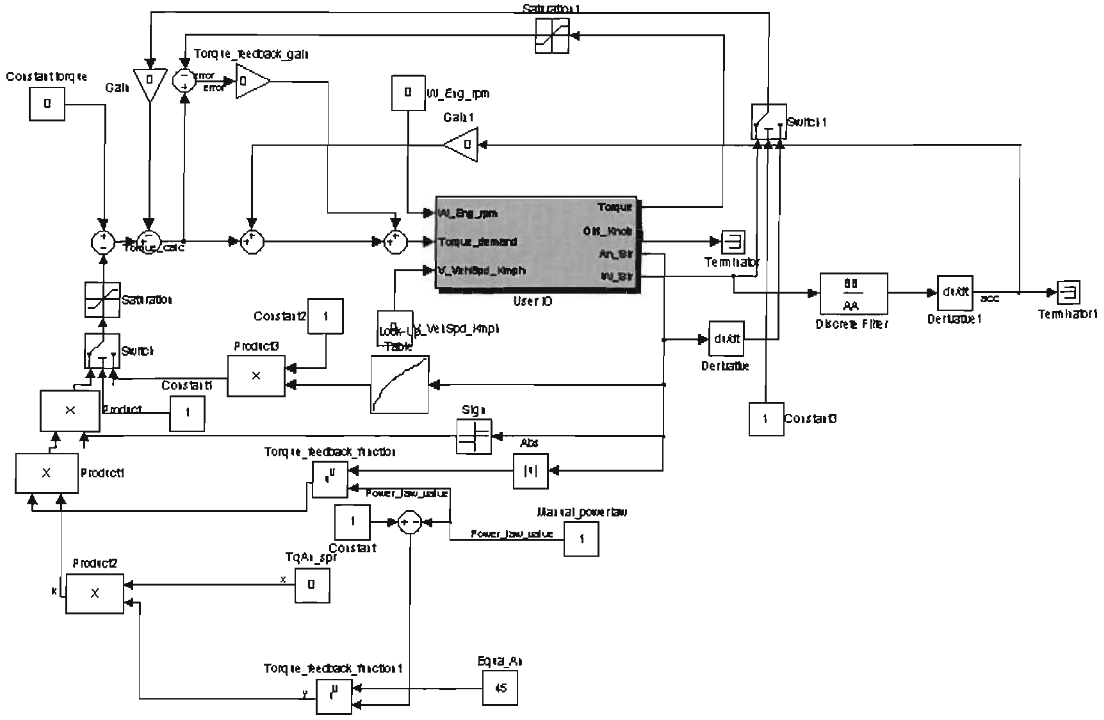


Figure 3.5: Top level of Simulink model

3.3.1.4. Computer and interface boards

Input and output signals were handled by a dSpace Control Box that held a real time model to control the rig.

The real time model was created in Simulink, and was downloaded onto the control box from a laptop. The laptop also provided a user interface to the Control box by ControlDesk software allowing real time manipulation of the model parameters.

3.3.2 Motor control

Control of the motor was achieved on a dSpace Control Box utilising a Simulink model. Figure 3.5 shows the top level of the Simulink model for illustrative purposes. The model was designed to allow control of the motor and control parameters from Controldesk. Several control strategies involving angle feedback from the angle encoder in order to specify the torque demand to the motor were available by using switches in the ControlDesk interface. Velocity information was also used in the formulation of the overall torque demand of the motor in order to cancel out the back electro motive force generated by the motor.

The angle and velocity specify the torque demand, which was transformed into a voltage request, and was sent to the three different coils of the motor.

3.3.3 Performance measures

The motor rig was tested to determine its response in two tests: a static force response test, and a sinusoidal isometric response test.

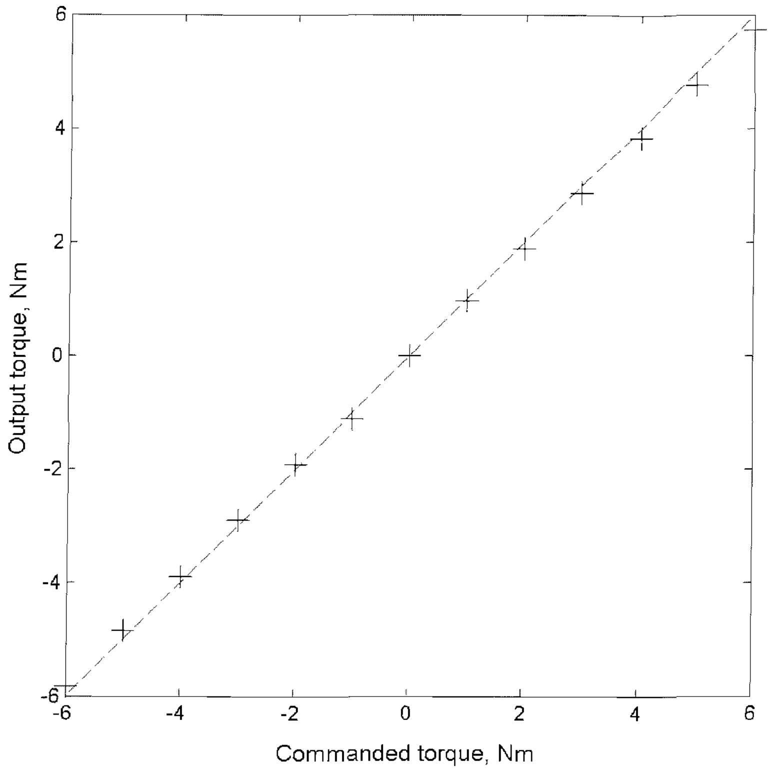


Figure 3.6: Isometric force output versus force command. Dashed line is ideal response

3.3.3.1. Static force response:

With the steering wheel clamped, a number of torque magnitude requests were sent to the motor. The torque cell recorded the response, and is shown in Figure 3.6.

The motor rig produced the commanded torque fairly accurately, with slight underproduction that increases as the torque command increases.

Static friction was typically 0.05 N·m, or 0.26 N (27 g) at the rim of a standard Jaguar S-Type steering wheel with diameter of 381 mm.

3.3.3.2. Sinusoidal isometric response:

Sinusoidal force commands were sent to the motor whilst the steering wheel was clamped to check the frequency response of the rig. Figure 3.7 shows the frequency response for frequencies from 0.2 Hz to 8 Hz.

Figure 3.7 shows that the motor is most capable and consistent to approximately 3 Hz. Therefore participants will be required to turn the wheel at a slow and comfortable rate to maintain the accuracy of this rig. The phase lag was measured as 0.06 s.

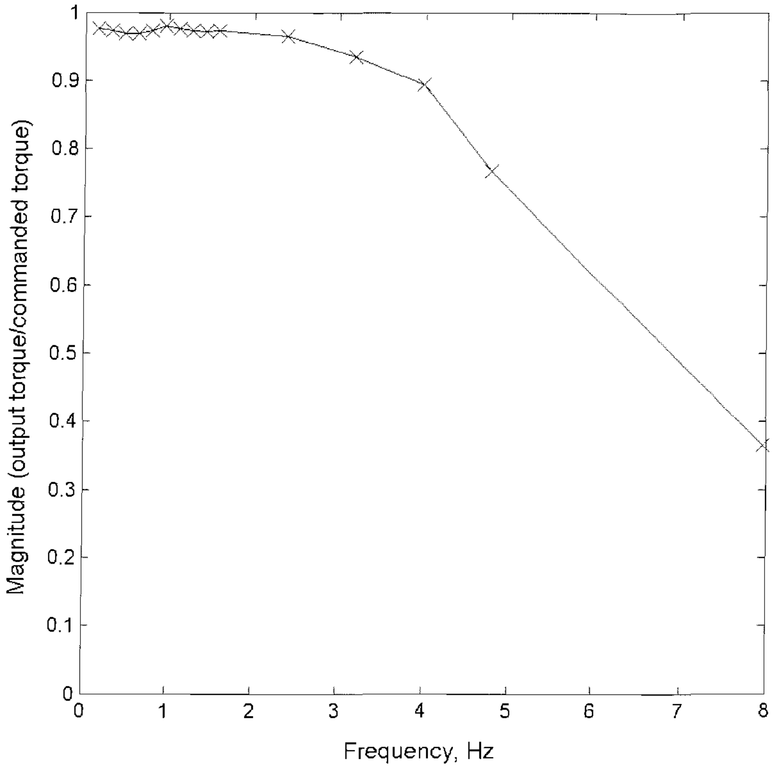


Figure 3.7: Magnitude of output force to commanded force, Isometric case

3.4 Summary

Two steering wheel rigs were designed to investigate human perception of steering feel. The static rig allows the perception of steering wheel force and steering wheel angle to be investigated separately, while the motor rig allows the perception of steering wheel force and steering wheel angle when they occur within the same movement to be investigated.

PART 2: PERCEPTION OF STEERING WHEEL FORCE AND STEERING WHEEL ANGLE

Chapter 4	Perceptual terminology for steering feel
Chapter 5	Sensitivity to steering wheel force and steering wheel angle
Chapter 6	Scaling steering wheel force and steering wheel angle

The review of haptic processes in Chapter 2 identified force, position and velocity as the main parameters perceived by the brain, with stiffness, damping and inertia thought to require higher order processing of the base parameters of force, position and velocity along with time. Considering only the steady-state feel of a steering system, the forces and positions are the most important parameters to consider.

Part 2 includes three chapters detailing experiments conducted to determine how humans perceive forces and movements through a steering wheel.

Chapter 4. Perceptual terminology for steering feel

4.1 *Overview*

In Chapter 2 a study by Van Doren (1998) was described and showed that different matching behaviours were observed in participants depending on the instructions given.

Before commencing any perceptual testing on human participants, it is important to get the instructions right so that the property that the human perceives is the one we ask for. Whilst it would be usual to describe a steering or rotating system's steady-state characteristics in terms of torque and angle, it is also possible to describe the system in terms of force and displacement.

In order to find the best terms to use for further perception studies, an experiment using ambiguous instructions was conducted.

The results show that when told to 'match' stimuli between different size steering wheels, participants have significantly higher correlations to steady-state steering wheel force than torque, and higher correlations to steering wheel angle than displacement.

4.2 *Introduction*

Frames of reference provide a means for representing the locations and motions of entities in space. There are two principal classifications for reference frames in spatial perception: the allocentric (a framework external to the person), and the egocentric (a framework centred on the person), with the choice of reference frame usually a matter of convenience.

In engineering terms, it is convenient to describe the motion of a steering wheel in a rotational frame of reference using steering wheel torque and steering wheel angle. However, drivers may use a different frame of reference when perceiving the feel of a steering system – they may perceive steering wheel force rather than steering wheel torque, and steering wheel displacement rather than steering wheel angle. Alternatively, it may be possible that neither purely allocentric or egocentric frame of reference are used by drivers, and instead some intermediate reference frame may be used as suggested by Kappers (2005).

This experiment aims to test whether drivers sense steering wheel force or torque, and whether they sense steering wheel angle or displacement.

The relationship between these properties is shown in equations 4.1 and 4.2. To investigate which variable is intuitively used by the driver, it is necessary to uncouple the relationship between a rotational and translation frame of reference by altering the radius of the steering wheel.

$$T = rF \tag{4.1}$$

$$x = r\theta \tag{4.2}$$

Drivers can be expected to reproduce a set torque (T), force (F), angle (θ) or displacement (x)

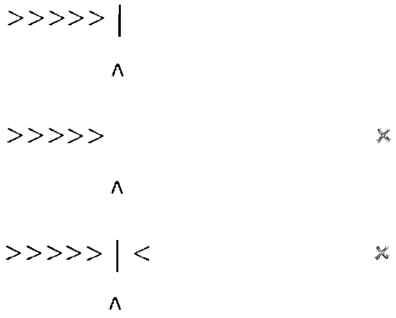


Figure 4.1: Graphical user interface. Achievement of reference condition

reasonably accurately if asked to do so, so it is important that the experimental method does not lead the participant to any particular setting.

4.3 Method

In order to test which property is more intuitive to the participants, a study was conducted using ambiguous instructions. Participants were simply told to ‘match’ the magnitude of the stimulus achieved in the reference to a steering wheel with a different diameter.

4.3.1 Apparatus

The static steering rig described in Section 3.2 was used in this experiment. The isometric set-up was used to investigate force and torque, and the isotonic set-up was used to investigate angle and displacement.

The output from the torque cell or angle encoder (depending on the condition) was acquired in real time, and used to generate a graphical user interface to inform the participant that the reference stimuli had been achieved. The interface used by participants to obtain the reference stimulus is shown in Figure 4.1.

Care was taken to ensure that the display remained ambiguous regardless of condition. The sensitivity of the user interface was set so the target value is ± 5%.

A multiple rimmed steering wheel was utilised to provide a small (205 mm diameter), medium (381 mm diameter), and large (555 mm diameter) steering wheel diameter.

The car seat used in the rig was electronically adjustable and allowed each participant to sit in a comfortable position whilst maintaining an angle at the elbow of 110° to ensure that participants did not sit too far or too close to the steering wheel.

4.3.2 Stimuli

Care was taken to ensure that the instructions and apparatus remained ambiguous, and similar precautions were taken with the reference stimuli.

For the isometric steering wheel condition, four references were used regardless of steering wheel size, 5 N, 15 N, 1.5 N·m and 3 N·m. For the isotonic steering wheel condition, references of 3°, 9°, 10 mm, and 30 mm were used. The forces and distances refer to forces and distances at the rim of the steering wheel, and were obtained by multiplying or dividing the torque or angle signal by the radius of the steering wheel.

4.3.3 Hypothesis

It was hypothesised that when asked to 'match' a reference condition using isometric steering wheels (i.e. a wheel that did not rotate) with varying diameter, participants would match either steering wheel force or steering wheel torque. It was similarly hypothesised that when using isotonic steering wheels (i.e. a wheel that rotated without resistance to movement) with varying diameter, participants would match either steering wheel angle or steering wheel displacement.

4.3.4 Design

4.3.4.1. Participants

Twelve male participants, aged between 18 to 26 years, took part in the experiment using a within-subjects experimental design where all participants participated in all conditions.
The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.
A questionnaire was used to collect personal details, health, and number of years driving experience of participants, and anthropometric data was measured according to Pheasant (1986). The measured data included stature, weight, sitting height, and shoulder-grip length. After the fixed column session, participants also gave a measure of their maximum voluntary contraction using a Jamar grip dynamometer.

4.3.4.2. Experimental procedure

Participants were given only basic practice in the technique required to make the matches between steering wheel rims so that their judgements would not be influenced by the practice. Participants were given four practices using the graphical user interface to achieve the reference, and were instructed to consider what they would do to achieve a match for the test trial using the same wheel diameter as the reference.
After this short practice, participants were required to wear a pair of headphones, which generated pink noise to prevent participants from being disturbed by noise around the laboratory. A cloth was also suspended over the multi-rimmed steering wheel so that participants could not use visual feedback to aid their matching trials.
There were four blocks with eighteen trials in each session. The orders of presentation for the four blocks of trials for each session are shown in Table 4.1. The eighteen trials included nine trials to cover each combination of wheel rim for reference and test, and a repeat. The presentation order of the reference and test rim sizes was randomised.
At any point in the experiment participants could redo a trial condition if they were not satisfied that they had achieved the reference or the test stimulus.

Table 4.1: Experimental condition order:

Participant	Session 1				Session 2			
1, 5, 9	5 N	15 N	1.5 N·m	3 N·m	10 mm	30 mm	3 °	9 °
2, 6, 10	15 N	5 N	3 N·m	1.5 N·m	30 mm	10 mm	9 °	3 °
3, 7, 11	1.5 N·m	3 N·m	5 N	15 N	3 °	9 °	10 mm	30 mm
4, 8, 12	3 N·m	1.5 N·m	15 N	5 N	9 °	3 °	30 mm	10 mm

Using the 'method of adjustment', participants 'matched' sensations from a 'reference' steering wheel to a 'test' steering wheel. When grasping the reference wheel, participants were required to achieve a desired stimulus magnitude by acting on the wheel in a clockwise direction using visual feedback from a fixed 11-point indicator scale on a computer monitor. The participants then moved their hands to the test wheel (with either a 'small', 'medium', or 'large' diameter) to 'match' the sensation experienced with the reference wheel.

The length of time that participants were required to hold a force or torque was minimised to prevent fatigue. Typically, participants took 10 seconds to reach the desired force or angle.

4.3.4.3. Instructions

The instructions for this experiment were as follows:

For each trial, you will use one wheel rim for the reference condition, and another for the test condition. The rim that each command is referring to is shown in Figure 1 (Figure 4.2).

For each trial, you will achieve the reference condition according to the computer instructions. You will then be required to ***match*** *the reference in a 'test condition' without feedback from the computer. You should aim to recreate the reference stimuli in this test condition to the best of your ability.*

If at any time you feel uncomfortable, or feel unable to create the stimulus required, please release the wheel, or speak to the experimenter. You will be able to redo any experimental trial if you are not satisfied.

4.3.4.4. Analysis

Participants were required to use the method of adjustment to 'match' the reference using three different sized steering wheel rims.

All data achieved with the isometric steering wheel was acquired with a torque transducer leading to a direct measurement of torque, but this magnitude was also transformed into force using equation 4.1 according to the radius of the steering wheel in use at the time. Similarly the measurements collected with the isotonic steering wheel were acquired with an angle encoder leading to a direct measurement of angle, but this magnitude was also transformed into displacement using equation 4.2.

A measure of the residuals between the match and the reference stimuli provide a measure of the error, but it is not appropriate in this case because the transformations mean that they are not directly comparable. Instead, a non-parametric measure of correlation between the

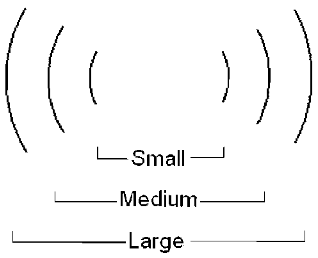


Figure 4.2: Steering wheel sizes

reference and test magnitudes created by the participants was used to test the correlation between reference and test data.

A Spearman rank-order correlation coefficient is a non-parametric correlation method that calculates correlation by ranking each magnitude of a variable, and then taking the difference or residual as the difference between the rank of the first variable (i.e. the reference) against the rank of the second variable (i.e. the match or test).

If the data are perfectly correlated, the reference and test data would have the same rank, and so the differences would be zero and the correlation would be perfect (i.e. $r = 1$).

4.4 Results

The results for a typical participant with the isometric control are shown in terms of force in Figure 4.3, and in terms of torque in Figure 4.4. The results for a typical participant with the isotonic control are shown in terms of angle in Figure 4.5 and in terms of displacement in Figure 4.6.

Correlation coefficients between the physical magnitudes of the reference condition and the test condition are presented for each participant in Table 4.2. For the isometric control, correlation coefficients were obtained for both torque and force at the steering wheel rim. For the isotonic control, correlation coefficients were obtained for both angle and displacement at the steering wheel rim. It was assumed that the variable with the greater correlation (i.e. either force or torque, and either angle or displacement) was the variable that was being matched by participants.

Over the 12 participants, with the isometric control, the correlation coefficients obtained for force were significantly higher than those obtained for torque ($p<0.01$, Wilcoxon matched-pairs signed ranks test). For the isotonic control, the correlation coefficients obtained for angle were significantly higher than those obtained for displacement ($p<0.01$, Wilcoxon matched-pairs signed ranks test).

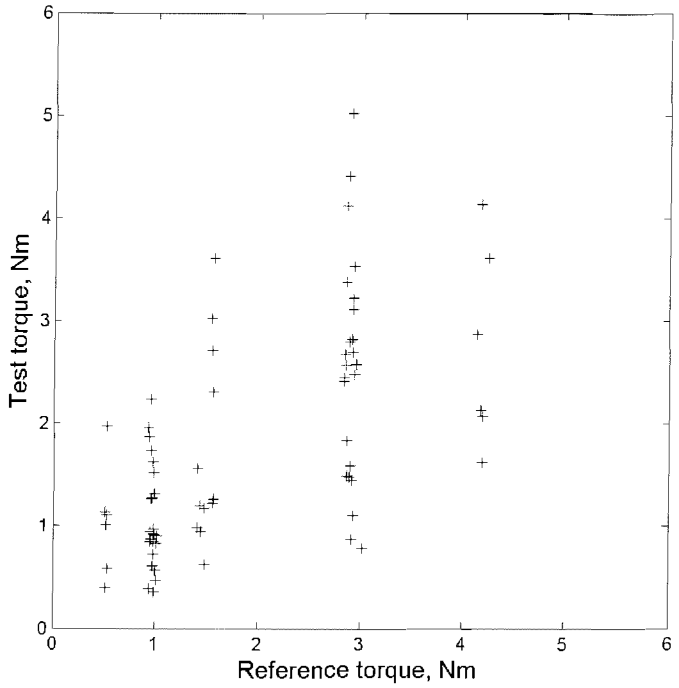


Figure 4.3: Reference and test magnitudes for the isometric control in terms of torque (data from one participant).

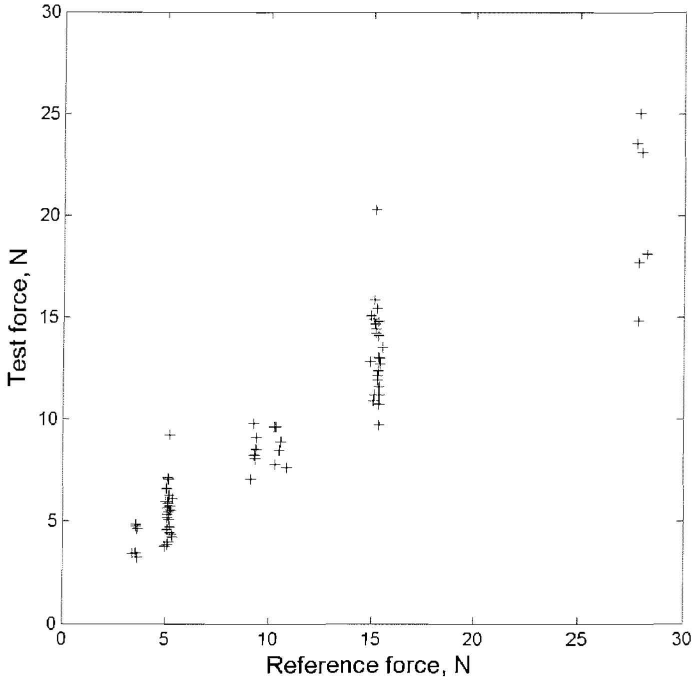


Figure 4.4: Reference and test magnitudes for the isometric control in terms of force (data from one participant).

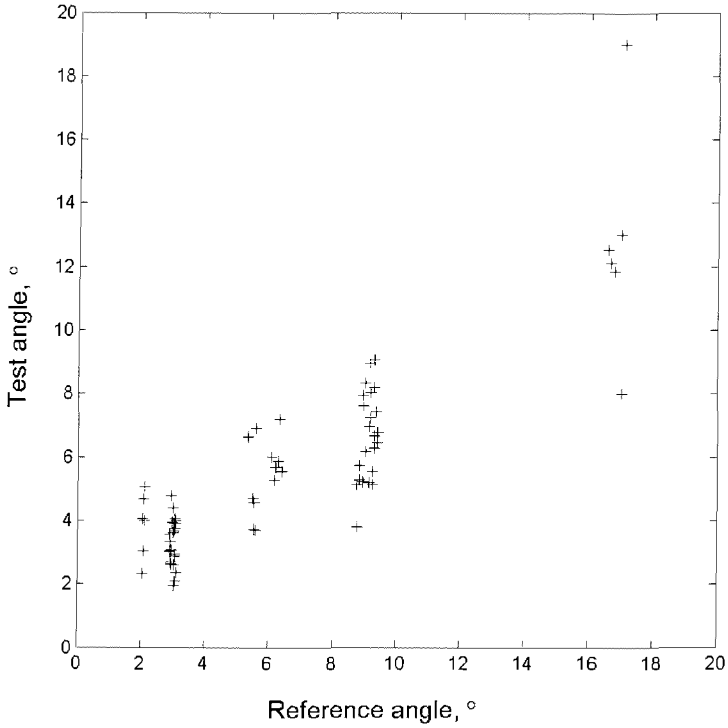


Figure 4.5: Reference and test magnitudes for the isotonic control in terms of angle (data from one participant).

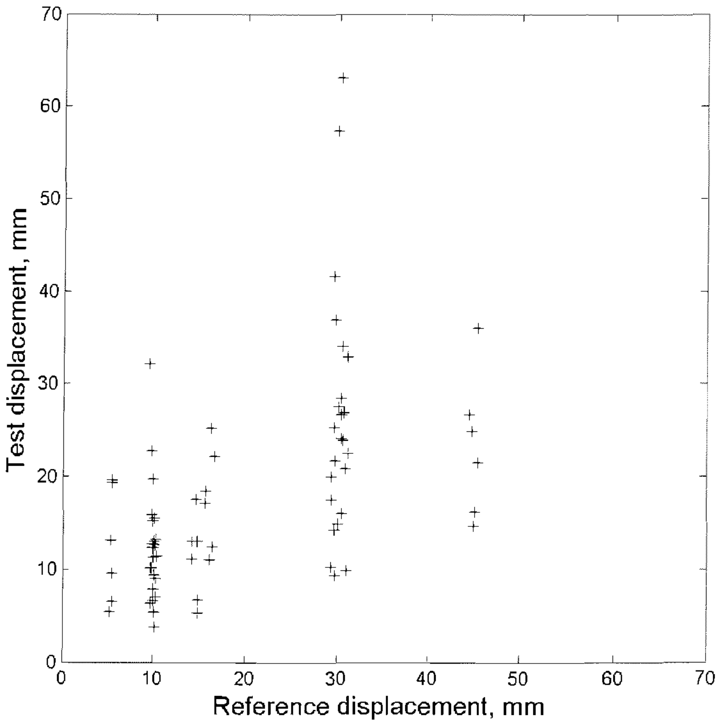


Figure 4.6: Reference and test magnitudes for the isotonic control in terms of displacement (data from one participant).

Table 4.2: Spearman rho correlation coefficients, *r*, between reference magnitude and test magnitude (all Spearman rho correlation coefficients in the table are significant at $p<0.01$).

Participant	Isometric wheel Torque	Isometric wheel Force	Isotonic wheel Angle	Isotonic wheel Displacement
1	0.36	0.73	0.89	0.49
2	0.43	0.82	0.79	0.48
3	0.56	0.89	0.82	0.55
4	0.71	0.82	0.69	0.46
5	0.71	0.81	0.74	0.69
6	0.79	0.76	0.79	0.66
7	0.68	0.77	0.75	0.73
8	0.72	0.76	0.80	0.62
9	0.53	0.84	0.89	0.60
10	0.72	0.84	0.78	0.53
11	0.53	0.89	0.79	0.69
12	0.62	0.85	0.90	0.60

No significant correlations were found between the participant's age, driving experience, weight, anthropometric data, handedness, and maximum voluntary contraction (Spearman rank-order correlation), and no significant differences were found in the presentation order (Friedman).

4.5 Discussion

The results suggest that with idealised isometric and isotonic controls, drivers have a more intuitive sense of steady-state steering wheel force than steering wheel torque, and a more intuitive sense of steady-state steering wheel angle than steering wheel displacement.

To judge torque, participants would need to combine estimates of force with knowledge of the distance between their hands and the centre of the steering wheel. To judge the displacement of the steering wheel rim, participants would need to combine estimates of their joint angles with the length of their limbs. The estimation of torque and distance requires more information and greater processing than the estimation of force and angle. Consequently, it is not surprising that torque and displacement result in less accurate judgements and are not preferred or 'natural'.

Visual inspection of the correlation figures for force (Figure 4.4) and angle (Figure 4.5) show that the ‘match’ magnitude is generally underestimated. To investigate this, lines of best fit were analysed. Every single line of best fit had a gradient of less than unity except for one participant. In a matching task, you would expect the gradient to be unity for a perfect match. The single participant that achieved a slope greater than 1.0 did so only for angle data. This could have arisen from an order effect due to the reference being presented first. Alternatively, it could indicate that the physical variables do not reflect the parameters adjusted by the participants. Regardless of the deviations of references and 'matches' from a perfect match, the Spearman correlations ranked the reference and 'match' data according to magnitude without making any assumptions about the exact values of the reference and the 'match'.

4.6 Conclusions

This study shows that the perception of steering wheel properties more closely correlates to steering wheel force and steering wheel angle than torque and displacement.

Although the matching behaviour was not perfect for force and angle, it is possible given the ambiguous nature of the experiment that the experimental conditions could have introduced experimental errors, or it could be possible that neither torque or force are perceived by participants, and instead another parameter is intuitively used by participants that is more closely related to force than it is to torque (and more closely related to angle than displacement).

In general, this experiment shows that for the idealised steering wheel column properties used in this experiment, participants will use their own frame of reference (force) to perceive and recreate stimuli for a clamped steering wheel column, but use the steering wheel frame of reference (angle) to perceive and recreate stimuli for a free moving steering wheel column.

In further studies, the terms force and angle should be used in the instructions.

Chapter 5. Sensitivity to steering wheel force and steering wheel angle

5.1 Overview

Difference thresholds were introduced in Chapter 2 as a useful way to describe how sensitive humans are to changes in environmental stimuli.

In order to determine how sensitive humans are to the steady-state properties at the steering wheel, an experiment was conducted to determine the difference threshold of steering wheel force and steering wheel angle. The results show that a 15% difference is required in steering wheel force and 14% in steering wheel angle in order to be just noticeable at an 80% correct detection rate.

5.2 Introduction

The difference threshold is the smallest change in a stimulus required to produce a just noticeable difference in sensation (see Section 2.3.1.1.2). Difference thresholds can be described in absolute terms, where the threshold is described in the physical units of the variable under test, or in relative terms, where the threshold is described in terms of a 'Weber fraction' or percentage. Weber proposed that the absolute difference threshold is a linear function of stimulus intensity, and can therefore be described as a constant percentage, or fraction, of the stimulus intensity. This is expressed in Weber's law:

$$\frac{\Delta\phi}{\phi} = c \qquad (5.1)$$

where ϕ is the stimulus intensity, $\Delta\phi$ is the change in stimulus intensity required to be just noticed, and c is a constant known as the 'Weber fraction', although it is often expressed as a percentage. The smaller the Weber fraction or percentage, the more sensitive the participant is to the stimuli.

Difference thresholds for the perception of force are available in a variety of forms. Jones (1989) reports the difference threshold as a Weber fraction of 0.07 (7%) for forces generated at the elbow flexor muscles. Difference thresholds for lifted weights have been reported in Laming (1986) based on an experiment by Fechner (1860) using weights from 300 to 3000 g, resulting in a Weber fraction of 0.059 (5.9%), and Oberlin (1936) measured difference thresholds for lifted weights from 50 to 550 g, giving a Weber fraction of 0.043 (4.3%). Haptic discrimination of finger span with widths varying from 17.7 to 100 mm have been reported as 0.021 (2.1%) by Gaydos (1958). Discrimination of elbow movement are reported as 8% by Jones, Hunter et al. (1992), while discrimination of sine wave movements of the finger studied by Rinker, Craig et al. (1998) produced difference thresholds that ranged from 10% to 18%.

The present experiment investigated difference thresholds for steering wheel force (using an isometric steering wheel), and difference thresholds for steering wheel angle (using an isotonic steering wheel).

5.3 Method

In order to determine the difference thresholds of steering wheel force and angle, participants were required to judge between two stimuli presented sequentially, and report which one was greater.

5.3.1 Apparatus

The static steering rig described in Section 3.2 was used in this experiment. The isometric set-up was used to investigate force sensitivity, and the isotonic set-up was used to investigate angle sensitivity.

The output from the torque cell or angle encoder (depending on the condition) was acquired in real time, and used to generate a graphical user interface to inform the participant that the reference stimuli had been achieved. The target sensitivity was adjusted on the graphical user interface to ± 2%.

A steering wheel diameter of 381 mm was used, which is the standard 2002 Jaguar S-Type steering wheel diameter.

The car seat used in the rig was electronically adjustable and allowed each participant to sit in a comfortable position whilst maintaining an angle at the elbow of 110° to ensure that participants did not sit too far or too close to the steering wheel.

5.3.2 Stimuli

There were two sessions to determine the difference threshold. One for the isometric set-up to determine the difference threshold for steering wheel force, and one for the isotonic set-up to determine the difference threshold for steering wheel angle.

Three reference magnitudes were used in each session: 5.25 N, 10.5 N and 21 N for the isometric steering wheel, and 4°, 8°, and 16° for the isotonic steering wheel.

The magnitude of the 'reference' remained the same for each threshold estimate, and the 'test' stimulus was presented at a greater magnitude than the reference in 4% incremental steps, with each threshold measurement starting at the same magnitude as the 'reference'.

5.3.3 Hypothesis

It was hypothesised that Weber's Law would apply to sensations of both steering wheel force and steering wheel angle, with constant relative difference thresholds expected across the stimulus range investigated.

5.3.4 Design

5.3.4.1. Participants

Twelve male participants, aged between 18 to 28 years, took part in the experiment using a within-subjects experimental design.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and number of years driving experience of participants, and anthropometric data was measured according to Pheasant (1986). The measured data included stature, weight, and shoulder-grip length.

5.3.4.2. Experimental procedure

Difference thresholds were determined with a two-alternate forced-choice procedure using an up-and-down transformed response (UDTR) method (see Appendix B).

The required magnitude for force or angle was presented on an ambiguous 11-point scale on a computer monitor. The reference stimulus and a test stimulus were presented sequentially, and in random order, to participants who were required to report which of the two stimuli ‘felt greater’.

The UDTR (up-down-transformed-response) method was used with a three-down one-up rule (i.e. three correct responses in a row resulted in the test stimulus getting closer to the reference stimulus whereas one incorrect response would result in the test stimulus getting further apart from the reference stimulus). The three-down one-up rule results in the difference threshold being observed at a 79.4% correct response level (0% being none correct, 50% being chance response, and 100% being certainty).

The order of presentation for the reference conditions was balanced across participants with six participants starting with the isotonic control, and six starting with the isometric control.

For steering wheel angle trials, the wheel was free moving and participants were asked to concentrate on the angle at the wheel. For steering wheel force trials, the wheel was clamped and participants were asked to concentrate on the force they were applying to the wheel.

Participants were given four practices before each session to familiarise them with the graphical user interface, equipment and procedure. For these practice trials, participants were told which of the two presentations were larger.

After successful completion of the practice trials, participants were required to wear a pair of headphones, which generated pink noise to prevent noise disturbance from the laboratory. A cloth was suspended over the steering wheel so that participants received no direct visual feedback of their hand position to aid the trials.

The ‘reference’ and ‘test’ stimuli were presented immediately after each other, followed by the participant’s response. Participants were then given a 10 second break before the next trial pair to prevent effects from fatigue or lack of concentration.

5.3.4.3. Instructions

The instructions for this experiment were as follows:

Before the experiment, there will be 10 seconds whilst the equipment calibrates. You should not touch the wheel in this time.

Afterwards the experiment will start and you will create 2 stimuli after which you will be asked:

'Did you judge the first or second to be the greater?'

To which you should answer either FIRST or SECOND.

Stimuli will be presented several times.

5.3.4.4. Analysis

To determine a difference threshold for each reference, participants made a sequence of judgements, with the total number of judgements dictated by their responses. Depending on the participant's response, the test stimulus magnitude would get closer or further away from the reference stimulus magnitude. The up-and-down transformed response method used in this study results in a zigzag or staircase in test stimuli magnitudes as the participant makes correct or incorrect responses.

The sequence was terminated after three 'up' and three 'down' reversals of direction in the test stimulus magnitude. The difference threshold was measured as the mean value of the last two 'up' and the last two 'down' reversals.

The number of trials required for each threshold measurement varied according to the participant's responses with an average of 28 trials per run. One threshold measurement run typically lasted 10 to 20 minutes.

It is recommended that the first peak and trough be removed from the analysis to prevent starting error affecting the result. For this experiment, the 3rd to 6th reversal (peak 2 and 3, trough 2 and 3) are used to calculate the difference threshold:

$$DT = \left(\frac{\left[\sum_{j=2}^{j=3} p_j + \sum_{j=2}^{j=3} t_j \right]}{N} - R \right) \times 100, \tag{5.2}$$

where DT is the difference threshold (expressed as a percentage), p_j is the magnitude (in force or angle) of the peak j, t_j is the magnitude of the trough j, N is the number of reversals (i.e. 4), and R is the reference magnitude.

5.4 Results

The median absolute and relative difference thresholds are shown in Table 5.1.

For both force and angle, the absolute difference thresholds increased significantly with increasing magnitude of the reference (p<0.01, Friedman).

Table 5.1: Median difference thresholds (N = 12).

	Reference					
	Force (N)			Angle (°)		
	5.25	10.5	21	4	8	16
Absolute difference threshold (N or °)	**0.87**	**1.58**	**2.42**	**0.68**	**1.12**	**1.84**
Relative difference threshold (%)	**16.5**	**15.0**	**11.5**	**17.0**	**14.0**	**11.5**

The median absolute and relative difference thresholds for both force and angle are shown in Figure 5.1 and Figure 5.2, respectively. The median relative difference thresholds tended to decrease (from 16.5% to 11.5%) with increases in the reference force and decrease (from 17.0% to 11.5%) with increases in the reference angle. However, the overall relative difference thresholds did not differ significantly over the three force references or over the three angle references (p>0.4, Friedman).

Correlations between the participant's characteristics and the measured difference thresholds were analysed using Spearman analysis. There was one significant difference evident in the analysis, which was a significant correlation between the absolute and relative difference threshold at 8° and the participant's weight (Spearman p<0.01). As there are no correlations between weight and the other angle references (4° and 16°) it is assumed that this correlation occurred by chance.

5.5 Discussion

The statistical analysis implies that the relative difference thresholds were independent of force and angle reference magnitudes and that Weber's Law can be upheld for the conditions of the study.

The mean relative difference thresholds across the magnitudes of the reference stimuli were 15% when detecting changes in force and 14% when detecting changes in angle. This suggests no fundamental difference in the accuracy of detecting changes in force and angle, implying that force and angle provide equally discriminable changes in feedback.

For the perception of force, the 15% relative difference threshold was obtained with a correct performance level of 79.4%. Direct comparison to the aforementioned studies of the perception of force are not possible, as correct response levels are not presented in those studies.

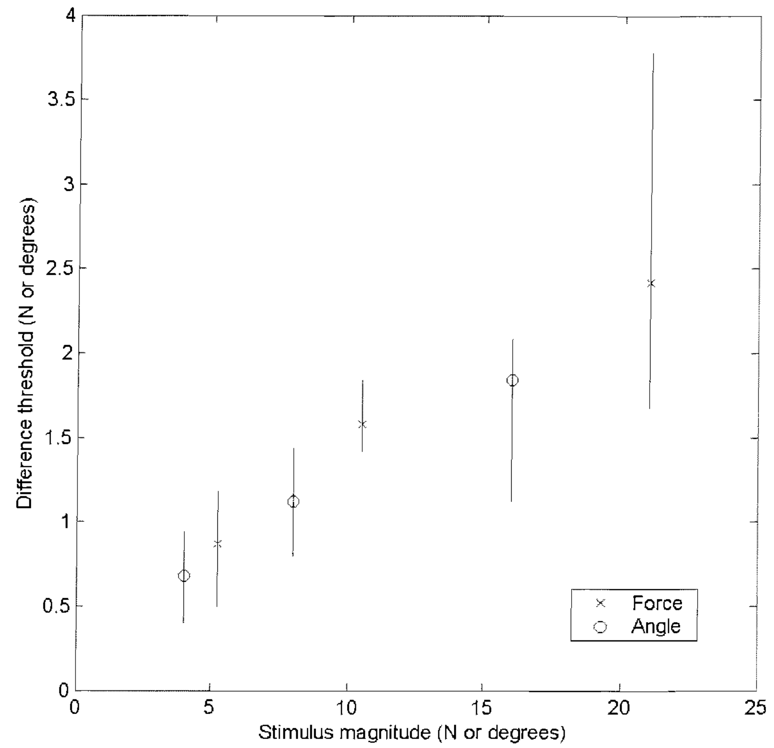


Figure 5.1: Absolute difference thresholds for force and angle (medians and inter-quartile range).

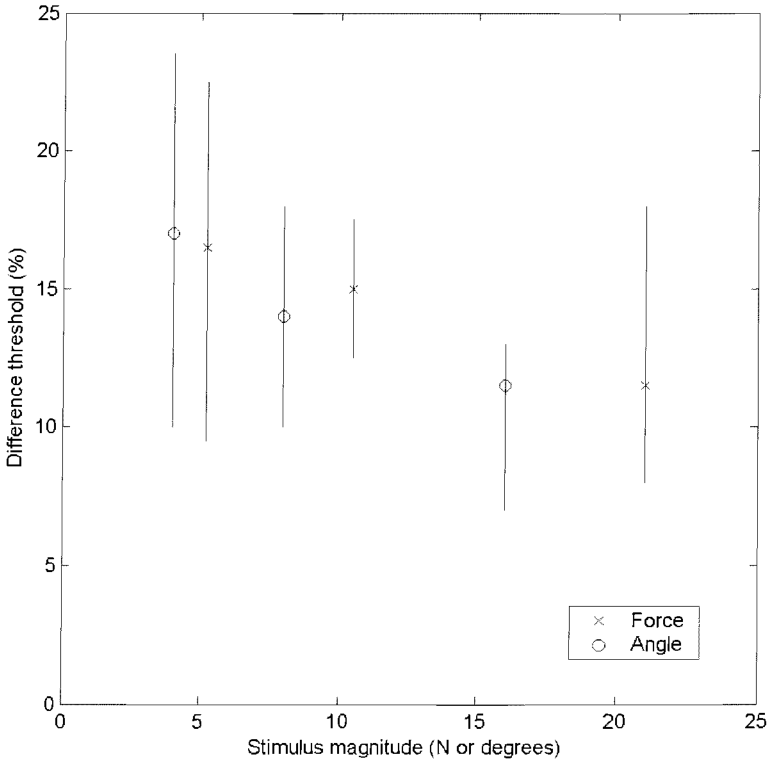


Figure 5.2: Relative difference thresholds for force and angle (medians and inter-quartile range).

For the perception of angle, 14% in the present study compares with a difference threshold for limb movement in the range 10% to 18% (for a 71% correct performance level) according to Rinker, Craig et al. (1998) for sine wave movements of the finger, and 8% (for a 71% correct performance level) according to Jones, Hunter et al. (1992) for movement of the elbow.

5.6 Conclusions

A 15% difference in steering wheel force, and a 14% difference in steering wheel angle is required for a human to notice the change approximately 80% of the time.

This result marks only one point in the statistical distribution of possible correct response rates, so differences of less than 15% and 14% respectively will be felt by some participants some of the time.

This chapter is concerned with the measurement of difference thresholds of force and angle when presented independently. In a vehicle, force and angle stimuli will be presented with other stimuli at the same time, both through the steering wheel, and through other receptors in the body.

If we were to apply these difference thresholds to steering wheel stimuli in a vehicle, then we would have to be certain that other stimuli do not change our perception of the force and angle stimuli.

Pang, Tan et al. (1991) investigated difference thresholds of force for a pinching task, and found that force discrimination was 7% regardless of the reference force, the distance squeezed, the initial finger span, and the velocity of the squeeze. For haptic stimuli at the steering wheel, we might therefore conclude that for force discrimination in the presence of other stimuli, such as rotation of the wheel, the difference threshold should remain constant.

If angle perception does not depend on steering wheel force and steering wheel velocity, then we should be able to determine an area within which steering wheel stimuli differences will not be noticed for sequential turns of the steering wheel.

Figure 5.3 shows the region that the difference thresholds for steering wheel force and angle prediction will be not noticed (79.4% of the time) where the reference and next turn stimuli start from zero, and end within the box.

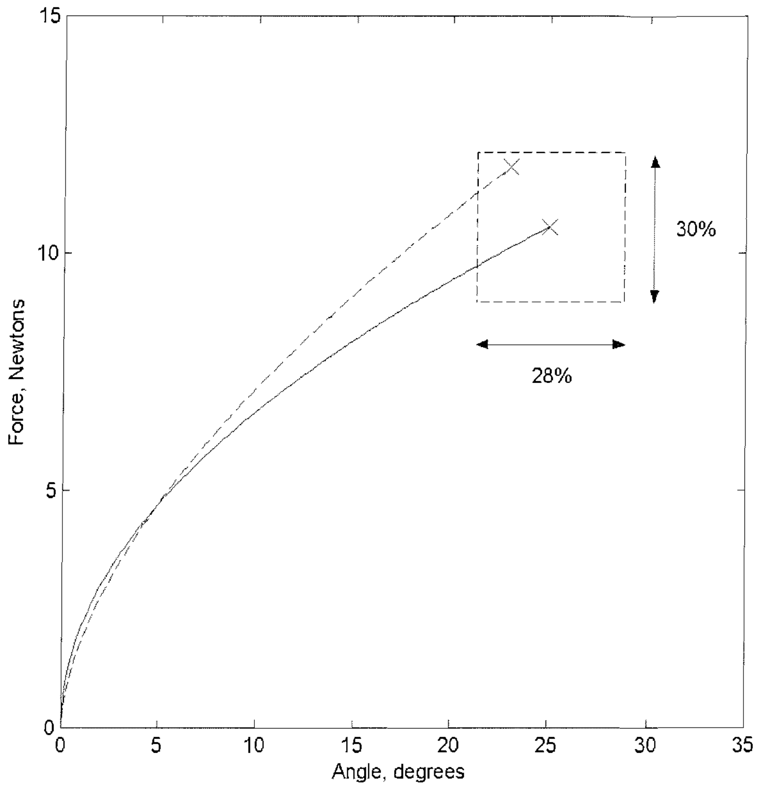


Figure 5.3: Difference threshold predicted 'just noticeable' region for subsequent turns of the steering wheel. [Solid line = reference, dashed line = next turn]

Chapter 6. Scaling steering wheel force and steering wheel angle

6.1 Overview

Psychophysical scaling was introduced in Chapter 2 as a method to relate sensation to physical stimuli.

The two major competing psychophysical laws, Fechner's logarithmic law and Stevens' power law (see Section 2.3.2.4), offer alternative methods to analyse scaling data. As a matter of convenience, we use Stevens' power law to analyse the data in this chapter, but Fechner's logarithmic might describe the data equally well. It is not the aim of this experiment to assess the merit of either psychophysical law.

In order to determine how the human perception of steady-state properties at the steering wheel build with the actual physical stimuli, an experiment was conducted using magnitude estimation and magnitude production techniques.

Scaling the stimuli in accordance with Stevens' power law, the results show that the perception of steering wheel force grows at a faster rate than the physical stimuli with a power law exponent of 1.39, whilst the perception of steering wheel angle grows at a slightly slower rate than the physical stimuli with a power law exponent of 0.93.

6.2 Introduction

The rate of growth of sensation of stimuli has often been determined using Stevens' power law:

$$\psi = k\phi^{n} \tag{6.1}$$

where ψ is the sensation magnitude, ϕ is the stimulus intensity, k is a scalar constant depending on the conditions, and n is the value of the exponent that describes the rate of growth of sensation of the stimulus and depends on the sensory modality (e.g. perception of force, or perception of loudness).

Previous studies (Stevens and Mack (1959), Jones (1986), Van Doren (1996), Toffin, McIntyre et al. (2003)) have reported rates of growth of sensation of force and weight with exponents between 0.8 and 2.0 over a variety of experimental conditions. A study of the haptic sensation of finger span by Stevens and Stone (1959) using widths of 2.3 to 63.7 mm reported an exponent of 1.33 using magnitude estimation.

The value of the exponent, n, may be determined by either magnitude estimation or magnitude production. Magnitude estimation requires participants to make numerical estimations of the perceived magnitudes of sensations, whereas magnitude production requires participants to adjust the stimulus to produce sensory magnitudes equivalent to given numbers. Both magnitude estimation and magnitude production have systematic biases which Stevens called a 'regression effect'. The biases are attributed to a tendency for participants to limit the range of stimuli they have control over, so with magnitude estimation they limit the range of numbers they report, and in magnitude production they limit the range of stimuli they produce. The bias results in magnitude production yielding steeper slopes (i.e. higher values for *n*) than magnitude estimation.

Stevens' recommends taking the geometric mean of the exponent obtained by magnitude estimation and magnitude production in order to provide a more accurate estimate of the exponent without regression bias.

6.3 Method

This experiment employs both magnitude estimation and magnitude production techniques to develop a scale of perception of steering wheel force and steering wheel angle.

Steering wheel force perception is determined using an isometric steering wheel, and steering wheel angle perception is determined using an isotonic steering wheel.

6.3.1 Apparatus

The static steering rig described in Section 3.2 was used in this experiment. The isometric set-up was used to investigate force sensitivity, and the isotonic set-up was used to investigate angle sensitivity.

The output from the torque cell or angle encoder (depending on the condition) was acquired in real time, and used to generate a graphical user interface to inform the participant that the reference stimuli had been achieved. The target sensitivity was adjusted on the graphical user interface to ± 2%.

A steering wheel diameter of 381 mm was used, which is the standard 2002 Jaguar S-Type steering wheel diameter.

The car seat used in the rig was electronically adjustable and allowed each participant to sit in a comfortable position whilst maintaining an angle at the elbow of 110° to ensure that participants did not sit too far or too close to the steering wheel.

6.3.2 Stimuli

The same reference condition was given for both magnitude estimation and magnitude production trials, with references of 10.5N for the isometric condition, and 9° for the isotonic condition.

The references were given a value of 100, and the test trials were given values of 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, and 200. In magnitude estimation trials, this test trial value would correspond to a percentage of the reference stimuli given in the test trial. In magnitude production trials, the test trial value is the number given to the participant.

6.3.3 Hypothesis

It was hypothesised that Stevens' power law would fit the both steering wheel force, and steering wheel angle data. If Stevens' power law was appropriate, the judgements against stimulus magnitude should describe a straight line on logarithmic scales.

6.3.4 Design

6.3.4.1. Participants

Twelve male participants, aged between 18 to 26 years, took part in the experiment using a within-subjects experimental design.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and number of years driving experience of participants. Anthropometric data was measured according to Pheasant (1986), including stature, weight, sitting height and shoulder-grip length.

6.3.4.2. Experimental procedure

Participants were given magnitude estimation and magnitude production examples using the length of a line as a practice of the techniques. Results from the practices are shown in Appendix C.

Each participant was given four practices using the experimental apparatus and technique before each condition. This allowed them to become familiar with the graphical user interface and the procedure.

After successful completion of the practice trials, participants were required to wear a pair of headphones, which generated pink noise to prevent noise disturbance from the laboratory. A cloth was suspended over the steering wheel so that participants received no direct visual feedback to aid the trials.

For magnitude estimation, a participant first applied a reference force (or angle) by acting on the steering wheel in a clockwise direction. The reference was 10.5 N on the isometric steering wheel and 9° on the isotonic steering wheel. Feedback was given on an 11-point scale, with the reference in the middle of the scale. Participants were told that the reference corresponded to 100. A participant then applied eleven different test forces (or angles) as indicated by the middle mark of the 11-point scale. The values corresponded to 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, and 200 relative to the reference of 100. For force, these stimuli ranged from 5.25 to 21 N, while for angle they ranged from 4.5 to 18°. After the presentation of a test stimulus, a participant was asked to report a number considered to represent the test in proportion to the reference. The presentation order of the test stimuli was randomised.

For magnitude production, a participant first applied a reference force (or angle) by acting on the steering wheel in a clockwise direction. Feedback was given on an 11-point scale, with the reference in the middle of the scale. The participant was told that this corresponded to 100. The reference was 10.5 N on the isometric steering wheel and 9° on the isotonic steering wheel. Participants were then given a number (50, 60, 70, 80, 90, 100, 120, 140, 160, 180, or 200) and asked to produce a force (or angle) corresponding to the number in proportion to the reference. The presentation order of the test stimuli was randomised.

Table 6.1: Experimental order for scaling conditions:

Subject	1st presentation	2nd presentation	3rd presentation	4th presentation
1, 5, 9	Steering wheel force		Steering wheel angle	
	Magnitude production	Magnitude estimation	Magnitude production	Magnitude estimation
2, 6, 10	Steering wheel force		Steering wheel angle	
	Magnitude estimation	Magnitude production	Magnitude estimation	Magnitude production
3, 7, 11	Steering wheel angle		Steering wheel force	
	Magnitude production	Magnitude estimation	Magnitude production	Magnitude estimation
4, 8, 12	Steering wheel angle		Steering wheel force	
	Magnitude estimation	Magnitude production	Magnitude estimation	Magnitude production

Participants attended two sessions with the order of presentation of the force, angle, magnitude estimation, and magnitude production conditions balanced across participants (see Table 6.1).

6.3.4.3. Instructions

The instructions for this experiment were as follows:

For magnitude estimation, you will be given feedback from the computer to achieve the test condition. You should assign this test condition a number in proportion to the reference (100), and verbally report it to the experimenter. You can use any numbers you wish to describe the magnitude of force or angle.

For magnitude production, you will be given a number, and you should create a force or angle that corresponds to that number, and in relation to the reference (100).

If at any time you feel uncomfortable, or feel unable to create the stimulus required, please release the wheel, or speak to the experimenter. You will be able to redo any experimental trial if you are not satisfied.

6.3.4.4. Analysis

The exponent indicating the rate of growth of sensation was determined by fitting Stevens' power law to the data. With the stimulus and sensation plotted on logarithmic axes, the exponent, n, is the slope:

$$\log\psi = n\log\phi + \log k \tag{6.2}$$

Exponents for the rate of growth of sensation were obtained from least squares regression between the median magnitude judgement of the 12 participants for each test magnitude and the actual test magnitude, with the apparent magnitude assumed to be the dependent variable (Alf and Grossberg (1979)).

6.4 Results

The calculated exponents, *n*, were 1.14 (force magnitude estimation), 1.70 (force magnitude production), 0.91 (angle magnitude estimation) and 0.96 (angle magnitude production).
The median data, and lines of best fit from all participants are shown in Figure 6.1, Figure 6.2, Figure 6.3, and Figure 6.4 for force estimation, force production, angle estimation and angle production, respectively and are compared in Figure 6.5.
The Spearman rank order correlation coefficient, *r,* between the physical magnitudes and the perceived magnitudes were 0.89 for force magnitude estimation, 0.65 for force magnitude production, 0.89 for angle magnitude estimation and 0.87 for angle magnitude production.
All correlations were significant (p<0.01, N=132), indicating high correlations between stimuli and the estimated or assigned magnitude.

6.5 Discussion

With magnitude estimation, the rank order of all median estimates of force and angle increased with increasing force and angle, except for the middle (100 and 120) force estimates. This deviation is assumed to have arisen by chance. To assess the impact this deviation had on the exponent obtained from the median data, an exponent was regressed to all data points from all participants. This yielded an exponent of 1.14, which is the same as the exponent determined from the median data. Similarly, with magnitude production, the median forces and angles increased with increasing required value, except for the two lowest forces. The lowest median force was produced when participants were asked to produce a force corresponding to an apparent magnitude of ‘70’ – the median force was slightly higher (although not significantly different) for apparent magnitudes of ‘60’ and ‘50’. This deviation from the expected order, which is assumed to have arisen by chance, means the exponent for force production (1.70) was higher than it would have been without the two lowest forces. Regression to all of the data from all participants for force production (instead of the median judgement) yielded an exponent of 1.38.
The regression effect was present in both the force and the angle data, although the greater difference between magnitude estimation and magnitude production in force data suggests the effect is stronger in the force data. An estimate of the unbiased rate of growth of sensation of apparent force and angle are taken as the geometric mean of estimation and production values. In this study, the means of the estimation and production slopes were 1.39 for steering wheel force and 0.93 for steering wheel angle.

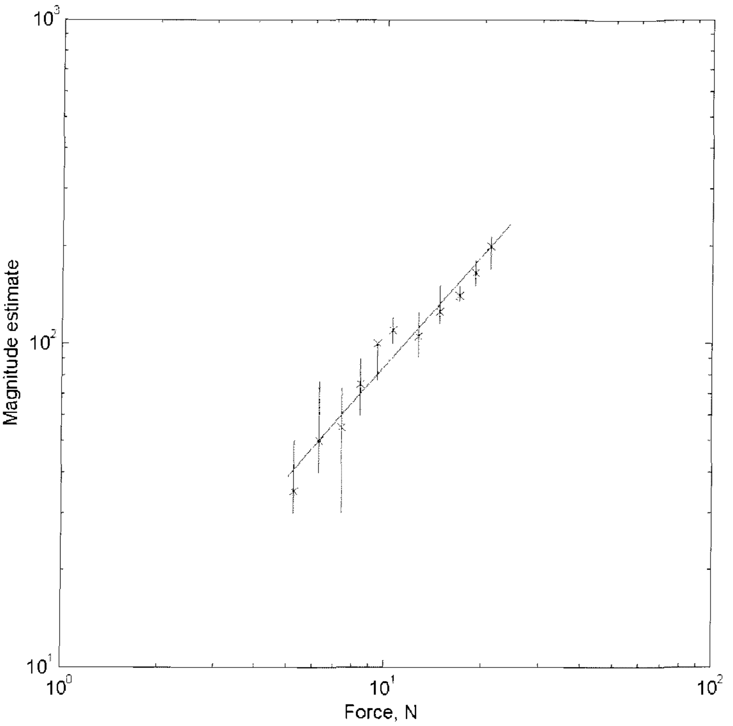


Figure 6.1: Rate of growth of apparent force using magnitude estimation. Median data from 12 participants, and inter-quartile range.

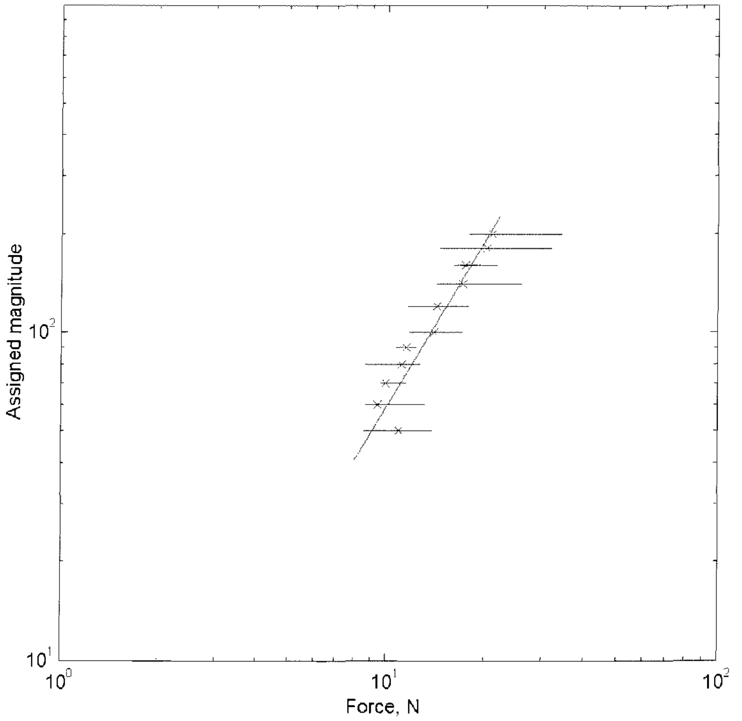


Figure 6.2: Rate of growth of apparent force using magnitude production. Median data from 12 participants, and inter-quartile range.

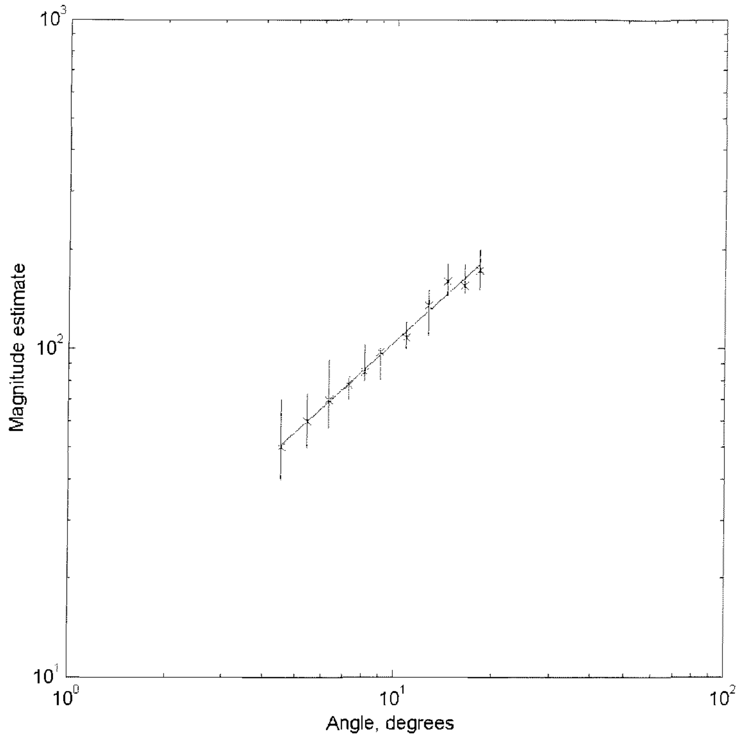


Figure 6.3: Rate of growth of apparent angle using magnitude estimation. Median data from 12 participants, and inter-quartile range.

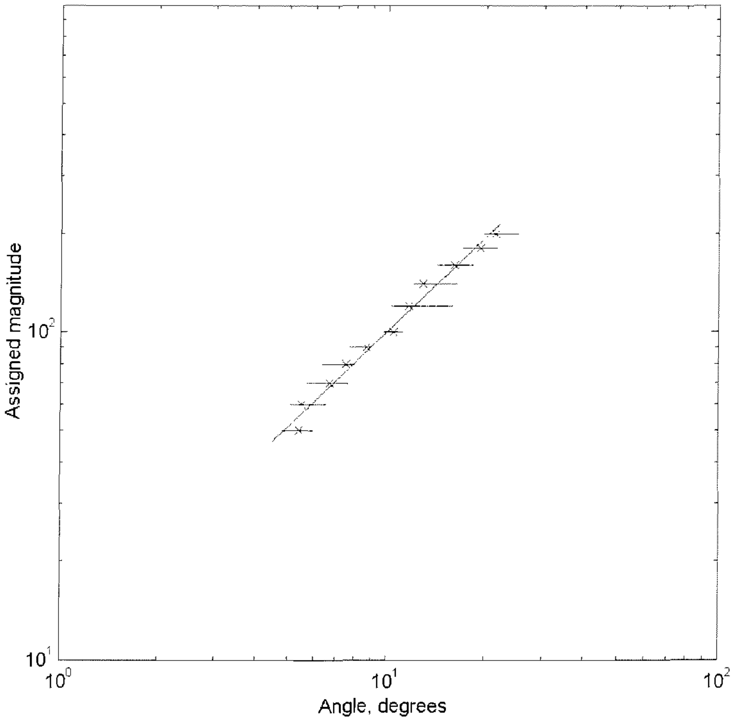


Figure 6.4: Rate of growth of apparent angle Using magnitude production. Median data from 12 participants, and inter-quartile range.

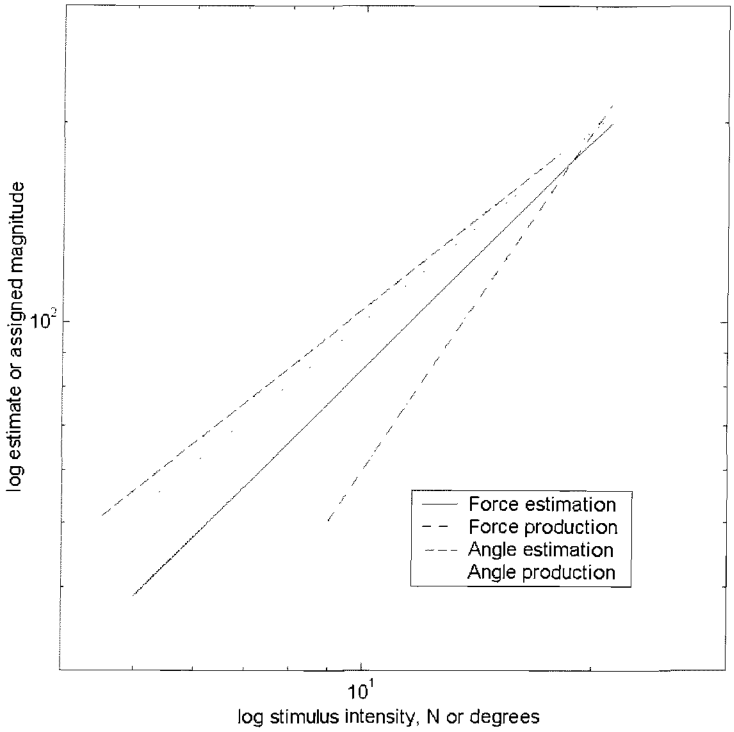


Figure 6.5: Rate of growth of apparent force and apparent angle.

6.6 Conclusions

The reported rate of growth of sensation of steering wheel force lies within the range previously reported for force. A rate of growth of 1.39 means the sensation of force grows more rapidly than the force causing the sensation. For example, a doubling of force will give rise to 162% increase in the perception of force.

Steering wheel angle had a mean rate of growth of 0.93, so the sensation of angle grows at a slower rate than the angle. For example, a doubling of angle would give rise to only a 91% increase in the perception of angle.

If we were to apply these results to steering wheel stimuli we would have to assume that the perception of force is independent of angle, velocity of application, and other parameters that are present in steering wheel stimuli in a real vehicle. We would also have to assume that the perception of angle is independent of force, velocity of application and any other parameters. Chapter 8 uses the results from this chapter to further knowledge about the way steering stiffness is perceived.

PART 3: PERCEPTION OF STEERING WHEEL STIFFNESS

Part 2 details some fundamental perceptual properties of steering wheel force and steering wheel angle. In order to produce a just noticeable difference in either stimulus so that it will be recognised most of the time, a 15% difference is required. Scaling reveals that the sensation of steering wheel force grows at a faster rate than the actual force, and the sensation of steering wheel angle grows at a slower rate than the actual angle.

A major limitation of the experiments conducted so far is that neither force nor angle occurs in isolation at the steering wheel in a car. Instead, the two properties or force and angle combine together to form a stiffness profile at the steering wheel.

As discussed in Chapter 2, there are not thought to be any specific receptors in the human body for stiffness, so instead, our perception of stiffness is most likely some combination of the force and angle data in the brain. Exactly how this is done is not known, and is beyond the scope of this thesis.

Part 3 contains four chapters. The first three (Chapters 7 to 9) deal with perception of steering wheel stiffness, and the Chapter 10 analyses the steering stiffness of a number of real vehicles.

Chapter 7. Stiffness profile sensitivity

7.1 Overview

Difference thresholds for steering wheel force and steering wheel angle were investigated in Chapter 5. The results show that approximately 15% change was required in the magnitude of either parameter in order for the participant to perceive a difference approximately 80% of the time.

The results obtained in Chapter 5 consider force and angle experienced in isolation, so the results are applicable to the differences required in terminal force or angle when the wheel is turned against some resistance on sequential turns. If sequential turns of the wheel have the same terminal force and angle, it might still be possible to distinguish between them based on the way the forces and angles build up.

In order to determine how sensitive humans are to changes in the stiffness profile (the relationship between force and angle of the steering wheel), this chapter details an experiment conducted to evaluate a difference threshold for the change in stiffness profile. As a single valued parameter is needed to describe the stiffness profile for this, the work done by turning the wheel to a particular angle is used (Tan, Durlach et al. (1995) report Weber fractions in terms of work done when terminal force cues are not available to participants). The results show that approximately 20% difference in the work done by a stiffness profile is required in order to be just noticeable.

7.2 Introduction

In order to determine the smallest perceptible difference in stiffness profile, where the start and end points are exactly the same in terms of force and angle, it is necessary to choose a function to describe the growth of force and angle at the steering wheel that should be a monotonically increasing function.

For convenience, the force-angle relationship is described as a power law:

$$F = k\theta^{n} \tag{7.1}$$

By changing the exponent, *n*, different stiffness profiles may be obtained, and the stiffness constant, *k*, can be used to equalise the profiles so that according to this form they all start at $\theta = 0$ with $F = 0$, and end with the same angle and force.

The perception of differences in stiffness has been investigated in the past, although a number of these studies use varying terminal forces, which would allow terminal force discrimination. Other studies by Tan, Durlach et al. (1995) have reported the influence of mechanical work cues (e.g. force integrated over distance) in the discrimination of stiffness when terminal force cues are not present. They report a difference threshold of 22% in terms of work done when terminal force cues are not available to participants.

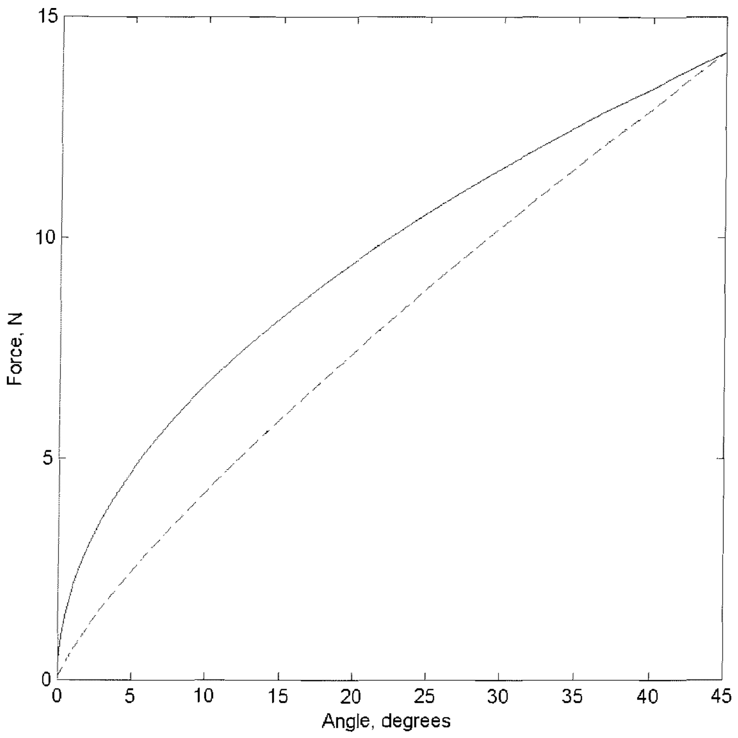


Figure 7.1: Reference conditions. (Solid line: $n = 0.5$, Broken line: $n = 0.8$)

7.3 Method

In order to determine the smallest perceptible difference between stiffness profiles, a difference threshold test was performed where 12 participants were asked to judge if two stimuli were the 'same' or 'different'.

7.3.1 Apparatus

The motor rig described in Section 3.3 was used for this study. The motor reproduced required stiffness profiles to within 5% accuracy. A mechanical stopper was implemented at zero degrees to provide a reference and somewhere to rest the steering wheel between trials. A cloth was hung between the steering wheel and the participant so that they could not see the wheel.

7.3.2 Stimuli

Two references were used in this experiment to determine two measurements of the difference threshold. The references were a power law exponent of 0.5 and a power law of 0.8 and the value of k adjusted so that whatever the exponent, n, the stiffness profile would create 14.2 newtons of force at 45°. The nominal value of k for an exponent of 1 was $k = 0.32$.

The test stimuli started at the same level as the reference, and upon an incorrect response, the exponent, n, would increase by 0.02. k was equalised for every test exponent.

7.3.3 Hypothesis

It was hypothesised that Weber's law would apply to this study, although initial and terminal angle and force magnitudes were the same, so it was hypothesised that the force integrated over distance (or angle for simplicity), or work done would be relevant in this case.

7.3.4 Design

7.3.4.1. Participants

Twelve male participants, aged between 26 to 41 years, took part in the experiment using a within-subjects experimental design.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and driving experience of participants.

7.3.4.2. Experimental procedure

Difference thresholds were determined with a two-alternate forced-choice procedure using an up-and-down transformed response (UDTR) method (see Appendix B). Participants were required to make two sequential turns of the steering wheel from 0 to 45° at a steady rate, and judge if the two stimuli were the 'same' or 'different'.

The UDTR (up-down-transformed-response) method was used with a three-down one-up rule (i.e. three correct responses in a row resulted in the test stimulus getting closer to the reference stimulus whereas one incorrect response would result in the reference and test stimulus getting further apart). If the participant responded with 'same', then the test stimuli power law exponent was increased making the difference between the reference exponent and test exponent larger. If the participant responded with 'different', then the test stimuli power law exponent was kept the same until the participant had responded with 'different' for the same test stimuli three times in a row, at which point the test stimuli exponent was decreased making the difference between the reference and test stimuli smaller.

The three-down one-up rule results in the difference threshold being observed at a 79.4% correct response level (0% being none correct, 50% being chance response, and 100% being certainty).

The order of presentation for the reference conditions was balanced across participants with six participants starting with $n = 0.5$, and six starting with $n = 0.8$.

7.3.4.3. Instructions

The instructions for this experiment were as follows:

This experiment uses the method of paired comparison. You will be asked to:

1. *Turn the wheel from 0 degrees (against the stopper) through to 45 degrees*
2. *Turn the wheel at the rate specified on the monitor*
3. *Make 1 turn for each stimuli*

4. *Concentrate on how the angles and forces vary as you turn at a constant speed to 45 degrees.*

The experimenter will then change the stimuli and you will be required to repeat the stages above. After presentation of both stimuli, you will be asked whether the two stimuli felt the 'same' or 'different'.

7.3.4.4. Analysis

To determine a difference threshold for each reference, participants made a sequence of judgements, with the total number of judgements required being dictated by their responses. The sequence was terminated after five 'up' and five 'down' reversals of direction. The difference threshold was measured as the mean value of the last two 'up' and the last two 'down' reversals.

The number of trials required for each threshold measurement varied according to the participant's responses with an average of 67 trials per run. One threshold measurement run typically lasted 20 to 30 minutes.

For this experiment, the 7th to 10th reversal (peak 4 and 5, trough 4 and 5) were used to calculate the difference threshold:

$$DT = \left(\frac{\left[\sum_{j=4}^{j=5} p_j + \sum_{j=4}^{j=5} t_j \right]}{N} - R \right) \times 100, \tag{7.2}$$

where DT is the difference threshold (expressed as a percentage), p_j is the magnitude of the exponent (in force or angle) of the peak j, t_j is the magnitude of the exponent of the trough j, N is the number of reversals (i.e. 4), and R is the reference exponent.

Analysis is conducted on both the value of the exponent, n, which relates to the curvature of the stiffness profile, and also due to the work done by the participant in rotating the wheel from 0 to 45°. For convenience, the work done will be expressed by integrating the function used to generate the stiffness profile, and so the units will be expressed in Newtons per degree (N·°).

7.4 Results

Two types of analysis are presented: one according to the value of the exponent, *n*, which relates to the curvature of the stiffness profile, and the other according to the work done in turning the wheel from 0 to 45°.

The difference thresholds obtained for exponent reference of 0.5 and 0.8 are shown in Table 7.1, Figure 7.2, and Figure 7.3.

The median value of the difference in exponent value is 0.37 (or 73%) is for the 0.5 reference, and a difference of 0.47 (or 58%) of the 0.8 reference.

Table 7.1: Difference thresholds according to exponent, *n*

	n = 0.5		*n* = 0.8	
Participant number	Absolute Difference	Percentage difference (%)	Absolute difference	Percentage difference (%)
1	0.35	70	0.47	58.13
2	0.31	62	0.24	29.38
3	0.11	21	0.19	23.75
4	0.43	86	0.44	55
5	0.38	76	0.73	90.63
6	0.5	100	0.74	91.88
7	0.31	62	0.69	85.63
8	0.4	80	0.76	95
9	0.4	79	0.57	71.25
10	0.33	66	0.27	33.75
11	0.23	45	0.37	46.25
12	0.61	122	0.47	58.75
Median	**0.37**	**73**	**0.47**	**58.44**

Statistical analysis shows that the absolute difference threshold increased with increasing exponent value, *n*, (Wilcoxon, $p<0.05$), but there was no significant difference between the percentage difference values with exponent value (Wilcoxon, $p>0.2$). This is consistent with Weber's law, although whether the exponent value translates into anything that is discernable to the human is speculative. It might be more likely that the property of work done under each curve is a better description of the processing that the participant undergoes in order to discriminate between the stimuli.

Analysis of the work done for each reference is shown in Table 7.2, Figure 7.4, and Figure 7.5. When transformed into work done, the 0.5 reference becomes 213 N·°, and the 0.8 reference becomes 177 N·°. The median value of the difference in work done is 42 N° (or 19.57%) of the 213 N·° reference (0.5), and a difference of 37 N·° (or 21%) of the 177 N·° reference (0.8).

Statistical analysis shows that there was no significant difference between reference conditions for either absolute or percentage differences (Wilcoxon, $p>0.3$).

7.5 Discussion

Analysis of the exponent value, *n*, follows Weber's law, but analysis of the work done does not provide a significant difference between absolute thresholds. However, when the two reference stimuli are analysed according to the work done to turn the wheel to 45 degrees, the work done values are fairly close together indicating that perhaps the stimuli were too close for the absolute differences to be that different.

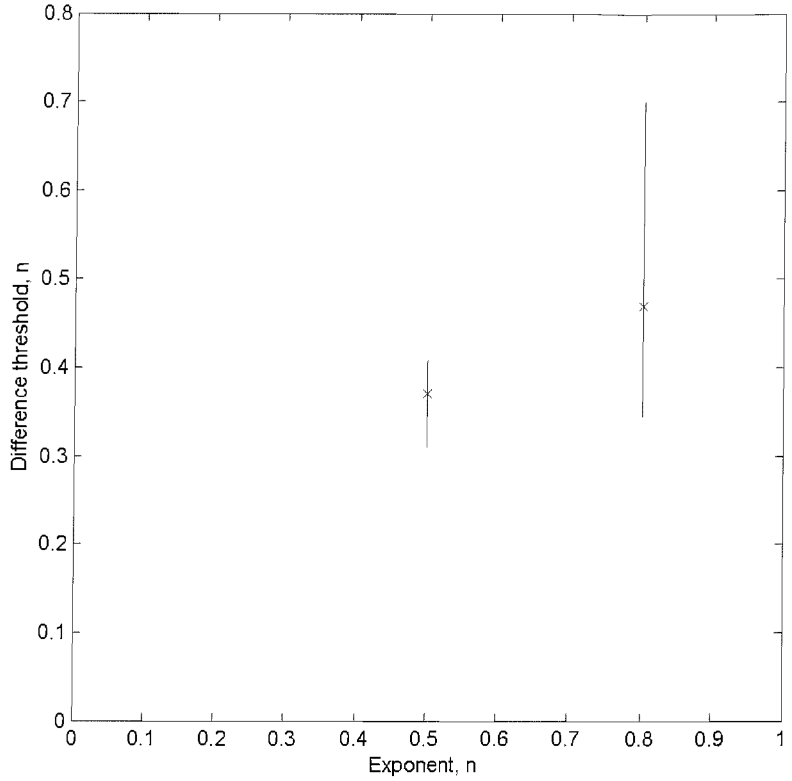


Figure 7.2: Absolute difference threshold in terms of exponent, *n*

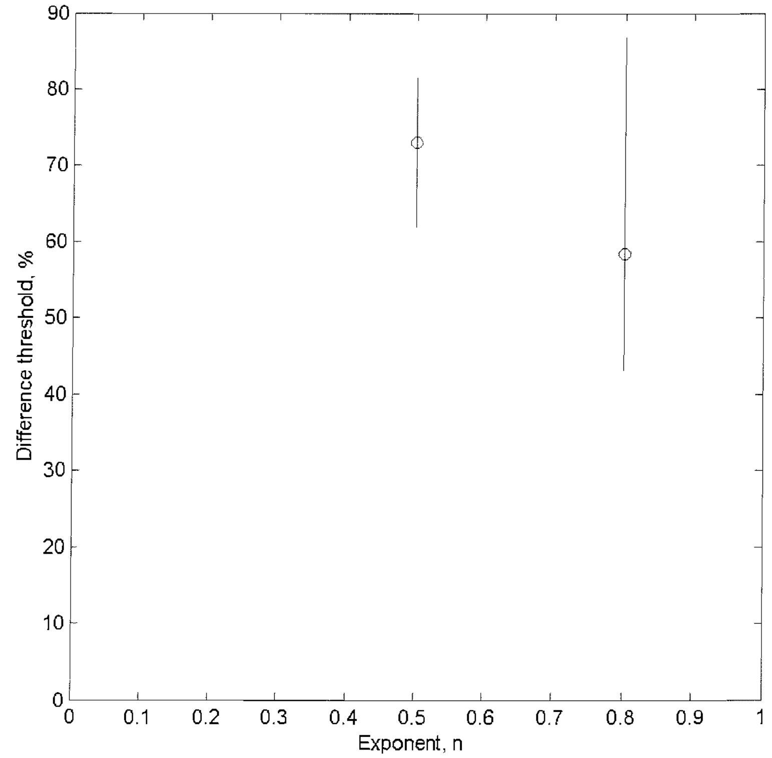


Figure 7.3: Percentage difference thresholds in terms of exponent, *n*

Table 7.2: Difference thresholds according to work done

Participant number	*n* = 0.5 [or 213 (N·°)]		*n* = 0.8 [or 177 (N·°)]	
	Absolute difference	Percentage difference (%)	Absolute difference	Percentage difference (%)
1	40.23	18.92	36.69	20.53
2	36.42	17.13	20.85	11.55
3	14.53	6.54	16.92	9.55
4	47.37	22.28	34.81	19.64
5	42.98	20.21	51.13	28.71
6	53.16	25.00	51.62	28.99
7	36.42	17.13	49.10	27.57
8	44.76	21.05	52.61	29.69
9	44.76	20.84	42.62	24.05
10	38.34	18.03	23.11	13.04
11	28.27	13.04	30.21	17.05
12	61.47	28.91	36.69	20.70
Median	**41.61**	**19.57**	**36.69**	**20.62**

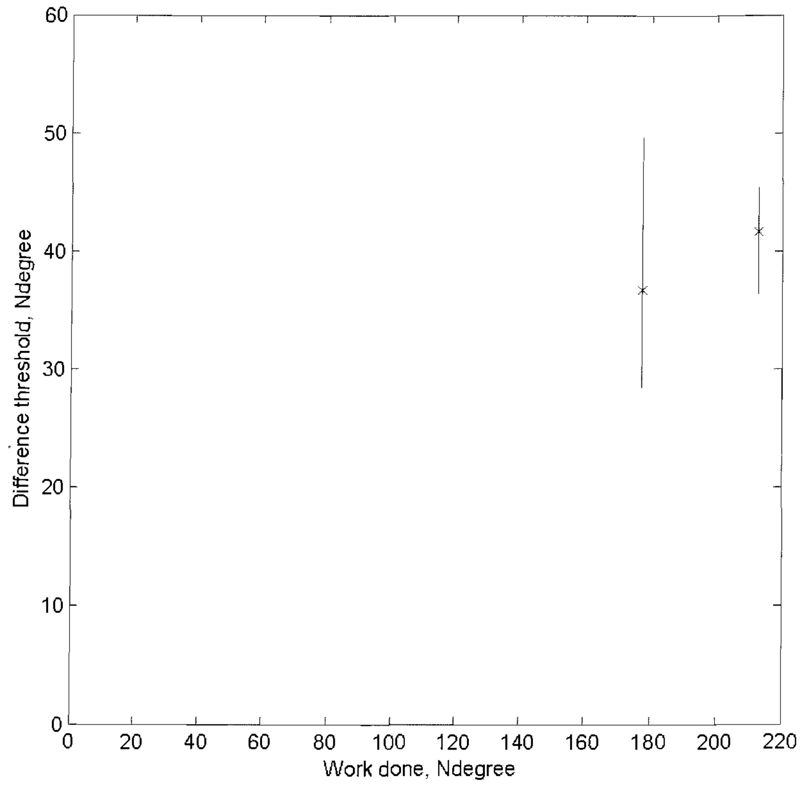


Figure 7.4: Absolute difference threshold in terms of work done (N·°)

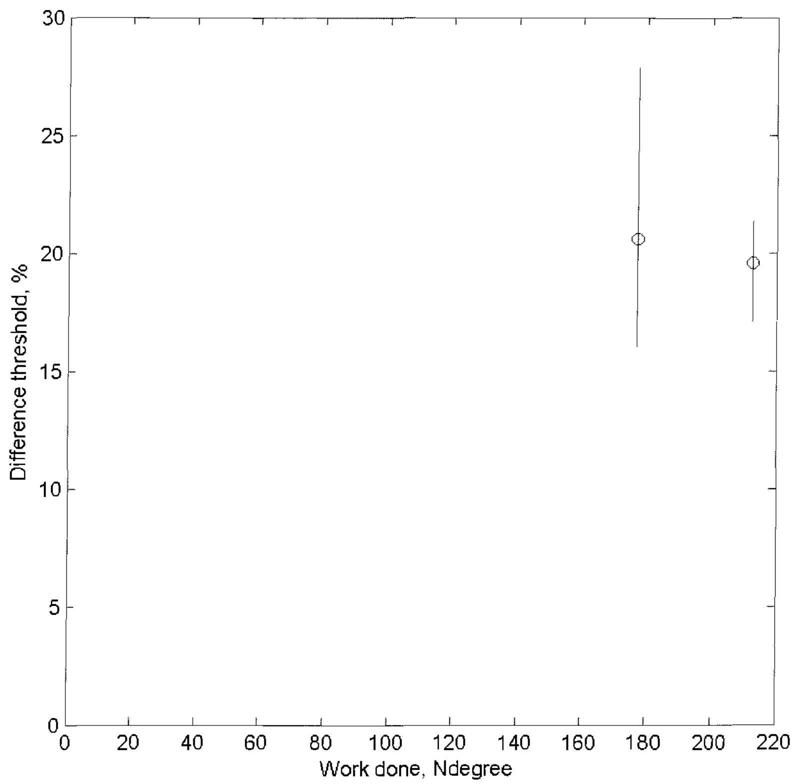


Figure 7.5: Percentage difference threshold in terms for work done (N·°)

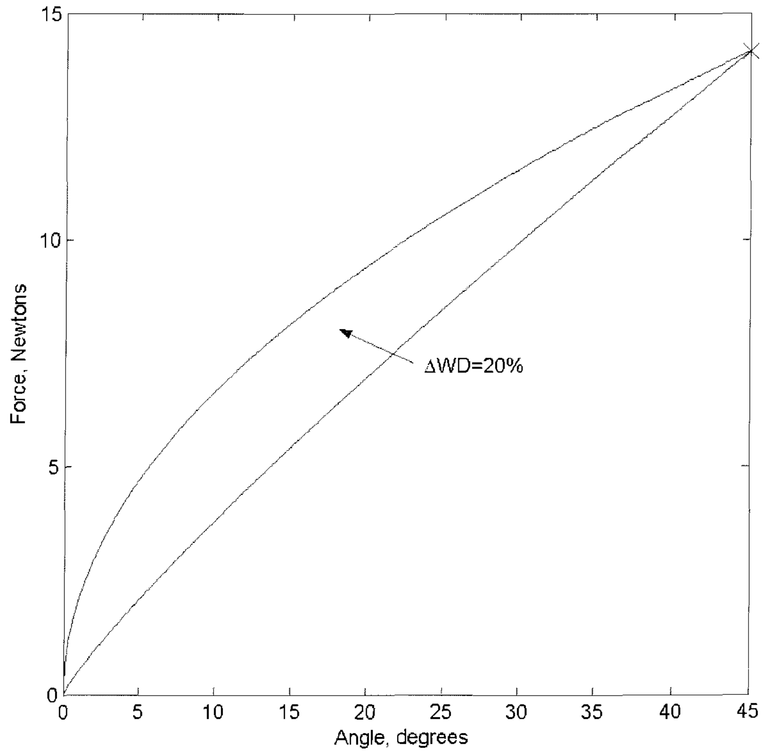


Figure 7.6: The change in work done required to detect a difference between two stimuli that start and end with the same force and angle.

The median difference threshold for the two reference conditions for work done are remarkably similar, both being approximately 20%, which is close to the difference threshold for work done determined by Tan, Durlach et al. (1995) who reported a value of 22%. Compared to the difference thresholds obtained with the exponent value, *n*, which was 73% for the exponent of 0.5 reference, and approximately 60% for the exponent of 0.8 reference, the difference threshold for work done appears to be more consistent.

7.6 Conclusions

The results of this test indicate that stimuli must be spaced at least 0.4 apart in exponent value (*n*), or a 60 to 70% change in the exponent value, when the start and end points are the same in order for the two stiffness profiles to be discriminated 79.4% of the time.
Analysis of the data in terms of the work done by the participant to turn the wheel to 45 degrees seems to provide more consistent results, with the difference threshold being a 20% change in work done by the participant in moving the wheel from 0 to 45° in order for the two stiffness profiles to be discriminated (see Figure 7.6).

Chapter 8. Linear feel

8.1 Overview

Chapter 5 and Chapter 6 provide a 'textbook' analysis of the perception of steady-state steering feel parameters of force and angle.

Whilst the sensitivity results provide an immediately useful result in specifying the differences required in a stimulus in order to be noticed, it is perhaps more difficult to see how the scales of steering wheel force and steering wheel angle might be used in practical steering system tuning and analysis.

Steering system tuners often talk about steering 'linearity' as a desirable property in steering feel, as it leads to predictability for the driver. The psychophysical functions for steering wheel force and steering wheel angle obtained in Chapter 6 according to an arbitrarily chosen power law function, and can be used to predict a linear steering profile.

This chapter describes a paired comparisons experiment using a number of different steering stiffness profiles in order to determine which felt more linear. The results show that from the exponents presented, an exponent of 0.8 was perceived as the most linear.

8.2 Introduction

The perception of stiffness (or its inverse, compliance) has been investigated in various ways over the years, especially the perception of mechanically linear stiffness. Many studies have investigated the discrimination of differences in stiffness (Roland and Ladegaard-Pedersen (1977), Jones and Hunter (1990), Jones, Hunter et al. (1992), Tan et al. (1992), Tan et al. (1993), Srinivasan and LaMotte (1995), Tan, Durlach et al. (1995)), while the scaling of stiffness perception has received less attention (Harper and Stevens (1964), Nicholson, Adams et al. (2000)).

The experiments conducted in Chapter 6 using magnitude estimation and magnitude production showed that the rate of growth in the perception of force and angle for a steering turning task is not perceived in proportion to the physical stimulus. This suggests that a steering system that feels linear to a human, would not be physically linear in the build up of force and angle.

As steering tuners often say that a linear feel at the steering wheel is desirable, we decided to conduct an experiment to test what stimuli feels linear from a choice of stiffness power laws. Using the results from the experiments conducted in Chapter 6, we devised an experiment to determine whether the steering characteristic predicted as being 'linear' from the previous study would be perceived as being more linear than alternative characteristics.

8.2.1 Stevens' power law and Fechner's logarithmic law and 'linear feel'

In Chapter 6 the data were analysed according to Stevens' power law, although Fechner's logarithmic law might fit the data equally well.

When describing ‘linear feel’, the characteristic is described as an analogue of Hooke’s law, but for perceived force and perceived angle:

$$F_p r = k\theta_p \tag{8.1}$$

If we assume that Stevens’ power law is an accurate fit to perceptual data, perceived force and perceived angle may be described as:

$$F_p = kF^{n_F} \tag{8.2}$$

$$\theta_p = k\theta^{n_\theta} \tag{8.3}$$

Then by substitution,

$$F = k\theta^{\frac{n_\theta}{n_F}} \tag{8.4}$$

or:

$$\log F = \frac{n_\theta}{n_F}\log\theta + \log k \tag{8.5}$$

So a linear feel takes a power law form, and will be characterised as a straight line in logarithmic space.

If we now instead assume that Fechner’s logarithmic law is an accurate fit to perceptual data, perceived force and perceived angle may be described as:

$$F_p = k\log F \tag{8.6}$$

$$\theta_p = k\log\theta \tag{8.7}$$

Then by substitution,

$$\log F = k\log\theta \tag{8.8}$$

or:

$$F = \theta^k \tag{8.9}$$

Again, this relationship has the characteristic of a straight line in logarithmic space. The only difference between the two formulations is the log*k* term, or the constant in the power law formulation of the relationship.

So both Stevens’ power law, and Fechner’s logarithmic law predict a power law relationship between two perceptual terms.

The exponents for force and angle were determined and detailed in Chapter 6, and were reported as 1.14 for force magnitude estimation, 1.70 for force magnitude production, 0.91 for angle magnitude estimation, and 0.96 for angle magnitude production. The geometric means of the exponents for magnitude estimation and magnitude production gave power law exponents of 1.39 for force and 0.93 for angle.

If the exponents determined in the preliminary experiment are appropriate, then the function relating force to angle for a linear feel would have the form of equation 8.4 with an exponent, *n*, of 0.79 for magnitude estimation, 0.56 for magnitude production, and 0.67 from the geometric mean of the magnitude estimation and magnitude production exponents:

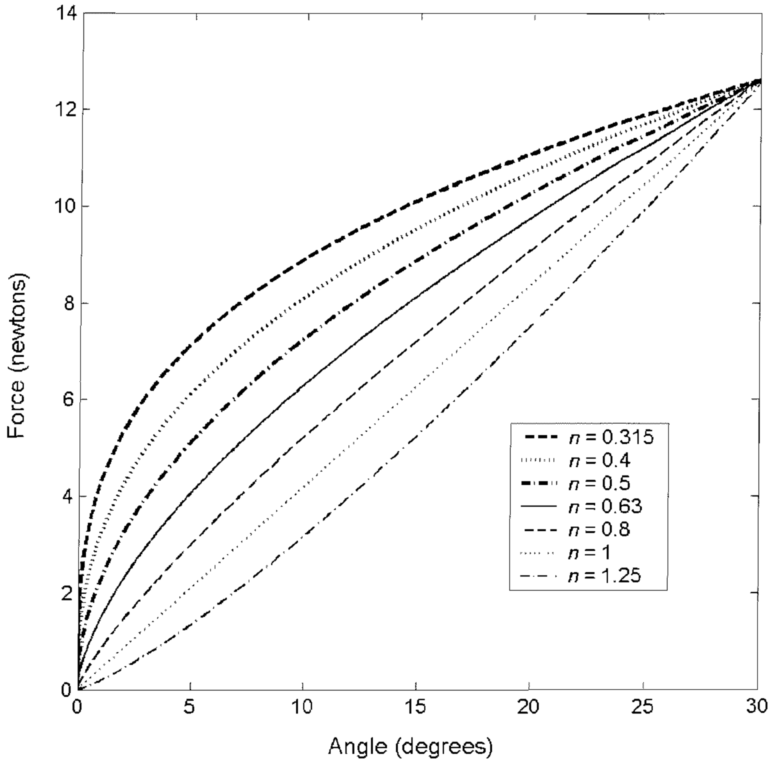


Figure 8.1: Seven stiffness profiles used in the study

$$F = k\theta^{0.67} \tag{8.10}$$

8.3 Method

By combining the exponents from two separate power laws into one equation, it is possible to test whether the exponents for force and angle in Stevens' power law provide a useful prediction of the relation between the perception of force and the perception of angle. The range over which we would expect a 'linear' exponent is given by the magnitude estimation and magnitude production exponents, 0.56 to 0.79, while equation 8.10 indicates the conditions that would feel linear from the averaging of magnitude estimation and magnitude production exponents. Steering systems with an exponent, *n*, much greater than or much less than about 0.67 would be expected to feel less linear than steering systems with an exponent of about 0.67.

It was hypothesised that a power law profile between force and angle with an exponent of 0.67 would be judged as linear more often than any other exponent. However, as an exponent of precisely 0.67 is not presented, it was expected that the profiles with exponents of 0.63 and 0.8 would be judged as 'more linear' that the other stiffness profiles.

8.3.1 Apparatus

The same apparatus as used in Chapter 7 was used in this experiment, and is described in Section 3.3. A mechanical stopper was put in place at zero degrees to provide a reference and somewhere to rest the steering wheel between trials. A cloth was hung between the steering wheel and the participant so that they could not see the wheel.

Participants listened to pink noise through headphones to mask the noise in the laboratory.

The motor reproduced required stiffness profiles to within 5% accuracy.

8.3.2 Stimuli

Seven stimuli, corresponding to power law exponents of 0.315, 0.4, 0.5, 0.63, 0.8, 1.0, and 1.25 were chosen to provide a range of stiffness profiles as shown in Figure 8.1. The value of k was chosen to provide a force of 12.5 Newtons at 30 degrees of steering wheel angle regardless of the power law exponent, with the nominal value of k being 0.42 Newtons per degree with an exponent of 1.0.

8.3.3 Hypothesis

It was hypothesised that a power law profile between force and angle with an exponent of 0.67 would be judged as linear more often than any other exponent. However, as an exponent of 0.67 is not presented, it was expected that the profiles with exponents of 0.63 and 0.8 would be judged as 'more linear' that the other stiffness profiles.

8.3.4 Design

8.3.4.1. Participants

Twenty one male participants, aged between 24 and 58 years, took part in the experiment. All participants were employees or contractors at Jaguar Cars Ltd in Coventry.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and driving experience of participants.

8.3.4.2. Experimental procedure

Participants compared all of the 21 possible pairs of seven different steering systems having exponents 0.315, 0.4, 0.5, 0.63, 0.8, 1, and 1.25. They made each of these judgements once. For each judgement, participants slowly rotated the steering wheel from 0 to 30 degrees with two stimuli (i.e. two different exponents) and then indicated which stimulus felt 'more linear'. The order of presentation of each stimulus within a pair was balanced between pairs of participants (except for the 21st participant), while the presentation order of the twenty-one pairs was randomised for each participant.

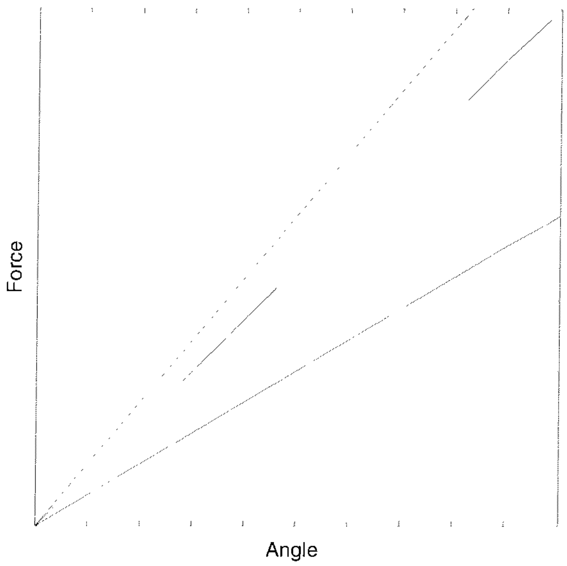


Figure 8.2: Instructions given to participants to define 'linear'

8.3.4.3. Instructions

The instructions for this experiment were as follows:

This experiment is concerned with how you perceive the build of forces and angles at the steering wheel. As such, you should try and identify which stimuli are more 'linear'. This could mean a 'linear build-up of forces and angles', or a 'linear stiffness'. It might be helpful to imagine how the forces and angles build up on a graph. The Figure 8.2 identifies a number of stimuli that are 'linear'. This should be what you judge 'linear' against.

8.3.4.4. Analysis

Analysis was conducted according to Thurstone's law of comparative judgement case V (Edwards (1957), Togerson (1958), Keats (1971)), which assumes that the standard deviations and the distribution of discriminable differences are constant for all pairs of stimuli. The distance between stimuli is represented as:

$$s_i - s_j = \sqrt{2}x_{ij} \tag{8.11}$$

where s_i and s_j are the scale values of stimuli *i* and *j*, and x_{ij} is the normal deviate that corresponds to the theoretical proportion of times stimulus *i* is judged greater than stimulus *j*.

8.4 Results

The results of the paired comparison experiment are presented in Table 8.1, which shows the frequency that the exponent in column *i* is judged 'more linear' than the exponent in row *j*. By summing all the frequencies for all columns an overall ordering for the exponents is obtained.

Table 8.1: The frequency with which each column exponent (*n*) is judged 'more linear' than the row exponent (*n*) (*N* = 21)

	0.315	0.4	0.5	0.63	0.8	1.0	1.25
0.315	-	14	16	13	13	11	11
0.4	7	-	10	14	11	13	8
0.5	5	11	-	15	11	9	9
0.63	8	7	6	-	15	10	11
0.8	8	10	10	6	-	10	3
1.0	10	8	12	11	11	-	9
1.25	10	13	12	10	18	12	-
Total	**48**	**63**	**66**	**69**	**79**	**65**	**51**
Rank	**7**	**5**	**3**	**2**	**1**	**4**	**6**

Scale values (case V) are obtained by the Thurstone method and are shown in Table 8.2. The mean scale values have been transformed so that the exponent with the lowest scale value is given a score 0.

The consistency of the scale values were checked by determining how well the observed proportions agree with the proportions expected from the derived scale values. The absolute average discrepancy was 0.02 for the seven stimuli and compares well with values usually reported when stimuli are scaled by the method of paired comparisons Hevner (1930).

The assumptions underlying the case V model can be tested for significance using a chi-squared distribution test (Edwards (1957)). This test, developed by Mosteller (1951), tests whether the observed and theoretical proportions are in agreement after they have both been transformed. If the property of additivity holds, then there should be agreement between the transformed values, and the value of χ^2 will be small. Formally stated, the null hypothesis of this test is that the assumptions involved in the model are tenable. The alternative to the null hypothesis could include rejection of any of the assumptions made under the case V model.

In this case, $\chi^2(15) = 19.02$. The probability of obtaining a value of χ^2 equal to or greater than 19.02 is between 0.10 and 0.20, when the null hypothesis is true. If we treat as significant those values of χ^2 that have a probability of 0.05 or less, the observed value would have to be 25.00 or larger. This indicates that the assumptions involved in finding the scale values of the seven exponents are tenable.

Inter-subject agreement was assessed using Kendall's coefficient of agreement statistic, *u* (Siegel and Castellan (1988)), which provides a measure of the extent to which a group agree in their comparative judgements. The value of *u* is 1.0 if all judges are in perfect agreement, and becomes smaller when departure from complete agreement increases. The minimum value of *u* for an odd number of participants is –1/(number of participants), which in this study is –0.048. The *u* statistic was calculated and tested for significance using a χ^2 distribution, resulting in $u = 0.034$, $\chi^2(22) = 35.29$. If the comparative judgements of all the participants

Table 8.2: Scale values of exponents (Thurstone case V)

Exponent (*n*)	0.315	0.4	0.5	0.63	0.8	1	1.25
Scale value	0.00	0.27	0.32	0.37	0.57	0.30	0.03

were made at random, the probability of obtaining a value of u as great as 0.034 is $p = 0.05$. It can be concluded that the 21 participants showed agreement in their comparative judgements.

8.5 Discussion

The results show that the scale values steadily increased from a power law exponent of 0.315 to a maximum value, possibly lying between 0.63 and 0.8, and then decrease. This is consistent with the hypothesis that profiles with exponents of 0.63 and 0.8 would be judged as 'more linear' more often.

The scale values for the exponents of 0.63 and 0.8 were 0.37 and 0.57, respectively, indicating that the stiffness profile with an exponent of 0.8 was felt as more 'linear'.

The stiffness profiles with exponents of 0.5, 0.63 and 0.8 were all judged as 'more linear' than the profile with an exponent of 1.0 (i.e. a profile that was physically linear), confirming that physical and perceptual scales differ for the stiffness of steering wheels.

The value of 0.8 is very close to the value predicted by magnitude estimation only, which may suggest that magnitude estimation is a more appropriate technique than magnitude production.

With two hands on the wheel, the hands will contribute varying proportions of force to the wheel and the perception of force depend on whether a hand is pushing up or pulling down, as well as the extent of the rotation that has been reached. Perception of force in the present experiment and when steering vehicles may therefore differ from that in the idealised conditions in which the separate exponents for force and angle were previously determined.

8.6 Conclusions

This experiment was designed to test whether separately determined power law exponents for the perception of steering wheel angle and steering wheel force could be combined to predict a steering wheel stiffness profile perceived as 'linear'. The previous studies suggested that 'linear' stiffness would be perceived with a stiffness profile having an exponent 0.67.

Using seven different power law exponents, from 0.315 to 1.25, and the method of paired comparisons in which 21 participants judged which stimulus felt 'more linear', the highest scale value was achieved with an exponent of 0.8. The results suggest the most 'linear' stiffness may lie between 0.63 and 0.8, consistent with theoretical prediction from the scaling experiment detailed in Chapter 6.

The results suggest that power law exponents determined using the methods of magnitude estimation and magnitude production may be combined to predict how two stimuli feel when presented together.

Chapter 9. Preferred feel

9.1 Overview

Chapter 8 shows that when asked to judge which stiffness profile felt 'linear' participants chose a power law with exponent of 0.8 more often than a selection of other power law exponents.

Despite vehicle dynamics engineers placing value of a 'linear' feel, it might be possible that they are talking about a different linearity than simply in the haptic feedback at the steering wheel, so a preferred haptic stiffness profile may be different to a linear feel.

In order to test what haptic stiffness profile is preferred we conducted two experiments.

The first was a repeat of the paired comparisons test outlined in Chapter 8, except that the participants were asked to judge which of the power law stimuli was preferred in the context of 50 mph country road driving.

The results show that a power law exponent of 0.5 is the most preferred by participants.

In the second experiment, participants were given full control of the stiffness profile and were allowed to adjust it to produce their ideal feel, allowing the preferred feel profile to take other forms than a power law.

Analysis of the profiles created by participants show that a power law is a good first approximation of the data, with an average power law exponent of 0.49.

9.2 Preferred feel from a choice of power law exponents using a paired comparisons technique

9.2.1 Introduction

Following on from the paired comparisons tests to determine 'linear' steering feel in Chapter 8, this experiment aimed to determine if 'linear' and 'preferred' steering feel are the same.

The aim was to repeat the procedure used for the 'linear' experiment, and instead give the participants a context of driving at 50 mph on a country road. Participants were presented with two stimuli and asked which they preferred.

9.2.2 Method

9.2.2.1. Apparatus

The same apparatus used in Chapter 7 and Chapter 8 was used in this experiment, and is described in Section 3.3. A mechanical stopper was put in place at zero degrees to provide a reference and somewhere to rest the steering wheel between trials. A cloth was hung between the steering wheel and the participant so that they could not see the wheel.

The motor reproduced required stiffness profiles to within 5% accuracy.

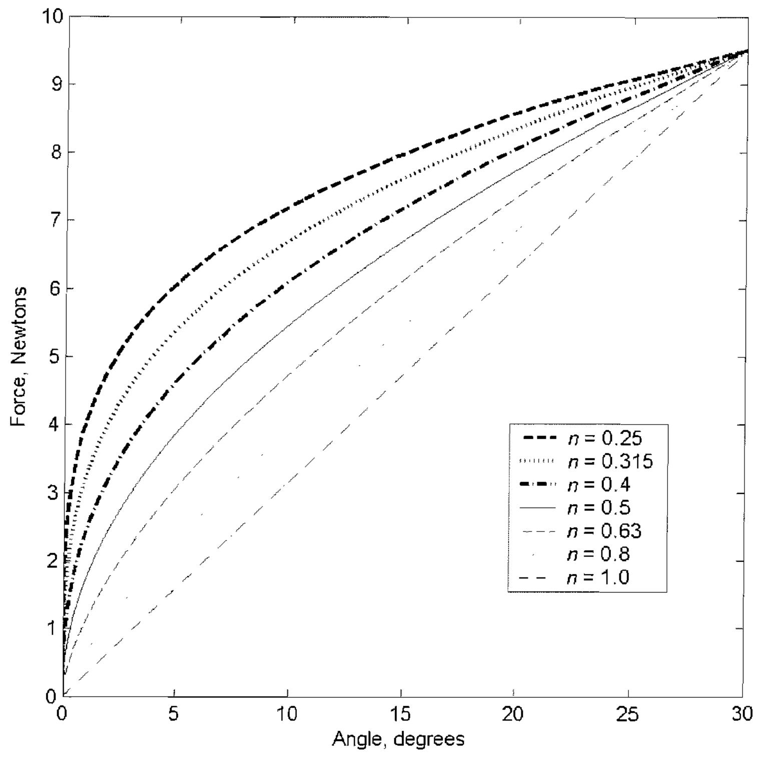


Figure 9.1: Seven stiffness profiles used in the study

9.2.2.2. Stimuli

Seven stimuli, corresponding to power law exponents of 0.25, 0.315, 0.4, 0.5, 0.63, 0.8, and 1.0 were chosen and are shown in Figure 9.1. The value of k was chosen to provide 9.5 newtons of force at 30 degrees of steering angle regardless of the power law exponent, with the nominal value of k being 0.31 newtons per degree with an exponent of $n = 1.0$.

9.2.2.3. Hypothesis

It was hypothesised that the exponents of 0.8 and 0.63 would be judged as preferred if participants prefer a linear steering stiffness as the haptic property at the steering wheel.

9.2.2.4. Design

9.2.2.4.1. Participants

Twenty one participants, 20 male, and 1 female, aged between 24 and 59 years took part in the experiment. All participants were employees or contractors at Jaguar Cars Ltd in Coventry.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and driving experience of participants.

9.2.2.4.2. Experimental procedure

Participants were shown a 3-minute video of 50 mph country road driving before comparing all of the 21 possible pairs of seven different steering systems having exponents of 0.25, 0.315, 0.4, 0.5, 0.63, 0.8 and 1.0. They made each of these judgements once. For each judgement, participants slowly rotated the steering wheel from 0 to 30 degrees with two stimuli (i.e. two different exponents) and then indicated which stimuli they 'preferred'. The participants were grouped as pairs, with each pair receiving the same randomised order of the twenty-one pairs, but with the order of presentation of each stimulus reversed for the second participant in the pair (except for the 21st participant).

9.2.2.4.3. Instructions

The instructions for this experiment were as follows:

This experiment uses a method of paired comparison. You will be asked to:

1. *Turn the wheel from 0 degrees (against the stopper) through to 30 degrees*
2. *Turn the wheel at the rate specified on the monitor*
3. *Make 1 turn for each stimulus*

The experimenter will then change the stimuli and you will be required to repeat the stages above. After presentation of both stimuli, you will be asked to specify which of the two stimuli you prefer.

If you are unsure of your judgement, or get distracted, you may ask to repeat the pair.

9.2.2.4.4. Analysis

Analysis was conducted according to Thurstone's law of comparative judgement case V, which assumes that the standard deviations and the distribution of discriminable differences are constant for all pairs of stimuli. The distance between stimuli is represented as:

$$s_i - s_j = \sqrt{2}x_{ij} \tag{9.1}$$

where s_i and s_j are the scale values of stimuli *i* and *j*, and x_{ij} is the normal deviate corresponding to the theoretical proportion of times stimulus *i* is judged greater than stimulus *j*.

9.2.3 Results

The results of the paired comparison experiment are presented in Table 9.1, showing the frequency with which the exponent in column *i* is judged 'more linear' than the exponent in row *j*. By summing all the frequencies for all columns an overall ordering for the exponents is obtained.

Scale values (case V) are obtained by the Thurstone method and are shown in Table 9.2. The mean scale values have been transformed so that the exponent with the lowest scale value is given a score 0.

Table 9.1: The frequency with which each column exponent (*n*) is judged 'more linear' than the row exponent (*n*) (*N* = 21)

	0.25	**0.315**	**0.4**	**0.5**	**0.63**	**0.8**	**1.0**
0.25	-	15	13	15	12	10	14
0.315	6	-	9	18	11	11	7
0.4	8	12	-	15	14	10	8
0.5	6	3	6	-	7	7	4
0.63	9	10	7	14	-	6	7
0.8	11	10	11	14	15	-	6
1.0	7	14	13	17	14	15	-
Total	**47**	**64**	**59**	**93**	**73**	**59**	**46**
Rank	**6**	**3**	**4**	**1**	**2**	**5**	**7**

9.2.4 Discussion

The results show that a power law exponent of 0.5 was chosen as the most 'preferable' most often, followed by an exponent of 0.63. Therefore the most preferred power law exponent could lie between these two values. We therefore reject our hypothesis that "linear' and 'preferred' steering stiffness profiles have the same power law exponent.

The scale values almost increase to the value of 0.5 and then decline, apart from one exception: that of the 0.315 and 0.4 exponents. It would be expected that 0.4 would have a higher scale value than 0.315, but the results show that it is the other way around. The exponent of 0.315 has a scale value of 0.36 whilst the exponent of 0.4 has a scale value of 0.22. This phenomenon could be due to the differing 'preferences' shown by the participants. After the test, participants were informally asked how they thought they were making their judgements, and it was clear that different preferences were exhibited by the participants with some reporting that 'it's good to feel some resistance as you enter the corner', and others reporting that 'I don't like ones that build up too quickly'.

The consistency of the scale values were checked by determining how well the observed proportions agree with the proportions expected from the derived scale values. The absolute average discrepancy was 0.02 for the seven stimuli and compares well with values usually reported when stimuli are scaled by the method of paired comparisons.

The assumptions underlying the case V model can be tested for significance using a chi-squared distribution test (Edwards (1957)). This test, developed by Mosteller (1951), tests whether the observed and theoretical proportions are in agreement after they have both been transformed. If the property of additivity holds, then there should be agreement between the transformed values, and the value of χ^2 will be small. Formally stated, the null hypothesis of this test is that the assumptions involved in the model are tenable. The alternative to the null hypothesis could include rejection of any of the assumptions made under the case V model.

Table 9.2: Scale values of exponents (Thurstone case V)

Exponent (n)	0.25	0.315	0.4	0.5	0.63	0.8	1.0
Scale value	0.01	0.36	0.22	0.83	0.52	0.10	0.00

In this case, $\chi^2(15) = 9.47$. The probability of obtaining a value of χ^2 equal to or greater than 9.47 is between 0.80 and 0.90, when the null hypothesis is true. If we treat as significant values of χ^2 as those that have a probability of 0.05 or less, than our observed value would have to be 25.00 or larger. This indicates that the assumptions involved in finding the scale values of the seven exponents are tenable.

Inter-subject agreement was assessed using Kendall's coefficient of agreement statistic, u, which provides a measure of the extent to which a group agree in their comparative judgements. The value of u is 1.0 if all judges are in perfect agreement, and becomes smaller when departure from complete agreement increases. The minimum value of u for an odd number of participants is –1/(number of participants), which in this study is –0.048. The u statistic was calculated and tested for significance using a χ^2 distribution, resulting in $u = 0.082$, $\chi^2(22) = 55.47$. Although agreement is far from perfect (where $u = 1$), the probability of obtaining a value of u as great as 0.082 is much less 0.01 if the comparative judgements of all the participants were made at random. It can be concluded that the 21 participants do show agreement in their comparative judgements.

The figures for agreement are much higher than previously reported for the 'linear' feel experiment. This could be due to a difference in the cognitive load placed on the participant – whereas being asked what is 'preferred' is a relatively easy judgment to make, making a judgement of 'linear' requires interpretation.

9.2.5 Conclusions

This experiment was designed to test whether 'linear' stiffness is the same as 'preferred' steering stiffness for 50 mph country road driving. The results suggest that the exponent for the 'most preferred' feel lies between exponents of 0.5 and 0.63, whilst the exponent for the 'most linear' feel is thought to lie between 0.63 and 0.8.

The exponents obtained for preferred feel at 50 mph are consistent with the stiffness profiles experienced in cars, and are much more consistent with profiles constructed by expert testers.

9.3 Free choice stiffness profile manipulation

9.3.1 Introduction

The first experiment in this chapter makes the assumption that preferred feel will take a power law form. However, the ideal curve might not take power law form. Allowing participants full control over the stiffness curve will allow the assumption to be tested.

Giving the participant full control of the stiffness profile might lead to errors depending on where the curve started from, particularly as the difference threshold may be as much as 20%

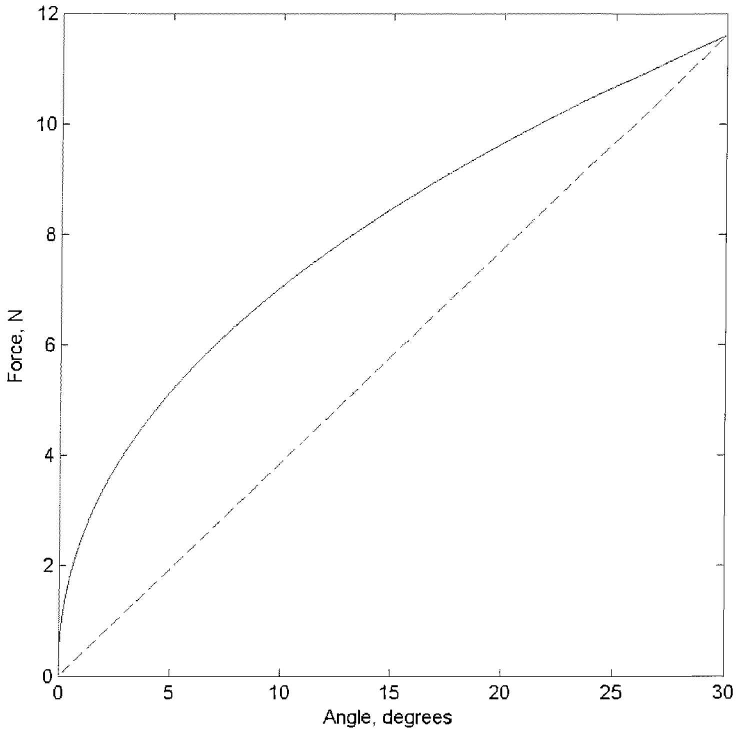


Figure 9.2: Starting point references for participants to manipulate (reference 1 = solid line, reference 2 = dashed line)

of the work done by the participant (see Chapter 7). It is therefore expected that if two references were used and adjusted by each participant, that the resulting stiffness profiles may be different.

To counterbalance this, we will require the participants to make two manipulations: one starting from an exponent below the 'preferred' exponent determined in Section 9.2 ($n = 0.45$), and the other starting from a true linear curve ($n = 1$).

9.3.2 Method

Participants were required to manipulate a stiffness curve until it was perfect for the context of 50 mph country road driving.

9.3.2.1. Apparatus

The same apparatus as used in Section 9.2 was used in this experiment, and is described in Section 3.3. A mechanical stopper was implemented at zero degrees to provide a reference and somewhere to rest the steering wheel between trials. A cloth was hung between the steering wheel and the participant so that they could not see the wheel.

The motor reproduced required stiffness profiles to within 5% accuracy.

9.3.2.2. Stimuli

Two references were used in this experiment. Both references produced a force of 11.6 N at 30°. Equation 9.2 shows the form of reference 1, and equation 9.3 shows the equation for reference 2.

$$F = 2.51\theta^{0.45} \tag{9.2}$$

$$F = 0.39\theta \tag{9.3}$$

Both references are shown in Figure 9.2.

9.3.2.3. Hypothesis

It was hypothesised that a power law relationship would provide a good first estimate of the preferred steering stiffness profiles.

9.3.2.4. Design

9.3.2.4.1. Participants

Twelve male participants, aged between 26 to 34 years, took part in the experiment using a within-subjects experimental design.

The study was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration at the University of Southampton.

A questionnaire was used to collect personal details, health, and driving experience of participants.

9.3.2.4.2. Experimental procedure

Participants were shown a 3-minute video of 50 mph country road driving before turning the wheel, and giving the experimenter verbal instructions to alter the stiffness profile.

Participants could alter the profile as many times as they like to achieve an 'ideal' feel, with both reference 1 and reference 2 requiring an average of four manipulations to get to achieve an 'ideal' feel.

The order of presentation for the reference conditions was balanced across participants with six participants starting with reference 1, and six starting with reference 2.

9.3.2.4.3. Instructions

The instructions for this experiment were as follows:

You will be asked to:

1. *Turn the wheel from 0 degrees (against the stopper) through to 30 degrees*
2. *Concentrate on the feel as you turn through to 30 degrees*
3. *Once the wheel is returned to centre, you should instruct the experimenter to manipulate the curve*
4. *Repeat until the curve feels ideal*

9.3.2.4.4. Analysis

Visual inspection was used to assess whether a simple linear, logarithmic, exponential or power function described the data. The equations considered are:

Linear form:

$$y = a + bx \tag{9.4}$$

This relationship describes a function that can be described as a straight line when plotted with linear abscissa and ordinate.

Logarithmic form:

$$y = a + b\log x \tag{9.5}$$

This relationship describes a function that can be described as a straight line when plotted with logarithmic abscissa and linear ordinate.

Exponential form:

$$\begin{gathered} y = Ae^{Bx} \\ \therefore \log y = \log A + Bx \end{gathered} \tag{9.6}$$

This relationship describes a function that can be described as a straight line when plotted with linear abscissa and logarithmic ordinate.

Power law form:

$$\begin{gathered} y = Ax^{B} \\ \therefore \log y = B\log x + \log A \end{gathered} \tag{9.7}$$

This relationship describes a function that can be described as a straight line when plotted with logarithmic abscissa and logarithmic ordinate.

Each of the relationships will describe a straight-line function once the abscissa or ordinate (or both) have been transformed.

Because it is not possible to take the natural logarithm of 0 (= -∞), we have discounted zero terms in our analysis.

9.3.3 Results

The stiffness profiles that the participants created for reference 1 are shown in Figure 9.3, Figure 9.4, Figure 9.5, and Figure 9.6, and the stiffness profiles that participants created for reference 2 are shown in Figure 9.7, Figure 9.8, Figure 9.9, and Figure 9.10.

Visual inspection of the transformations of reference 1 shows that transforming both the abscissa and ordinate into logarithmic scales has the best straight-line characteristic. For reference 2, although the data is much more varied, one participant has a good approximation to a straight line with linear abscissa and ordinate, however it is likely that this participant did not change the reference (which was linear) that much. The logarithmic abscissa and ordinate transformations again seem to have the best approximation to a straight-line characteristic although there are deviations from a straight-line.

Given the choice of simple characteristics that could be used to describe the force and angle characteristic, the power law form seems to provide the best first approximation of the data.

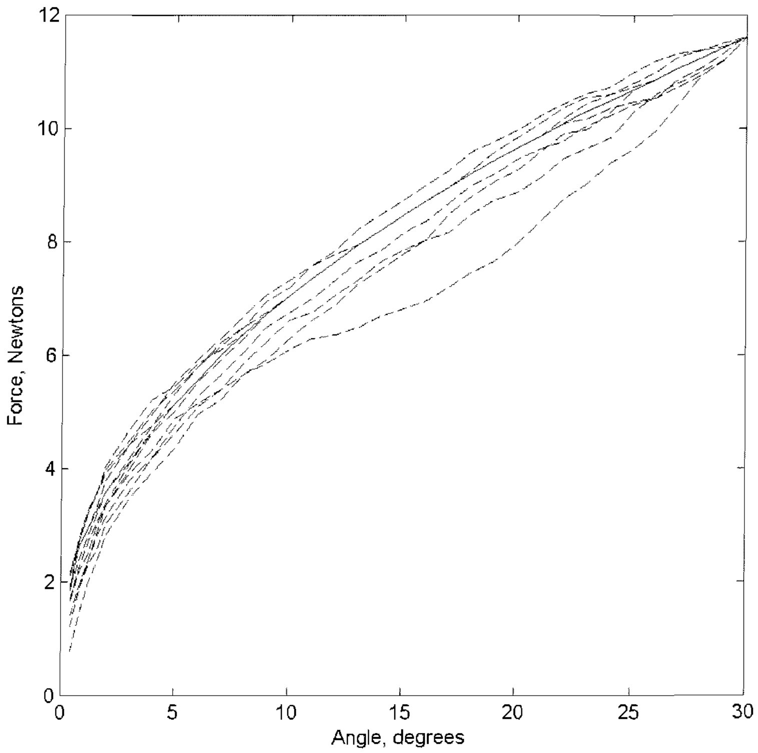


Figure 9.3: Stiffness profiles in linear abscissa and ordinate for reference 1 (12 participants)

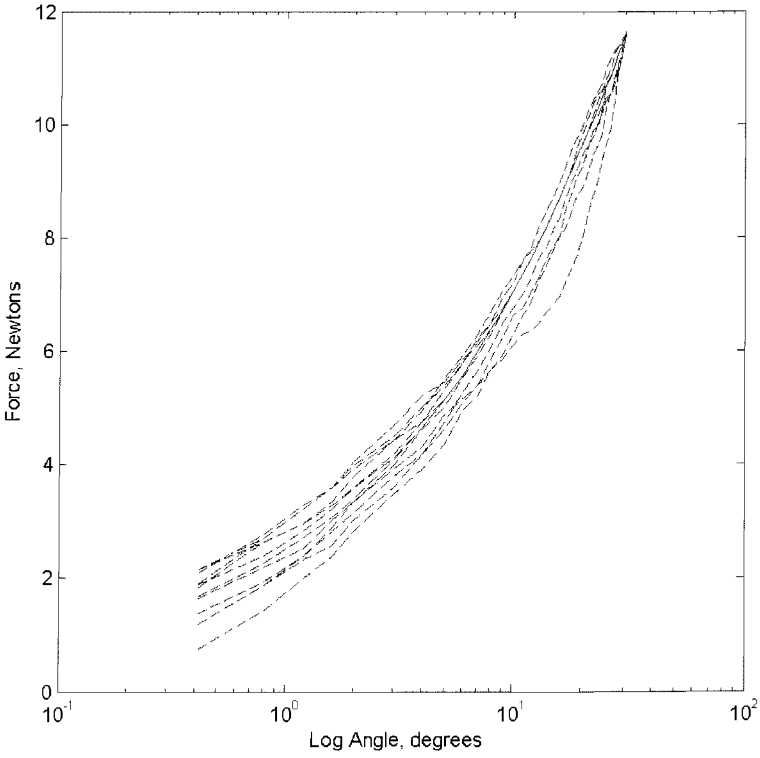


Figure 9.4: Stiffness profiles with logarithmic abscissa for reference 1 (12 participants)

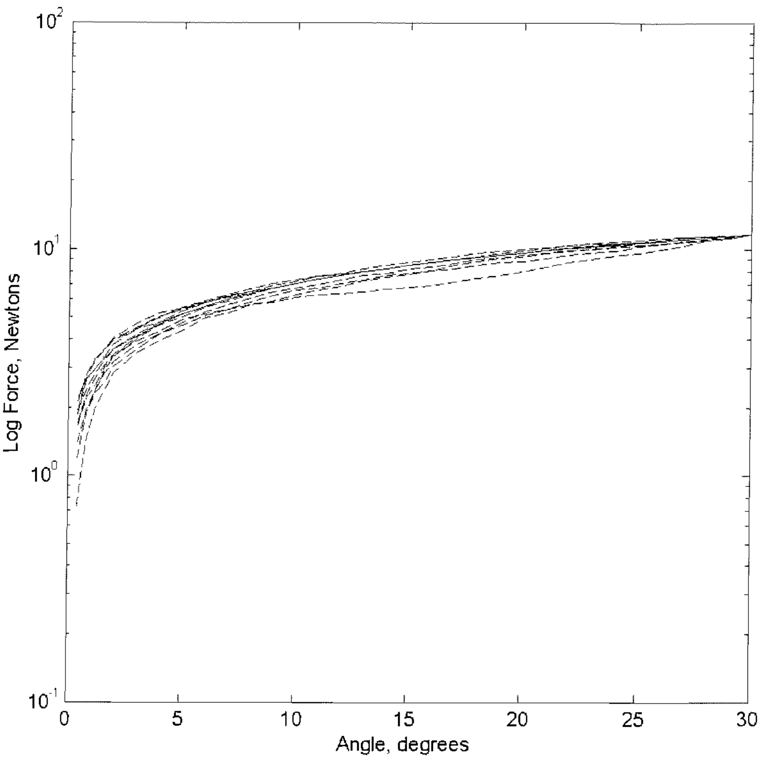


Figure 9.5: Stiffness profiles with logarithmic ordinate for reference 1 (12 participants)

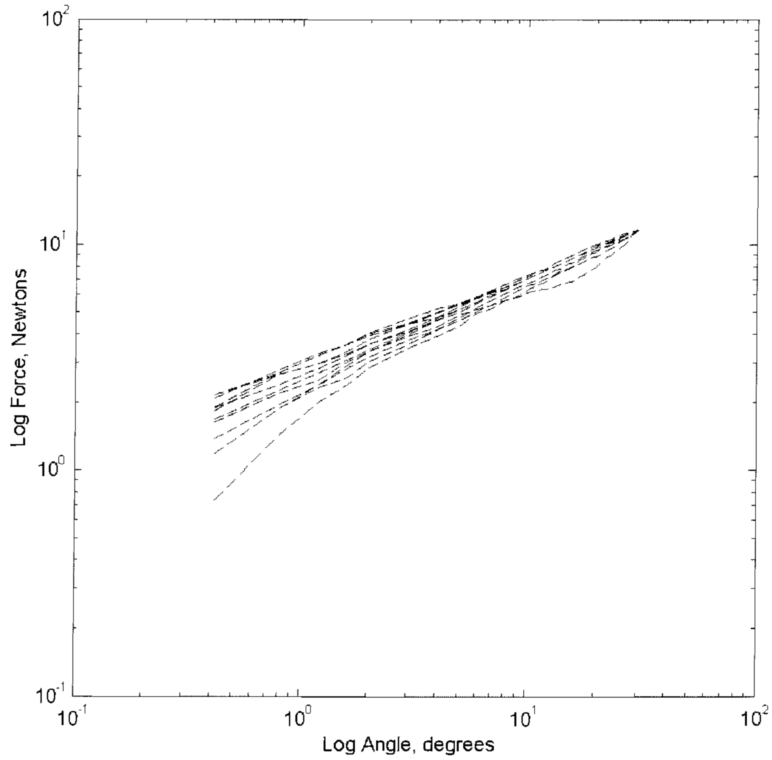


Figure 9.6: Stiffness profiles with logarithmic abscissa and ordinate for reference 1 (12 participants)

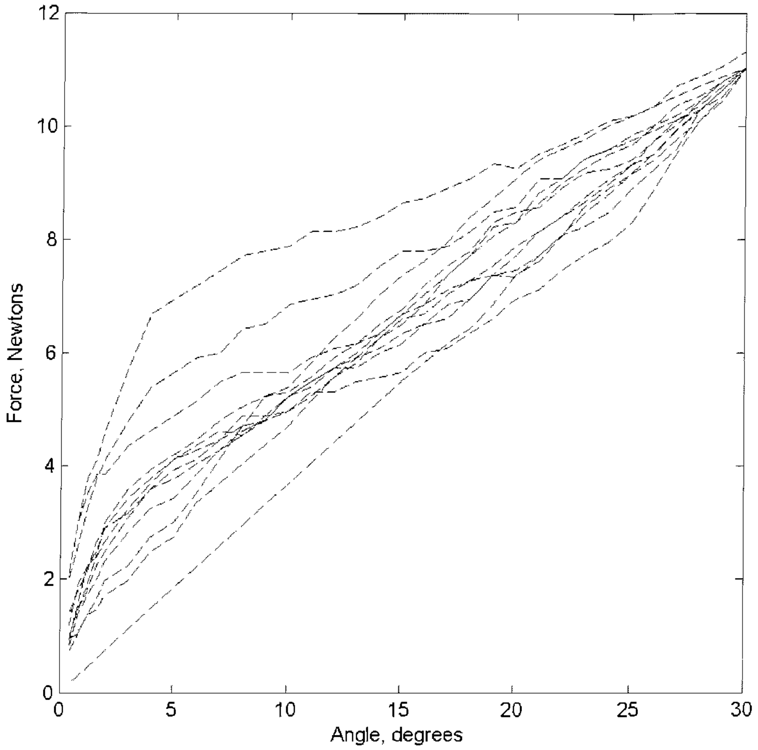


Figure 9.7: Stiffness profiles in linear abscissa and ordinate for reference 2 (12 participants)

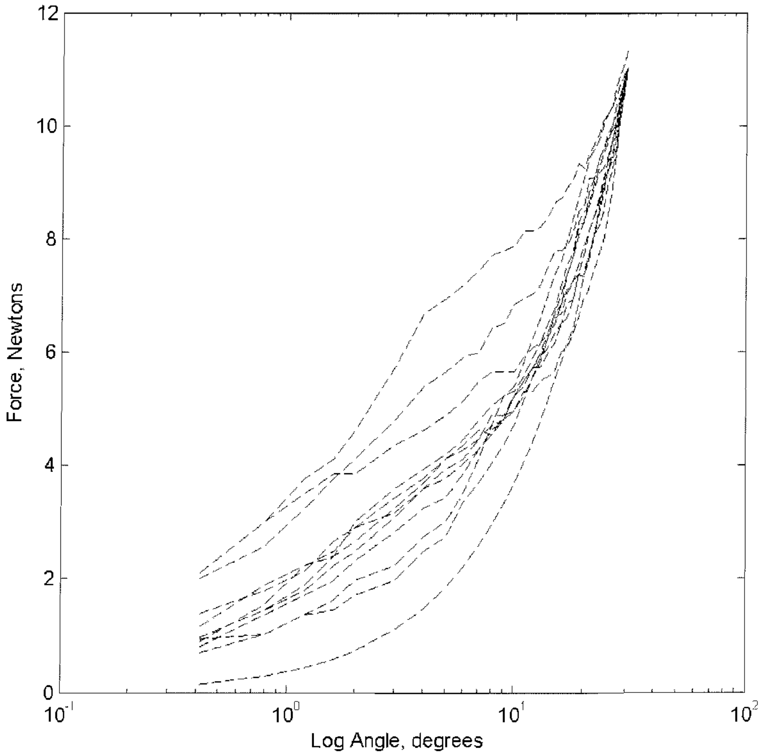


Figure 9.8: Stiffness profiles with logarithmic abscissa for reference 2 (12 participants)

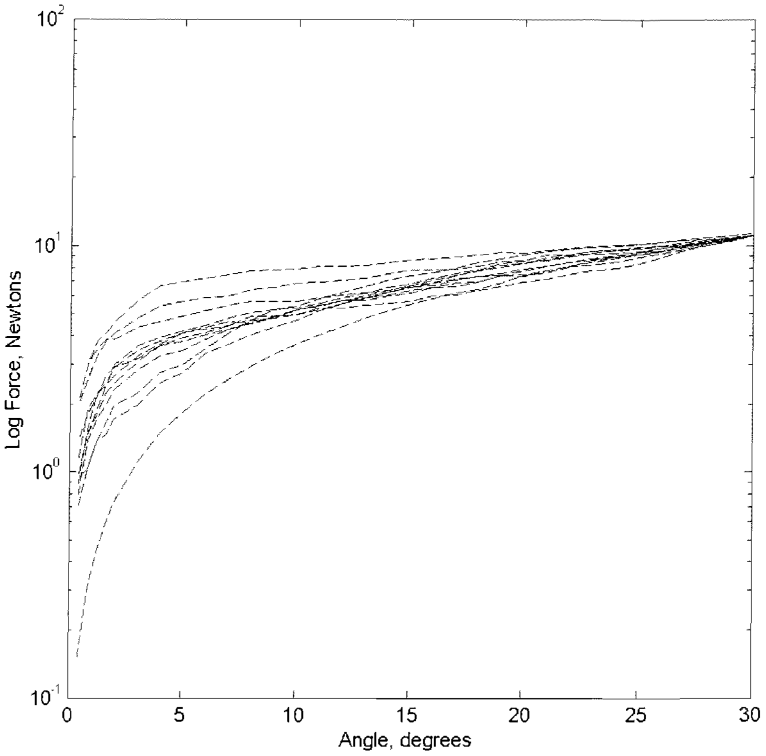


Figure 9.9: Stiffness profiles with logarithmic ordinate for reference 2 (12 participants)

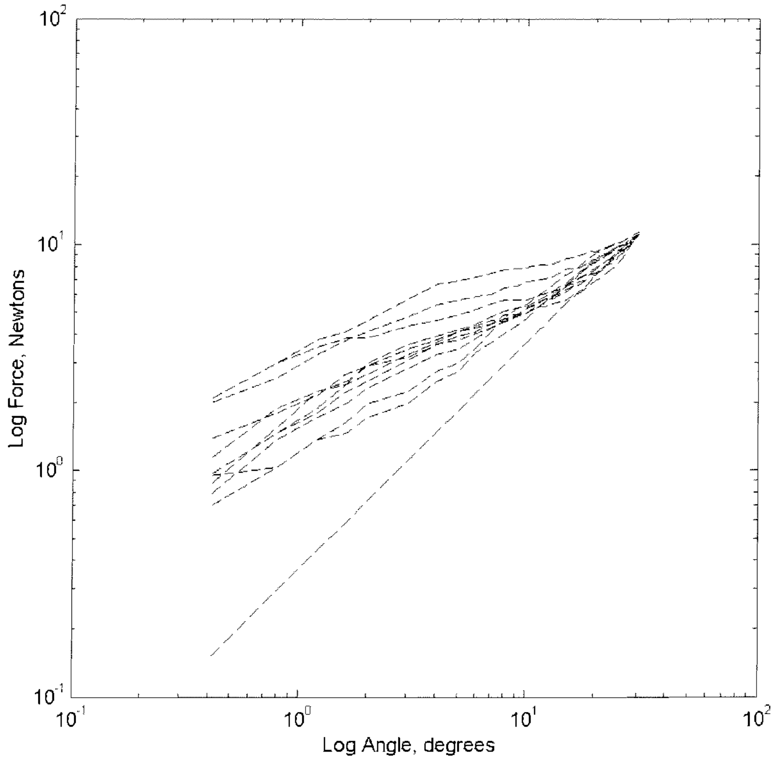


Figure 9.10: Stiffness profiles with logarithmic abscissa and ordinate for reference 2 (12 participants)

Table 9.3: Power law exponent, n, obtained for each participant

Participant	n_{ref1}	n_{ref2}	n_{mean}
1	0.4206	0.5601	0.49
2	0.4243	0.5256	0.47
3	0.4332	0.3474	0.39
4	0.4142	0.6691	0.54
5	0.5022	0.4663	0.48
6	0.3923	0.3420	0.37
7	0.5043	0.5292	0.52
8	0.5826	0.9978	0.79
9	0.4051	0.6437	0.52
10	0.4884	0.5225	0.51
11	0.3986	0.3650	0.38
12	0.4552	0.4480	0.45
Average	**0.45**	**0.53**	**0.49**

Least squares regression is used to determine the exponent, n, and the stiffness constant, k, by treating the data in power law form. The exponent, n, for all participants and for both references are shown in Table 9.3.

Visual inspection of Figure 9.6 and Figure 9.10 show that the preferred feel line is different from reference 1 to reference 2. This is also show by the different value of the exponent, n, determined in Table 9.3 for reference 1 and reference 2. It can be expected that when a participant is asked to adjust to their preferred curve twice, that there may be some difference in the curve they produce simply because of their difference threshold meaning that participants would be unable to perceive the difference between the two preferred curves created.

The exponent obtained with reference 1 and reference 2 are different for each participant and analysis was conducted to see if there is significance between the exponent obtained in when starting from reference 1, and that exponent obtained when starting with reference 2. A Wilcoxon signed ranks test shows that there is no significant difference between the exponent obtained with reference 1, and the exponent obtained with reference 2 ($p>0.15$). This suggests that if there is a bias involved in the different reference start points, it is not a significant bias.

Visual inspection of Figure 9.6 and Figure 9.10 show that reference 1 had less scatter in the final curves of participants than reference 2. As the average preferred power law exponent, n, is calculated as 0.49, this may signify the different abilities of participants in making adjustments to the reference curve. Reference 1 had an exponent of $n = 0.45$ which is much closer to the average preferred exponent calculated in the experiment. The second reference had an exponent of $n = 1$ which requires a larger adjustment to get to the average preferred feel exponent than reference 1. It is possible that some participants were not as good at making adjustments as others, or their difference threshold in order to tell the difference between their two preferred curves may have been larger than other participants. This would be signalled as a greater scatter of results when the reference starts further away from the preferred exponent.

The average of the exponent obtained from reference 1 and 2 was used at the best estimate of an ideal steering stiffness profile (see Table 9.3). This averaging shows that participants ‘ideal’ stiffness profile exponents ranged from 0.37 to 0.79, although the average exponent from all participants is an exponent of 0.49.

9.3.4 Discussion

Analysis of figures that are a combination of linear and logarithmic axes reveals that the power law is a good first estimate of participant’s data for their ‘ideal’ curve.

Analysis of the best-fit power law exponents obtained from each participant and each reference show that the average exponent is 0.49, with the minimum average from individual participants being 0.37 to 0.79 suggesting that different participants had different ‘ideal’ stiffness profiles. In particular, participants 3, 6, and 11 had smaller exponents than the average for both reference 1 and reference 2, with their average exponent being below an exponent of 0.4. Participants 3, 6 and 11 regularly drove a Peugoet 106, Porsche Boxster, and Ford Focus respectively.

Only participant 8 obtained power law exponents that were higher than the average in both reference 1 and reference 2, with an average exponent of 0.79 (the next highest average being 0.54 for participant 4). This participant regularly drove a Honda Accord.

It is possible that the vehicle the participants drive have an influence over their perception of an ‘ideal’ steering stiffness function. Although objective data is not available to analyse and compare the stiffness profiles of the vehicles mentioned above, steering experts at Jaguar independently subjectively rated the vehicles that the participants used on a scale of ‘better than average’, ‘average’, and ‘poor’ for steering feel. The Peugoet 106, Porsche Boxster, and Ford Focus all fell into the ‘reasonable’ rating, with the Honda Accord achieving an ‘average’ rating. This suggests that the type of vehicle that the participants drive might have an effect on their ‘ideal’ stiffness profile. However, participant 12 drove a vehicle with a ‘poor’ steering feel, but achieved a much lower exponent than participant 8. This would suggest that rather than the vehicle that participants drive influencing the results, it is the preference of the participants that causes the difference in stiffness profile that is chosen as ‘ideal’.

9.3.5 Conclusions

This experiment was designed to test whether an 'ideal' stiffness is best described using a power law function for 50 mph country road driving.

The results suggest that 'ideal' steering stiffness profiles are best described in power law form rather than linear, logarithmic or exponential forms.

Analysis of the exponents obtained from participants ideal curves reveals that the average power law exponent is $n = 0.49$.

9.4 General conclusions

The two experiments detailed in this chapter investigated 'preferred' feel at the steering wheel in terms of stiffness profile for the context of 50 mph country road driving.

The results show that 'linear' and 'preferred' feel are different, with a power law exponent of 0.5 describing the most preferred feel at the steering wheel in the paired comparisons experiment.

The most preferred exponent from the free choice experiment was surprisingly similar with an average exponent of 0.49 for all participants' preferred feel.

These two experiments also indicate that the preferred stiffness profile is different for different people. The first indications was from the paired comparisons test, where unlike the linear feel experiment there was not one peak in the psychological scale values, instead there were two, the major peak at an exponent of 0.5, and a smaller peak with an exponent of 0.315. This was also indicated in the free choice experiment where participants 3, 6, and 11 produced average preferred exponents of less than 0.4, and participant 8 produced an average preferred exponent of 0.79.

Chapter 10. Analysis of real vehicle data

10.1 Overview

The experimental chapters of Parts 2 and 3 of this thesis detail some fundamental studies into driver perception of steering wheel force, steering wheel angle, and steering wheel stiffness profiles.

By studying the perception of steering wheel stiffness profiles in the preceding chapters of Part 3 we now have data that can be compared to a real vehicle data from objective tests. The results suggest that a power law function is a good first estimate of participant's perceptual data.

This chapter analyses the force and angle profile that is obtained in objective testing of real vehicles. Analysis of the stiffness profile from several vehicles shows that a power law relationship between force and angle is a good first estimate of the stiffness profile, and that most vehicles have a power law exponent of between 0.3 and 0.55.

10.2 Introduction

Objective tests are conducted on vehicles in the development process, with data collected and analysed in order to set and determine vehicle targets.

In the perception studies detailed in Chapters 7, 8 and 9, participants were required to judge stimuli as they slowly turned the wheel from centre to 30 or 45 degrees. The most relevant objective vehicle test procedure is the low-g swept steer test where the vehicle travels at a specified speed with the vehicle starting the manoeuvre from on-centre driving, then a slow but steady steering input is applied.

The steering wheel torque (or force) and steering wheel angle data can be plotted against each other to show the steering stiffness of a real vehicle in a steady-state manoeuvre.

10.3 Method

The data was analysed by regressing a line of best fit to power law data (see equation 10.1). This relationship described in equation 10.1 is characterised as a straight line if the force and angle data is plotted with a logarithmic abscissa and ordinate.

$$\begin{aligned} y &= kx^{n} \\ \therefore \log y &= n \log x + \log k \end{aligned} \tag{10.1}$$

10.3.1 Vehicles

Data from a Jaguar XK (X150), Jaguar S-Type (X202), Land Rover Freelander (L359), Ford S-Max (CD340), Ford Focus (C307), Ford Fiesta (B257), and BMW 520i low-g swept steer data was analysed.

10.3.2 Hypothesis

It was hypothesised that a power law function would provide a good visual fit to the vehicle data.

10.3.3 Analysis

A line of best fit was determined for each vehicle, for both right and left hand turns at 75 kph and 120 kph. In order to achieve the best fit to the data, the data were only analysed from 3° to prevent errors from non-zero start points, and errors from the tolerance of the measurement equipment (see Appendix D).

10.4 Results

The raw data, and best fit power law for the Jaguar XK (X150), Jaguar S-Type (X202), Land Rover Freelander (L359), Ford S Max (CD340), Ford Focus (C307), Ford Fiesta (B257) and BMW 520i are shown in Figures 10.1 to 10.7.

The power law exponent, n, obtained for each vehicle is shown in Table 10.1, and stiffness constant, k, is shown in Table 10.2.

The stiffness constant, k, in a power law equation is compromised by the exponent, n. The stiffness constant does not specify the force or torque at a given angle as the exponent directly affects the force or torque at a specific angle. In order to maintain the same force or torque at a given angle as the exponent, n, changes, the value of k must be scaled according to the exponent. This means that the k value must not be compared in isolation unless the exponent is the same for the stimuli being compared. As this is rarely the case, it might be better to use the stiffness constant, k, and the exponent, n, to define what force or torque is achieved at a specific angle (which can be chosen arbitrarily). Table 10.3 shows the force at the steering wheel for the vehicles at a steering wheel angle of 5°.

10.5 Discussion

The analysis of the Jaguar XK (X150), Jaguar S-Type (X202), Land Rover Freelander (L359), Ford S-Max (CD340), Ford Focus (C307), Ford Fiesta (B257), and BMW 520i low-g swept steer data shows that in most cases a power law fits well to the data.

The exponent, n, describes the curvature of the function, and the stiffness constant, k, scales the stimuli.

There is evidence of some issues with the power law fit. For instance the zero point where the car starts the manoeuvre seems to be offset slightly on some vehicles (see Ford Focus (C307) in Figure 10.5 and Ford Fiesta (B257) in Figure 10.6). This type of offset means that the exponent, n, will be over estimated on one side, and underestimated on the other. An average of the two will provide a better estimate of the true exponent of the vehicle.

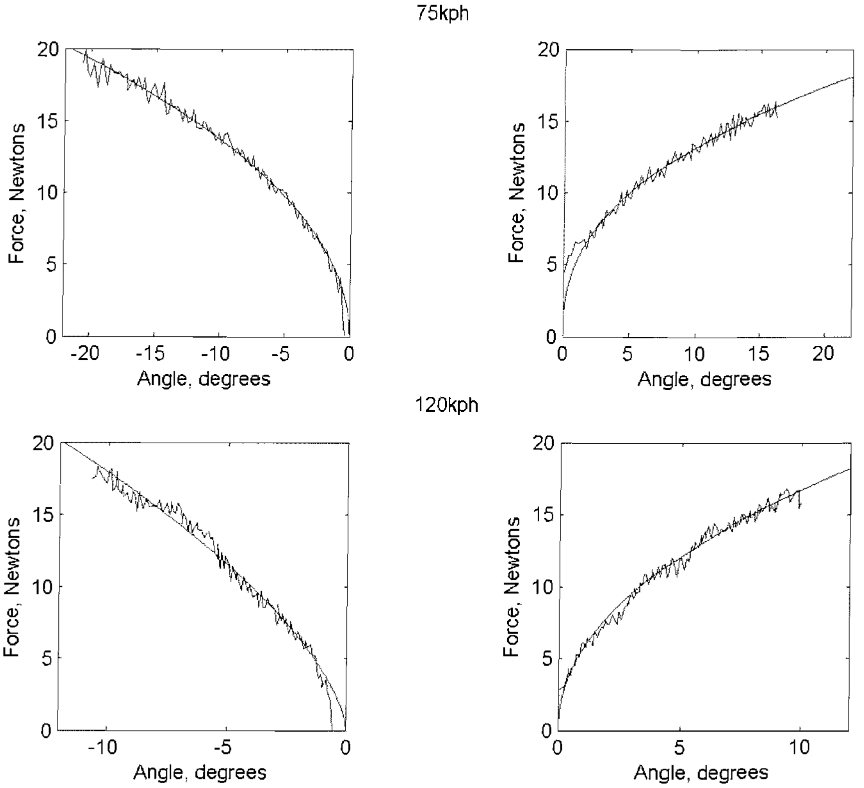


Figure 10.1: Low-g swept steer data from Jaguar XK (X150)

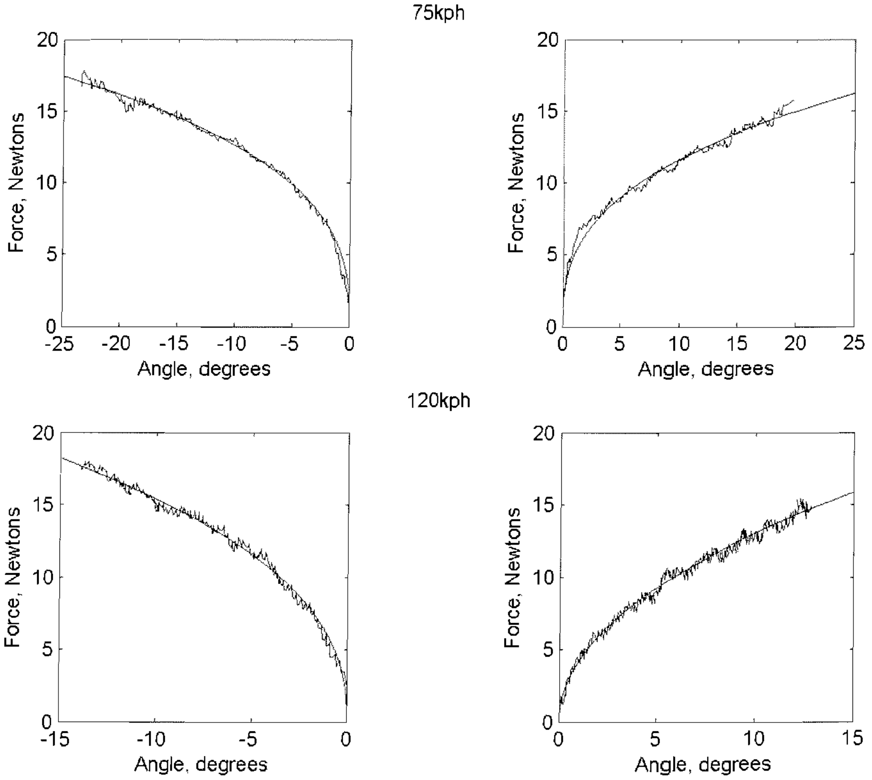


Figure 10.2: Low-g swept steer data from Jaguar S-Type (X202)

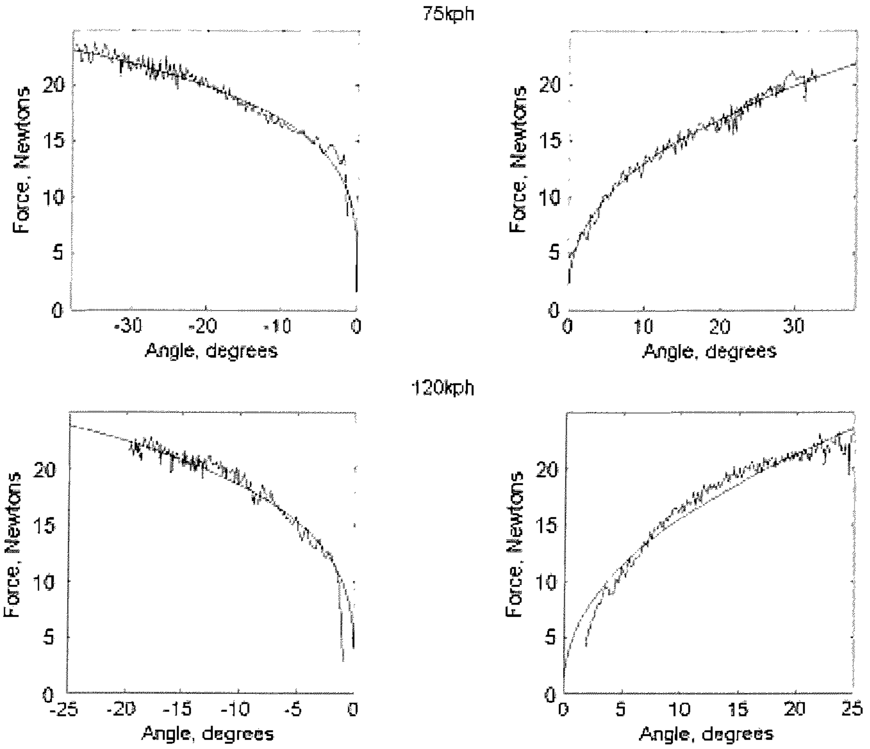


Figure 10.3: Low-g swept steer data from Land Rover Freelander (L359)

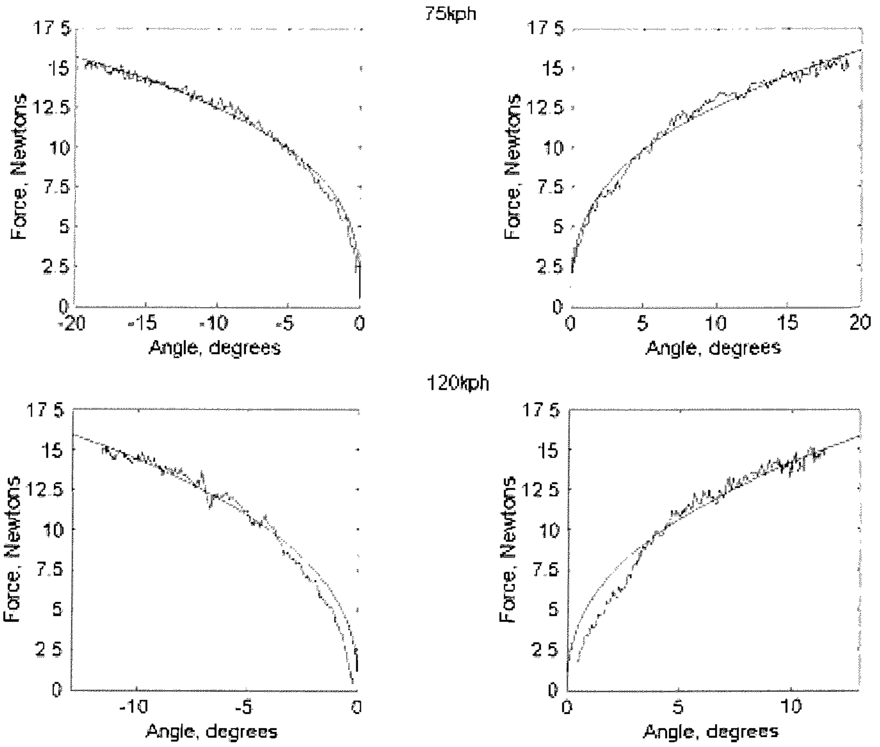


Figure 10.4: Low-g swept steer data from Ford S-Max (CD340)

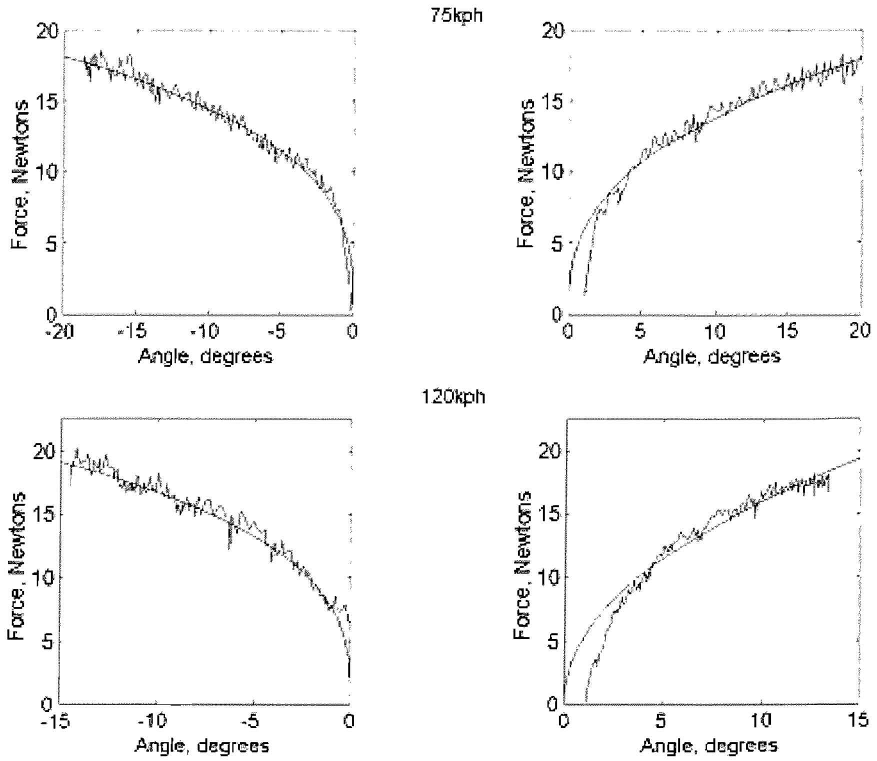


Figure 10.5: Low-g swept steer data from Ford Focus (C307)

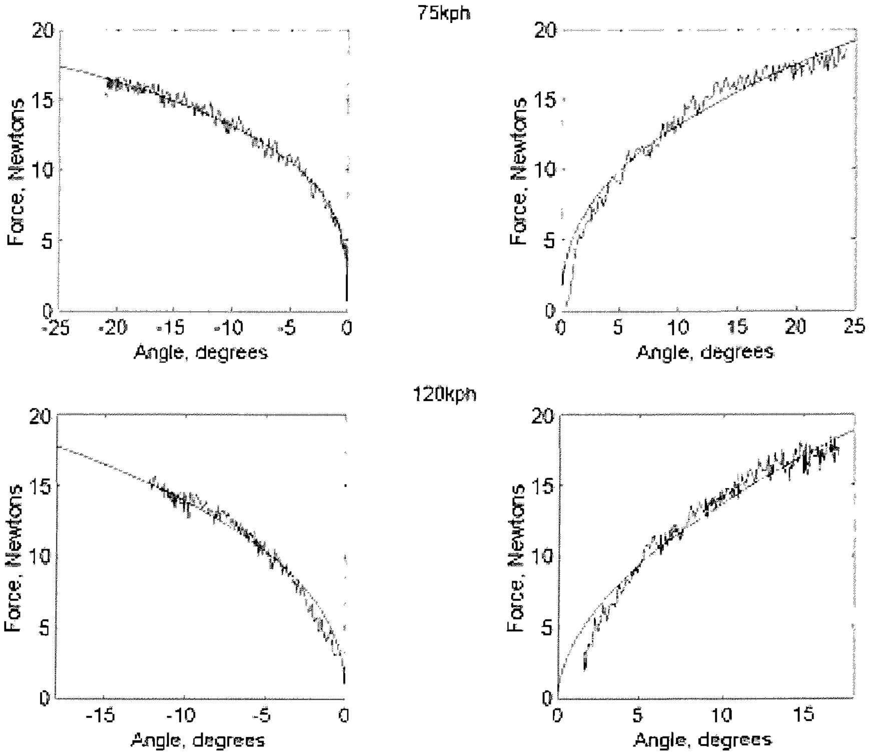


Figure 10.6: Low-g swept steer data from Ford Fiesta (B257)

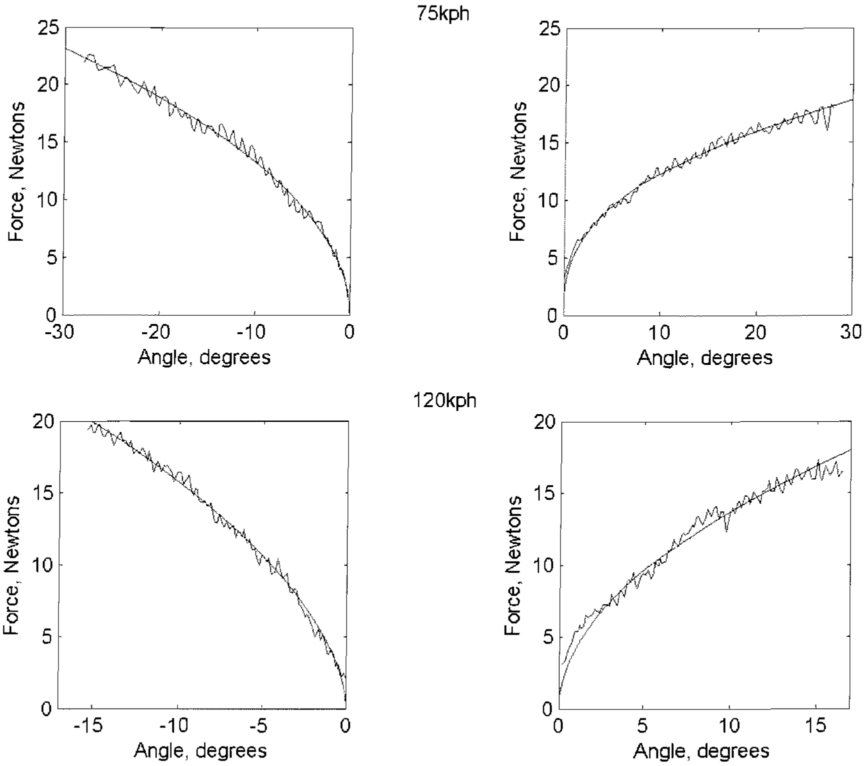


Figure 10.7: Low-g swept steer data for BMW 520i

Table 10.1: Power law exponent, *n*, comparison between vehicles

	75kph			120kph		
	right	left	average	right	left	average
Jaguar XK (X150)	0.40	0.50	0.45	0.47	0.64	0.55
Jaguar S-Type (X202)	0.36	0.36	0.36	0.49	0.42	0.45
Land Rover Freelander (L359)	0.39	0.24	0.31	0.45	0.28	0.36
Ford S-Max (CD340)	0.35	0.33	0.34	0.41	0.40	0.41
Ford Focus (C307)	0.37	0.33	0.35	0.48	0.34	0.41
Ford Fiesta (B257)	0.41	0.31	0.36	0.54	0.43	0.48
BMW 520i	0.38	0.51	0.44	0.51	0.57	0.54

Table 10.2: Stiffness constant, *k*, in terms of torque

	75kph			120kph		
	N/°$_{right}$	N/°$_{left}$	N/°$_{average}$	N/°$_{right}$	N/°$_{left}$	N/°$_{average}$
Jaguar XK (X150)	5.25	4.33	4.79	5.72	4.10	4.91
Jaguar S-Type (X202)	5.04	5.51	5.28	4.22	5.87	5.05
Land Rover Freelander (L359)	5.43	9.80	7.62	5.58	9.75	7.67
Ford S-Max (CD340)	5.99	6.15	6.07	5.94	6.04	5.99
Ford Focus (C307)	6.26	7.17	6.72	5.72	8.24	6.98
Ford Fiesta (B257)	5.51	6.84	6.16	4.22	5.56	4.89
BMW 520i	5.10	4.12	4.61	4.26	4.22	4.24

Table 10.3: Steering wheel force produced at 5 degrees

	75kph			120kph		
	N$_{right}$	N$_{left}$	N$_{average}$	N$_{right}$	N$_{left}$	N$_{average}$
Jaguar XK (X150)	10.0	9.7	9.9	12.1	11.5	11.8
Jaguar S-Type (X202)	9.0	9.8	9.4	9.3	11.5	10.4
Land Rover Freelander (L359)	10.1	14.6	12.4	11.6	15.1	13.4
Ford S-Max (CD340)	10.7	10.7	10.7	11.2	11.8	11.5
Ford Focus (C307)	11.2	12.3	11.8	12.3	13.9	13.1
Ford Fiesta (B257)	10.7	11.2	11.0	10.2	11.2	10.7
BMW 520i	9.4	9.3	9.4	9.6	10.6	9.4

There can also be asymmetries in the steering system, which is visible from the steering stiffness profile (for example, see Land Rover Freelander (L359) data in Figure 10.3). Taking the average exponent of the left and right hand turns will conceal this. It might be more appropriate to ensure that the vehicle is properly zeroed before acquisition.

The Land Rover Freelander (L359) data at 120 kph shows another problem (see Figure 10.3). This time it does not seem that the zero point is offset, but that neither the right or left turn pass through zero, which will lead to an underestimate of the exponent. This shows that the vehicle either has a significant 'dead band' or a stiction problem in the steering, or there may be a problem with zeroing the vehicle for the test.

The combined power law exponents are shown in Table 10.1, and range from 0.31 to 0.55, with the exponents for 120 kph being significantly higher than the exponents determined for 75 kph (Wilcoxon, $p<0.02$) suggesting that a slower growth of stiffness is required at higher speeds.

Analysis of the stiffness constant is more difficult due to its dependence on the exponent, *n*. Direct comparisons of the value of *k* are therefore meaningless. Evaluating the force at a specific angle (or vice versa) will allow direct comparison, although the specific angle (which is arbitrary) may affect the result. For instance, a vehicle with a low exponent, *n*, evaluated near the origin may have more force than another vehicle with a higher exponent, but if the force for a much larger angle were compared, the vehicle with the higher exponent may have more force than the vehicle with the low exponent. It may therefore be desirable to choose more than one point if comparisons are to be made. There are no significant differences between the stiffness constant values at 75 kph and 120 kph (Wilcoxon, $p>0.35$).

The force at the steering wheel at 5 degrees of steering angle is shown in Table 10.3 for all vehicles. The force at 5 degrees steering angle is significantly higher at 120 kph than 75 kph (Wilcoxon, $p<0.03$), which suggests that there is a speed dependency in the steering feedback.

10.6 Conclusions

This chapter has shown that a power law function is a good first estimate of low-g swept steer steering data.

Analysis of the exponent, *n*, can provide information about the linearity or growth of sensation of the steering stiffness profile, analysis of the stiffness constant, *k*, is more difficult due to its dependence on the exponent, *n*.

The power law exponents obtained from vehicles ranged from 0.31 to 0.45 for 75 kph data, and 0.36 to 0.55 for 120 kph.

PART 4: CONCLUSIONS

Chapter 11 Conclusions and further work

Part 4 is a summary of the experimental work conducted in this thesis, along with details of further work that could be conducted to expand on the work that has been presented in the preceding chapters.

Chapter 11. Conclusions and further work

This thesis has investigated driver perception of the steady-state characteristics at the steering wheel using psychophysical techniques, as outlined in Part 2 and Part 3. Headline conclusions may be found in Table 11.1.

This final chapter considers the major findings and results from the review chapter (Chapter 2), and the chapters in Part 2 and Part 3, before making recommendations for further work.

11.1 Summary of main findings and results

11.1.1 Summary of Part 1 (Chapter 2)

The literature review in Chapter 2 shows that humans can perceive forces from the signals sent from tendon organs in the body, and also from the signals sent from the brain to create movement. Positions and movements could be perceived from signals sent to the brain from receptors in the body such as muscle spindles, cutaneous mechanoreceptors and joint receptors.

Other mechanical stimuli, such as stiffness, viscosity and inertia are not thought to have specific receptors in the human body. Instead, it is thought that humans integrate force, position and movement signals in the brain to develop a sense of stiffness, viscosity or inertia. Considering these findings, it was decided to investigate steering wheel force and steering wheel angle in Part 2 to determine the steady-state perception of stimuli received through the steering wheel.

11.1.2 Summary of Part 2: Perception of steering wheel force and steering wheel angle

Chapter 5 investigated the difference thresholds of steering wheel force and steering wheel angle, determined at a 79.4% correct response rate. The threshold for steering wheel force was determined as 15%, and the threshold for steering wheel angle was determined as 14%. This suggests that there is no fundamental difference in the accuracy of judging steering wheel force and steering wheel angle.

Chapter 6 investigated the growth in sensation experienced by participants, and found that sensation of steering wheel force could be scaled with an exponent of 1.39, and steering wheel angle with an exponent of 0.93.

This means that the perception of growth of force is a lot faster than the growth of actual force, with a doubling of force being perceived as a 162% increase in perceived force. Steering wheel angle sensation grows at a slower rate than the actual angle. A doubling of steering wheel angle will be perceived as a 91% growth in perceived angle.

Table 11.1: Thesis conclusions

Headline Conclusions	
Part 2	Perception of steering wheel force and steering wheel angle
Chapter 4	Force is more intuitive at the steering wheel than torque Angle Is more intuitive at the steering wheel than displacement
Chapter 5	The difference threshold for steering wheel force is 15% for an 80% correct detection rate The difference threshold for steering wheel angle is 14% for an 80% correct detection rate
Chapter 6	If modelled as a power law, perceived force grows as actual force with an exponent of 1.39 (doubling of actual force will give rise to 162% increase in the perception of force) If modelled as a power law, perceived angle grows as actual angle with an exponent of 0.93 (doubling of actual angle will give rise to a 91% increase in the perception of angle)
Part 3	Perception of steering wheel stiffness
Chapter 7	20% change in the work done by the participant is required in order for two stiffness profiles to be discriminated with an 80% correct detection rate
Chapter 8	If modelled as a power law, where perceived stiffness is equivalent to Hookes law, a linear stiffness can be described with an exponent of between 0.63 and 0.8
Chapter 9	When asked to choose a preferred stiffness profile from a set preferred stiffness had an exponent of 0.5 Free manipulation of the stiffness profile reveals a preferred stiffness with an exponent of 0.49
Chapter 10	Analysis of seven vehicles shows that a power law is a good first estimate of the stiffness profile at the steering wheel where the power law exponents ranged from 0.31 to 0.55

11.1.3 Summary of Part 3: Perception of steering wheel stiffness

Part 2 considered the perception of steering wheel force and steering wheel angle when presented in isolation at the steering wheel. Part 3 considered perception when they are presented together.

Stiffness profiles were modelled as a power law function in Chapter 7, where the start and end forces and angles were the same. A 20% difference in the work done by the force applied by the participant was required for participants to tell the difference between two stimuli (at a 79.4% correct response rate).

The perception of linear stiffness was investigated in Chapter 8. Using the method of paired comparisons, an exponent of 0.8 was chosen as the 'most linear' stimuli, followed by 0.63, 0.5, 1, 0.4, 1.25 then 0.315. It is interesting to note that a stimulus that is physically linear was not perceived as linear, and was only fourth on the list.

Chapter 9 investigated preferred steering stiffness profiles using a context of 50 mph country road driving. Using the same technique as Chapter 8, an exponent of 0.5 is preferred, followed by 0.63, 0.315, 0.4, 0.8, 0.25 and 1. Another experiment in Chapter 9, which does not make the assumption of a power law, participants data are well fitted by a power law, and the average exponent obtained by participants for their preferred feel is $n = 0.49$.

The data from both experiments in Chapter 9 suggests that linear feel and preferred feel are different. There is also evidence that participants have different preferences.

Real vehicle data was analysed in Chapter 10. Low-g swept steer tests for a number of vehicles was analysed, and show that a power law is a good first estimate of the force and angle data. The exponents determined from a variety of vehicles were between $n = 0.31$ to 0.55. Low-g swept steer data is collected at both 75 kph and 120 kph. Analysis showed that there seemed to be a correlation between the exponent, n, and vehicle speed suggesting that vehicles has a higher exponent, n, at higher vehicle speeds.

11.2 Conclusions and implications for vehicle dynamics

The research conducted in Part 2 and Part 3 goes some way to quantify driver perception of steering wheel force, angle and stiffness. Whilst individual experiments have their own conclusions, it is now worth considering the work in Part 2 and Part 3 together.

11.2.1 Sensitivity

The investigations into human sensitivity in Part 2 and Part 3 show that humans are relatively inaccurate at making judgments about changes in steering wheel force, angle and stiffness if compared to the human perception of other stimuli. This inaccuracy will allow vehicle engineers to allow a certain amount of error between sequential turns of the steering wheel without the driver noticing. For instance, the Land Rover Freelander (L359) analysed in Chapter 10 had a relatively large difference in power law exponent for steering wheel stiffness for right and left hand turns. The sensitivity investigations suggest that the difference between the two will not be noticed most of the time. However, the data shown for the Land Rover Freelander (L359) was on a pre production vehicle that was picked up by expert assessors as having substandard feel which was later rectified before production.

It is therefore possible for asymmetries in a vehicle's design to occur, or be designed in without the customer noticing, but they cannot be too large.

11.2.2 The power law

A consistent finding from the scaling studies was that perception of steady-state stimuli at the steering wheel is not linear, at least not in an engineering sense with SI units.

The power law form has been used extensively to describe perceptual data throughout the experiments in Part 2 and Part 3.

The power law form was originally used to scale the perceptual data for steering wheel force and angle according to Stevens' power law in Chapter 6. An adaptation to the classical formation of Stevens' power law was considered in Chapter 8 to predict a linear perception when two sensations (steering wheel force and steering wheel angle) were presented simultaneously. The prediction for a linear growth of force and angle (or linear stiffness) took a power law form, and was consistent with the experimental data.

The consequence of the power law form of linear stiffness is that if a power law exponent, n, is less than the linear exponent (i.e. $n < 0.67$), participants will feel that the force grows too quickly initially compared to angle (or that angle does not grow enough compared to force), and conversely if the stiffness exponent is more than the linear exponent (i.e. $n > 0.67$), participants will feel that the force does not grow fast enough compared to angle initially (or that angle grows too much compared to force).

Engineers place great importance on linearity in tuning work due to the assumption that a linear system will be predictable to the driver (e.g. the characteristic within one range will lead to an expectation for the characteristic in another range). Despite this, a conclusion that can be drawn from Chapter 8 and Chapter 9 is that linear feel and preferred feel are not the same subjectively. This may be because their assumption is fundamentally flawed and linearity is no more predictable that a perceptively non-linear stimulus, or it may be possible that when engineers talk of linearity, they are referring to linear force build up with lateral acceleration, angle build up with lateral acceleration, or linearity between some other combination of vehicle feedback. It might be interesting to investigate the perception of the feedback of vehicle response available to the driver through other sensations (for instance the sensation of lateral acceleration or yaw rate) in the future, and determine if there is a linear feel between haptic feedback and other feedback sensations.

The power law descriptions in this thesis are taken from psychophysical literature, and are thought to describe many sensations. It could just be a happy coincidence that a power law seems to fit the steering stiffness functions of real vehicles well due to the properties of the tyres, suspension and steering system, or the real world data may be a result of a large tuning effort by steering experts who perceive the system in terms of power laws.

A power law might be a good description of other vehicle response data, such as lateral acceleration, and yaw, particularly if there are receptors in the body that respond to the stimulus under consideration. For instance, if it were possible to scale lateral acceleration sensation using a power law, then it should be possible to scale lateral acceleration and force data, or lateral acceleration and angle data with the resultant linear build up predicted as a power law exponent. Analysing objective data in power law form might also go some way to solve some of the vehicle manoeuvre time history problems that Sharp (2000) highlighted, as a power law may describe the response of the vehicle more completely than arbitrary points chosen from the time history.

11.2.3 Limitations of the experimental studies

The perception experiments in Part 2 and Part 3 all have the same implicit assumption that the results from a laboratory study will remain valid when the stimuli are presented in a vehicle. This might not be the case as driving a car introduces a number of stimuli that could influence perception of steering wheel force, steering wheel angle and steering wheel stiffness.

For instance, fatigue and vibration are known to affect the function of the muscle spindles, which are implicated in both the perception of force, and movements of the hand and arm. Both fatigue and vibration are present when driving in a car, fatigue due to long journeys, and vibration transmitted to the drivers through the seat, floor pan, pedals, and also through the steering wheel.

Other stimuli that are present in a vehicle that were not present in the laboratory studies are auditory noise, whole body movements, visual scene, and the driver may also take up a different hand position, or use just one hand rather than two. These factors could all have an influence on the perception of steering feel, and should all be investigated.

Another limitation that applies to all of the perception studies is the way in which the stimulus was applied. Sensitivity measurements were taken as the ability of the participant to distinguish between two sequential movements of the steering wheel. Scaling, linearity and preferred feel were also measured by comparing two sequential turns of the steering wheel. This means that the results presented here are only relevant to sequential turns of the wheel. Further investigation would be required to determine perception changes if participants are exposed to different steering situations, such as double apex corners, or a smooth slalom passing through centre. The velocity of the steering wheel turn was not considered as an independent variable in any of the perception experiments. It is possible that the steering velocity may alter the perception of steering feel even for slow movements at the steering wheel.

The results summarised in Section 11.1 were based on median or averaged results from many participants. It is possible that there are individual differences between the participants, however these differences will be lost in the averaging process. In order to identify differences amongst individuals, each individual would have to undergo testing. A description of the intra- and inter-subject variability is detailed in Appendix E.

11.3 Further work

The further work section has been split into two: a further laboratory based segment, and a segment outlining the steps to take the laboratory based studies further towards real vehicle testing.

11.3.1 Further laboratory based studies

The experiments outlined in this thesis are just a small step towards a full understanding of driver perception of steering feel, and more broadly the generic feel of a vehicle. Some avenues of investigation have already been mentioned previously in this chapter, but for clarity they are listed here.

11.3.1.1. Investigation of individual differences

The experiments detailed in this thesis have used psychophysical methods to quantify steering feel by using group data. Any individual differences that may be in the data are lost when the results report the median or average over all participants. In order to test this much more data needs to be collected for each individual and analysed to test if there are significant differences between the individuals.

There may be age related differences in perception related to the degradation in the ability to detect and perceive stimuli as aging process occurs, and there also might be differences due to participant preference. If there is evidence that there are differences in steering wheel angle and steering wheel force perception, or evidence that individual preferences exist that are not due to adaptive reasons (for instance due to the car they normally drive), then it would suggest that vehicle manufacturers should consider offering different 'steering feel' modes in their vehicles.

11.3.1.2. Haptic perception in the presence of other vehicle stimuli.

The immediate practical application of the work in this thesis is dependent on the perception of steering wheel force, angle and stiffness being independent of the additional stimuli available in a vehicle. Chapter 10 suggests that data collected in a real vehicle does approximate the perception data from perception studies, but it is possible that the presence of vibration and body motion and acceleration may change haptic perception.

In a vehicle, it can be necessary to use the steering wheel for other purposes other than directional control. For instance, the wheel will sometimes be used to support the upper body in cornering.

Other aspects that could also be considered include the effect of haptic perception at the steering wheel when the driver uses different hand postures. For instance steering using one hand, or holding the wheel at the top or bottom could be investigated as well as the influence of different steering wheel grips and materials.

11.3.1.3. Relationship of haptic steering feel with vehicle response

As outlined in Section 11.3.2, the presence of additional stimuli in a vehicle may have an effect on the perception of steering wheel force, angle, and stiffness. It is also possible that some of the additional stimuli give the driver feedback on the lateral movement of the vehicle (for example, lateral acceleration), which could be used in combination with the feedback at the steering wheel in the brain.

The way that these stimuli combine is not known, however, if it is possible to apply a power law function to the growth of sensation of lateral acceleration it might be possible to combine the power law exponents obtained for steering wheel force and steering wheel angle to predict a linear feel between these variables.

11.3.1.4. Dynamic aspects of steering feel – the role of damping and inertia

Dynamic aspects of steering feel have not been investigated in this thesis. The literature review in Chapter 2 suggests that damping and inertia will not be perceived directly by humans (as they do not have specific receptors in the body to sense these stimuli), however, damping in the steering system will create hysteresis in the steering stiffness profile, and inertia will create an initial resistance to motion. The influence of these parameters on steering feel should be investigated.

11.3.2 Step by step studies to extend laboratory based results to real vehicle testing

A fundamental limitation of laboratory-based studies is how to prove they are still valid in the real environment. This section outlines some of the additional steps that could be taken to investigate haptic perception of driving a vehicle all the way to real vehicle testing.

11.3.2.1. Simulator studies

Simulator studies may allow the introduction of one or many different additional stimuli that would be present in a real vehicle. For instance, the visual scene could be included using a projection, and interaction between the driver and the road could be added by using a computer to render a path according to the input the driver makes at the steering wheel.
By introducing additional stimuli one at a time, it would be possible to test the haptic perception whilst various other stimuli are present. For instance, the experiments of Chapter 9 could be repeated but instead of having to set the context beforehand as in the preference studies of Chapter 9, the participant would 'drive' the context and eliminating the need for them to imagine the driving scenario.
Simulator studies are a step forward, but are limited in the degree of immersion the simulator can provide, with varying levels of immersion depending on the type of simulator – from a desktop steering wheel linked to a computer console, through to six axis motion simulators.

11.3.2.2. Proving ground testing

To immerse the participant more fully in the environment of driving a vehicle, proving ground testing could be conducted allowing the real vehicle to be represented. Specified test routes could be driven by each participant in order to provide their response to specific questions. For instance, the experiments of Chapter 9 and the real vehicles of Chapter 10 could be combined to obtain haptic perception data for specific manoeuvres in real vehicles.
Care would need to be taken to assess if other factors were causing an effect. For example, if several different vehicles were to be used during the assessments, the perception of brand or preconceptions may influence the judgement given.
Proving ground tests will fully immerse the participant in the environment, although the manoeuvres conducted may not be representative of the way participants drive their own vehicles.

11.3.2.3. Real vehicle studies

The last stage of testing in terms of realism is actual driving in a car. Without specified paths to follow, the participant can be free to drive a real vehicle in whatever way is most natural to them.

With the added benefit of realism of the task and vehicle comes the complication of what questions to ask, and how to gather reliable and repeatable data. Much care and attention will be need to gather data about the haptic perception of the vehicle, but the data will be the most valid for the driving task of that person.

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Appendix A. Classical threshold measurement methods (adapted from Gescheider (1997))

Many classical techniques can be used to determine absolute or difference thresholds. Whilst thresholds are often reported by a single fraction (or percentage), it is important to note the statistical foundations of this number. Biological systems are not fixed, but are variable in their reaction, so a participant may respond in a different way when the stimulus is presented several times. Because of this, it is not possible to report a threshold value below which detection or discrimination never occurs. Rather in the classical methods outlined below, the absolute threshold is defined as the stimulus value that is perceptible in 50% of trials, and the difference threshold is defined as the stimulus value that is perceptible at $p = 0.25$ for the lower limit, and $p = 0.75$ for the upper limit.

A.1 Method of constant stimuli

Absolute threshold measurement

The method of constant stimuli involves repeated presentations of the same set of stimuli (usually between 5 and 9 values) throughout an experiment and participants are asked whether they can detect the stimulus (Yes|No). The 50% threshold should be located somewhere in the range of test stimuli, with each stimulus having an associated detection probability that can be determined after testing. The detection probability can be plotted against the stimulus intensity to obtain a psychometric function (see Figure A.1).

The psychometric function can often be described as an ogive curve, which results in a linear relationship when probabilities are transformed into z values. A line of best fit may be determined from the z and stimulus intensity relationship, and where $z = 0$ (or $p = 0.5$) is determined as the threshold.

Difference threshold measurement

Here participants are asked to examine pairs of stimuli and report which stimuli produced the 'greater' sensation. The standard stimulus is kept constant whilst the comparison stimuli are changed (usually 5 to 9 comparison stimuli).

Ideally the standard and comparison stimuli should be presented together in space and time to permit optimal discriminability, but this is impossible. Either the two stimuli must be presented to the same area at different times, or different areas at the same time. Spatial and time errors can occur, so counterbalancing is used so that the reference and comparison stimuli appear in both areas, or both times. It is assumed that the counterbalancing will make any errors cancel out.

As with absolute threshold measurement using this method, the probabilities of 'greater' responses are plotted against the stimulus intensity for each test stimuli. It is assumed that when the participant cannot perceive a difference between the reference and comparison stimuli, judgements will be confused, so that the probability of choosing the reference or the

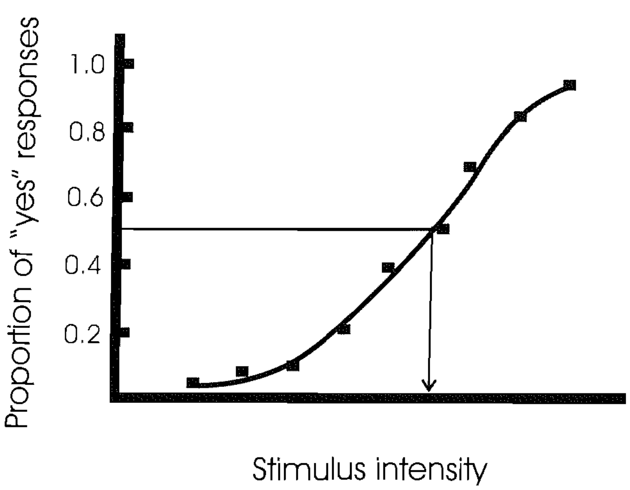

Figure A-1: Typical psychometric function obtained when the absolute threshold is measured by the method of constant stimuli. An ogive curve has been fitted to the points. The threshold is the stimulus intensity that would be detected 50% of the time (figure taken from Gescheider (1997))

comparison as 'greater' is equal (i.e. $p \approx 0.5$). The stimulus magnitude associated with p=0.5 would be expected to correspond to the standard stimulus value, although in practice it can be different. This difference is often described as a 'constant error', and is thought to reflect the influence of uncontrolled factors on the measurement.

A probability or p value of 0 or 1 indicate perfect discrimination of the stimuli, so portions of 0.25 and 0.75 are typically used to find the difference threshold, sometimes the average of the stimulus magnitude at probabilities of 0.25 and 0.75 is taken to give one value for the difference threshold.

If the test does not happen to use stimuli whose probabilities are 0.25 and 0.75 exactly, they can be estimated from the psychometric function.

A.2 Method of limits

The method of limits is probably the most frequently used method to determine thresholds. It is less precise than the method of constant stimuli, but is much less time consuming.

Absolute threshold measurement

The test stimulus is started either well above or below the threshold, and the participant is asked whether they perceive a stimulus. On descending trials, the participant should start by reporting 'yes' with the trial run stopping when the participant changes their response to 'no'. On ascending trials, the participant should start by reporting 'no' with the trial run stopping when the participant changes their response to 'yes' (see Table A.1). The point at which the response changes is an estimate of the threshold.

Usually a number of ascending and descending trials are taken for each participant, with the threshold determined by the average transition point.

Table A-1: Determination of the absolute threshold for hearing by the method of limits. Mean threshold value is 4.1dB (from Gescheider (1997)

Stimulus Intensity (dB)	A	D	A	D	A	D	A	D	A	D
10						Y				
9		Y				Y				Y
8		Y				Y				Y
7		Y		Y		Y				Y
6		Y		Y	Y	Y		Y		Y
5	Y	Y		Y	N	Y	Y	Y		Y
4	N	Y	Y	N	N	N	N	Y	Y	N
3	N	N	N		N		N	Y	N	
2	N		N		N		N	N	N	
1	N		N		N		N		N	
0	N		N				N		N	
-1	N		N				N			
-2	N						N			
-3	N						N			
-4	N									
-5	N									
-6	N									
-7	N									
-8	N									
-9	N									
-10	N									

Errors can occur in the determination of the transition point through participant habituation or expectation. In order to minimise these errors, training and instructions may be required.

Difference threshold measurement

Standard and comparison stimuli are presented in pairs and the participant reports 'greater', 'equal', or 'less' in response to the presentation of each pair. Starting lower (or higher) than the standard stimulus, the comparison stimulus is increased (or decreased) so that judgements go through two transition points: 'less' to 'equal', and 'equal' to 'greater'. A number of ascending and descending trials are conducted and all the 'less' to 'equal' transitions are averaged to provide a lower limit, and 'equal' to 'greater' transitions are averaged to provide an upper limit.

Variations on the method of limits

There are a number of variations that can be made to the method of limits:

Up-and-down or Staircase method:

Instead of making a discrete number of ascending and descending trail runs, only one ‘run’ is conducted, but instead of terminating the run when the judgement changes, the direction of the comparison stimulus change is reversed creating a ‘zigzag’ of comparison stimulus magnitudes over time. The trial ends once a specific number of transition points or direction changes have occurred. The threshold is taken as the average of the transition points.

Threshold tracking method:

This technique is much like the up-and-down method, but instead of using 'steps', the test or comparison stimulus is continuously variable. The test ends once a desired period of stability is obtained.

Forced-choice methods:

The participant chooses between several specified observations, and has to report if they see a stimulus or not. The performance level can be specified (e.g. two correct responses in a row). Forced choice methods eliminate response bias and force the participant to choose between observations containing a stimulus and others that don't.

A.3 Method of Adjustment

The method of adjustment is primarily used to determine difference thresholds, but it can also be used to measure absolute sensitivity.

Absolute threshold measurement

The test begins with the stimuli far below or above threshold, and the participant is asked to increase or decrease the stimuli until it is just perceptible.

A large number of ascending and descending trials are required, and the absolute threshold is taken as the average of these. To prevent expectation and habituation, random starting points can be used.

Difference threshold measurement

The participant is required to adjust a comparison stimulus until is seems equal to the standard (this method is sometimes referred to as the 'method of average error'). After a number of trials are complete, the data should approximate a normal distribution (although transformations may be necessary e.g. lognormal). The threshold is described using the standard deviation. Frequency distributions with high central tendency indicate good discrimination.

Appendix B. Methods of the theory of signal detection

Adapted from Gescheider (1997).

Table B-1: Theory of signal detection methods

Procedure	**Description**
The yes-no procedure	The yes-no procedure consists of a long series of trials where the participant must judge the presence or absence of a signal. Some proportion of the trials is from the signal plus noise distribution, and the remaining proportion comes from the noise distribution. This will enable one point on the receiver operating characteristic curve to be plotted. Additional points of the receiver operating characteristic curve can be determined by altering the signal probability or payoff conditions.
The forced choice procedure	The forced choice procedure measures sensitivity uncontaminated by fluctuations in the criterion. Two or more observation intervals are presented, and the participant must report which interval contained the signal. The participant must choose one interval, with the assumption being that the participant will choose the interval with the largest sensory observation. As the participant **must** select one interval, the criterion does not affect the judgement. The probability of correct responses can therefore be used as a direct measure of sensitivity.
Confidence rating procedure	This procedure allows more than one point along the receiver operating characteristic curve to be determined in the same experiment by having the participant rate the confidence of each yes-no judgement. Instead of changing the signal probability or the payoff contingency, the hit and false alarm rates for each category are used to construct a receiver operating characteristic curve.
The same-different procedure	Here the participant must respond whether the stimuli are the same or different. This procedure tests the ability of the participant to discriminate signal a from signal b. There are 4 signal combinations that may be used for presentation: (SaSa), (SbSb), (SaSb), (SbSa). This procedure is especially useful when the relevant stimuli cues are not known.
The oddity procedure	This method is used to discriminate between stimuli. 3 or more stimuli contain the stimuli whilst an additional 4th interval contains an odd stimulus. The participant must pick the odd stimuli.

There are a number of procedures (see Table B-1) that have been designed to give response proportions that can easily be converted into theoretical constructs of sensitivity, criterion, distribution variation, and distribution shape.

All of the techniques described above observe the sensitivity as the dependent variable while the independent variable is manipulated (signal intensity).

Another way to measure sensitivity is to change the detectability and measure signal intensity, which are called adaptive methods, and are shown in Table B-2. This also has the advantage of ensuring successful outcomes in experiments.

Table B-2: Adaptive methods

Procedure	**Description**
Forced-choice tracking	Here the next comparison or stimuli is determined by the participant's response (and whether it was correct or incorrect).
Up-down transformed response (UDTR) method	Developed by Wetherill and Levitt (1965), the performance levels are set and the threshold is tracked. Step size and initial start point are important to choose wisely.
Parameter estimation by sequential testing (PEST)	This method is like UDTR, but the step size starts large, and then gets smaller as the threshold is approached.
Maximum likelihood methods	A statistical estimation of the participant's threshold determines the next step size, and direction.

Appendix C. Line length practice

C.1 Introduction

In order to prepare subjects to participate in the scaling experiment, they were given a number of magnitude estimation and magnitude production tasks to complete based on the length of a line. The results from this practice are presented here.

For magnitude estimation, participants were required to estimate the length of a 'test' line in relation to a 'reference' line, which was given the value 100.

For magnitude production, participants were required to produce a line according to a 'test' number in relation to a 'reference' line, which was given the value 100.

It is widely reported that the sensory experience of a line length is directly proportional to the actual length, so a power function with exponent equal to 1 is expected.

It is also widely known that the techniques of magnitude estimation and magnitude production are biased due to a regression effect (a tendency for the participant to shorten the range of whichever variable he is allowed to adjust) causes magnitude production to yield a steeper slope than magnitude estimation.

Twelve participants participated in this experiment, and their results are in Figure C-1, Figure C-2, and Figure C-3.

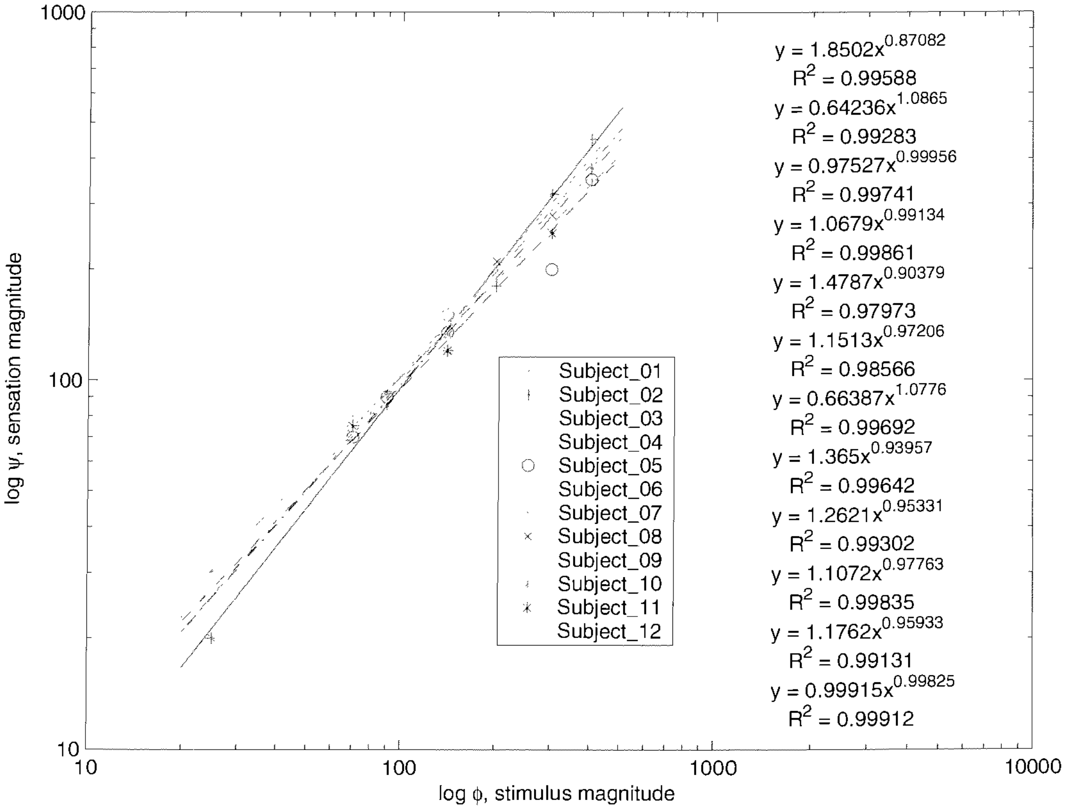

Figure C-1: Magnitude estimation line length practice

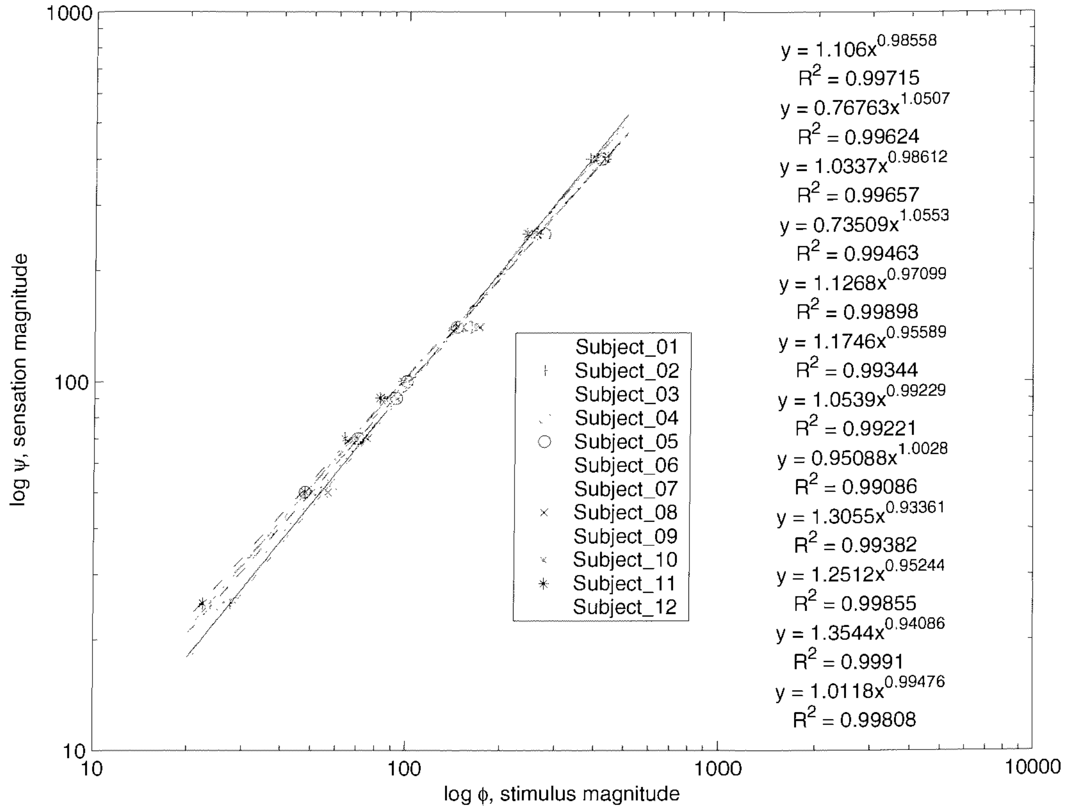

Figure C-2: Magnitude production line length practice

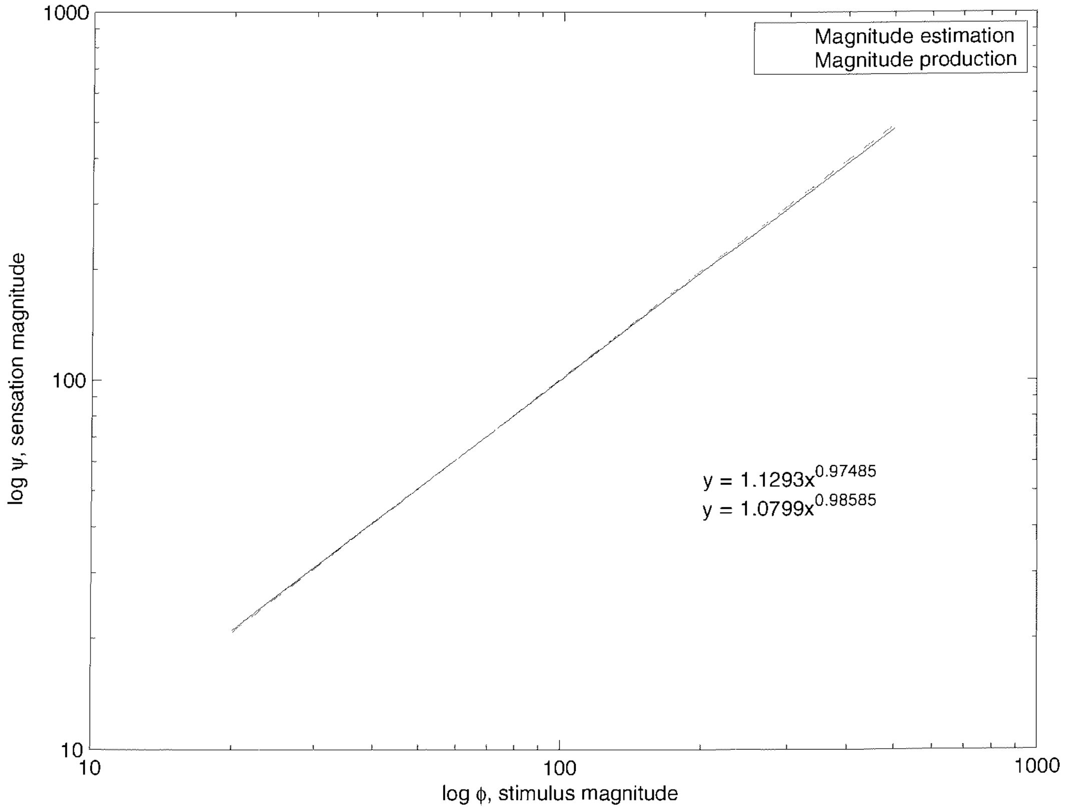

Figure C-3: Median data for line length practice

Appendix D. Accuracy of regression

D.1 Introduction:

Chapter 3 outlines the rig's capabilities. The aim of this chapter is to assess the implications of the rig's limitations on analysis. This chapter also looks at the accuracy of the data collected in real vehicles.

A major aspect of Chapter 10 is the analysis of real vehicle data by fitting power law functions to the data. This chapter looks at what influence the errors in measured data would have on the power law function.

Motor rig accuracy:

Chapter 3 details the motor rig, and the measurement accuracy. The torque cell is accurate to 0.01N·m, or 0.05 N (with the standard wheel diameter of 381mm). The angle cell is accurate to 0.1 of a degree.

If a typical stiffness profile is analysed with function:

$$F = 2.11\theta^{0.5} \tag{D.1}$$

and add an error of 0.05 N and 0.1 ° to the function.

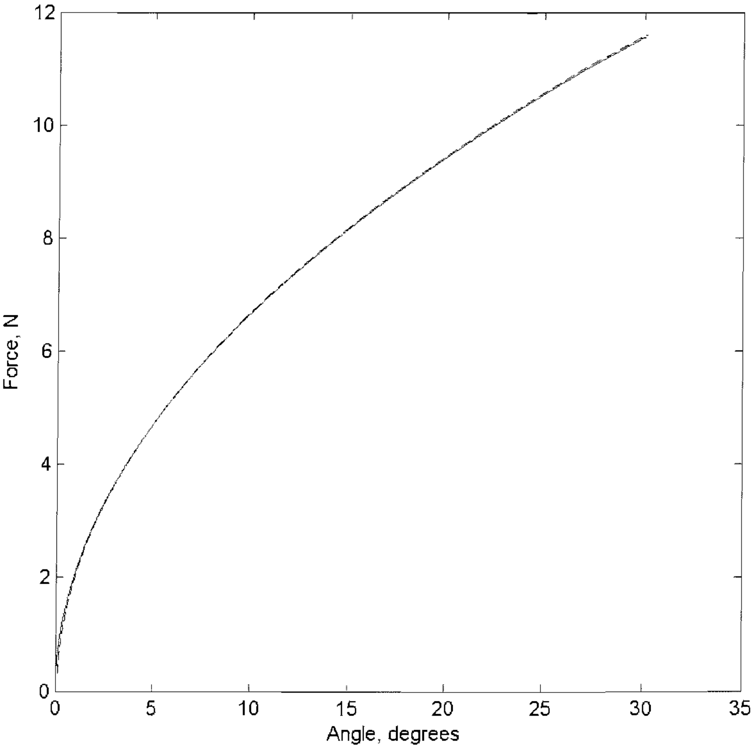

Figure D-1: Linear abscissa and ordinate

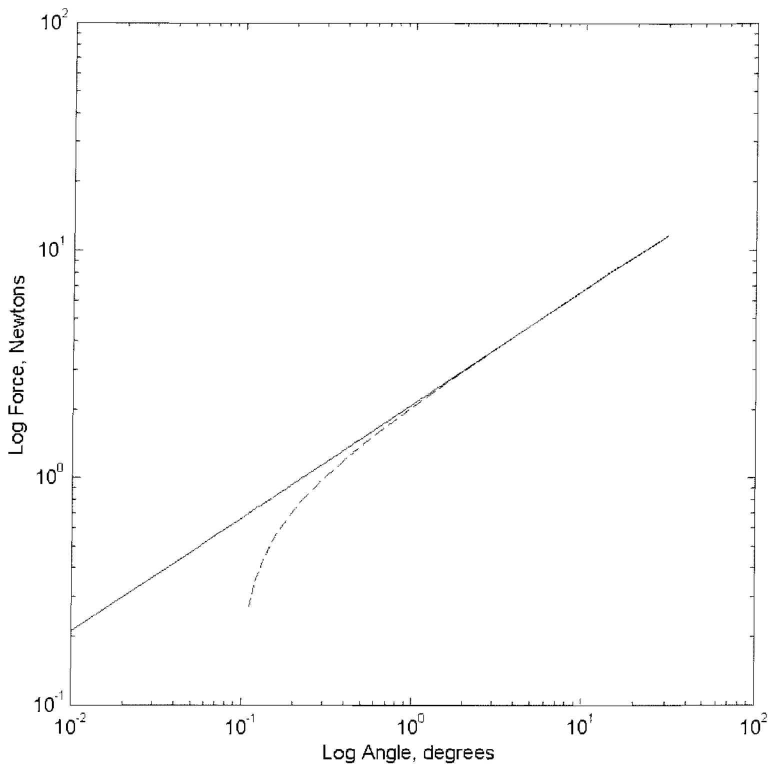

Figure D-2: Logarithmic abscissa and ordinate

Figure D-1 and Figure D-2 show that the error has minimal effect on the linear-linear function, but there is an effect on the logarithmic-logarithmic presentation. The function, which should be a straight-line in logarithmic axes, appears as a straight line at higher magnitudes, but bends towards the abscissa at low magnitudes.

In order to achieve the correct fit from empirical data, it may be necessary to disregard low magnitudes from the analysis. In this case, angles below 3 degrees would need to be disregarded to accurately assess the data.

Objective vehicle accuracy

Real vehicle data is collected with Datron wheel (the specification sheet can be found here: http://www.corrsys-datron.com/Support/Data_Sheets/Datasheets-Sensors/cds-d_MSW_e.pdf). The angle encoder has an accuracy of 0.09 °, however, the torque resolution is not mentioned. As the transducer technology is much the same as the motor rig, it can be assumed that the same approximate errors might exist in real world data.

Recommendation

In order to prevent the errors that are measured on the rig affecting the power law regression, it is recommended that the first 3 degrees of data be disregarded from the analysis.

Appendix E. Intra and Inter-subject variability

The use of human judgements as a measurement of sensation can be influenced by a variety of factors that are commonly classified into two groups: intra-subject variability and inter-subject variability.

In any psychophysical experiment, some participants may respond in a slightly different way than other participants. This variability is called inter-subject variability and it might be caused by recognisable characteristics of the participant (such as age, gender, strength etc.), by the conditions of the experiment (for example, participant 1 may receive a different condition than participant 2 first), or it might be unexplained (random variation).

In the matching task in Chapter 4, correlation coefficients between a reference stimuli and test stimuli were obtained to determine which transformation of the data gave the better correlation. A Wilcoxon matched-pairs signed ranks test was used to determine a significant result, however, inspection of the data in Table 4.2 shows that some participants did not have as strong a result than others. Whilst the correlation coefficients were generally higher for force and angle than torque and displacement, the difference between the respective correlation coefficients varied a lot. Some participants had hardly any difference between their correlation coefficients (for example, participant 6), which indicates that they were matching torque and force equally well (or equally badly), whereas some participants had a much larger difference between their correlation coefficients (for example, participant 3). This could suggest that different participants actually had a different matching procedure, despite the group statistics that indicate that there is a significantly higher correlation coefficient for force and angle rather than torque or displacement for the perceptual matching task.

Difference thresholds were investigated in both Chapter 5 and Chapter 7 and analysed using averaging techniques. Median difference threshold and interquartile ranges were reported and show that there is some variability in the data. It is possible that some participants were more sensitive than others, responding to changes in the stimuli faster and at smaller magnitudes than others. This could be of great importance to the application of this work to steering feel. If a certain part of the population are more sensitive to these stimuli and are part of the target audience of Jaguar's products, then those products must be designed with their sensitivity in mind. There was no evidence from the sensitivity studies in this thesis that a characteristic of the participant (for example, age, height etc.) affected our result, but in a fairly small study, these influences may not be significant.

Psychophysical scaling was used in Chapter 6, and analysed, according to Stevens' instructions, by taking a median of the participants data, applying a line of best fit to logarithmic data, and taking the geometric mean between magnitude estimation and magnitude production techniques. This analysis takes any inter-subject variability away from the data. To test for inter-subject variability, enough data from each participant must be collected so that there are high correlation coefficients between the physical magnitudes and perceived magnitudes just for that participant. If an inter-subject variability could be found in the scaling of perceived force and perceived angle, it might suggest that vehicle manufacturers should consider giving drivers the option of several 'steering feels' so that they might choose the one that aligns with their perception, or even that the steering feel should be customised in some way (although the sensitivity studies in Chapter 5 and Chapter 7 would suggest that even if there were recognisable differences in participants scaling of steering feel, they would not be able to detect the difference between two fairly dissimilar 'feels' at the steering wheel). It is also possible that differences may exist in the scaling judgements of individuals because of the way the individual uses numbers. To a certain extent, this difference could be accounted for by assessing the way participants assign numbers to line length examples (see Appendix C).

A different form of psychophysical scaling (Thurstone's law of comparative judgement) was used in Chapter 8 and Chapter 9 to scale linear feel, and preferred feel. While the consistency and inter-subject agreement were tested for significance, there may be disagreement between participants that would only be revealed by a much larger experiment. It is possible that different participants perceived linear feel and preferred feel differently to others, and if this were the case, there would be further evidence to allow a user selected or defined feel in all vehicles.

Intra-subject variability is concerned with the differences in judgement expressed by the same participant, and could be assessed over time (for example the same test could be conducted at 1 week, 1 month, and 1 year intervals).

None of the experiments conducted in this thesis contain enough data from individuals to test if judgements changed over time, so it is not possible to rule out the prospect of shifting perception of steering feel. If further work proved that perception of steering feel parameters is not fixed within a driver, the implication on steering system design would be that some people may not like a particular steering feel to start with, but may come to like it over time. If this were the case, the way in which vehicles are sold should be optimised so that the driver will like the steering feel when they make the decision to buy the car. It might also be possible that practice with a new steering system is required before a driver will like the steering feel in a vehicle.

Appendix F. Individual data

Individual data from the experiments are presented here.

F.1 Raw data from Chapter 4: Perceptual terminology

Table F-1: Reference and test magnitudes for Participant 1

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.96	4.39	14.36	14.60	0.97	0.74	3.48	7.19
3.01	3.04	14.59	14.73	1.02	1.94	3.69	7.01
2.90	3.27	14.05	5.85	1.02	1.42	3.69	7.48
3.02	4.48	10.03	14.88	0.97	1.29	5.09	6.75
3.02	2.68	10.03	4.80	0.96	0.76	5.03	7.38
2.90	4.44	9.66	21.51	0.96	2.51	5.06	9.03
2.90	2.63	5.18	4.70	0.96	1.28	9.39	12.52
2.95	3.83	5.27	12.74	1.00	2.62	9.77	13.73
2.92	2.50	5.22	12.11	0.98	4.83	9.60	17.41
3.05	3.64	14.77	17.65	1.05	1.98	3.77	19.35
2.98	3.17	14.46	10.53	1.03	3.42	3.72	12.34
3.08	2.27	14.94	4.05	1.04	3.52	3.73	18.50
3.00	2.80	9.97	5.00	1.03	3.56	5.43	18.71
2.99	3.27	9.95	15.84	1.01	2.45	5.32	23.90
2.94	3.53	9.78	11.73	0.98	3.30	5.16	11.88
2.85	4.71	5.09	22.79	0.99	1.04	9.62	10.12
3.03	3.68	5.41	6.57	1.01	3.96	9.82	20.79
3.10	5.20	5.54	17.30	1.02	6.86	9.94	24.70
9.06	8.94	43.89	29.72	3.05	1.62	10.98	15.83
9.21	9.68	44.61	46.89	3.09	3.68	11.13	13.25
9.10	6.43	44.09	11.49	3.03	2.77	10.93	14.54
8.93	10.51	29.69	34.94	2.94	3.39	15.46	17.79
8.85	5.70	29.42	10.19	3.05	1.79	16.03	17.46
8.56	8.47	28.46	41.02	2.91	5.10	15.25	18.38
9.17	11.75	16.38	20.99	2.87	3.43	28.04	33.43
9.44	11.73	16.87	38.99	2.98	6.62	29.05	34.74
9.22	10.16	16.47	49.20	3.00	10.00	29.24	36.04
8.97	8.79	43.43	42.57	2.86	2.41	10.31	23.51
8.75	7.15	42.36	23.76	2.92	4.61	10.54	16.60
9.15	7.72	44.33	13.79	2.93	4.12	10.56	21.61
8.77	5.11	29.15	9.14	2.94	3.77	15.44	19.78
9.03	12.25	30.02	59.34	2.94	2.29	15.41	22.31
9.03	10.45	30.01	34.75	2.94	5.09	15.42	18.33
9.00	14.52	16.08	70.32	2.94	3.24	28.72	31.57
9.14	9.05	16.34	16.17	2.88	6.24	28.11	32.78
9.41	10.93	16.82	36.35	2.92	10.00	28.49	36.04
2.04	1.73	9.89	5.75	1.45	1.93	5.24	18.87

2.05	2.46	9.93	11.91	1.43	3.49	5.17	12.57
2.01	0.66	9.72	1.18	1.54	3.05	5.55	16.03
2.99	3.61	9.95	11.99	1.02	2.77	5.35	14.57
2.94	1.65	9.79	2.94	1.01	1.86	5.31	18.12
2.99	3.55	9.93	17.17	1.03	4.70	5.41	16.92
5.73	8.55	10.23	15.28	0.56	1.45	5.44	14.14
5.64	6.66	10.08	22.13	0.53	2.82	5.20	14.80
5.57	8.69	9.95	42.07	0.54	4.04	5.30	14.56
2.15	4.60	10.39	22.29	1.52	1.20	5.49	11.74
2.06	2.24	9.99	7.45	1.47	3.96	5.28	14.27
2.09	2.59	10.11	4.62	1.41	1.37	5.07	7.19
2.90	1.29	9.65	2.30	1.03	1.65	5.38	8.67
3.02	4.94	10.05	23.94	0.96	1.33	5.05	12.94
2.90	3.16	9.64	10.51	1.00	3.68	5.26	13.27
5.64	8.28	10.09	40.13	0.53	1.45	5.14	14.12
5.39	7.99	9.63	14.27	0.52	2.30	5.04	12.09
5.57	6.84	9.96	22.74	0.54	3.61	5.27	13.00
6.40	4.88	31.02	16.21	4.49	2.46	16.19	23.96
6.08	8.19	29.47	39.65	4.34	6.51	15.65	23.47
5.98	4.01	28.96	7.16	4.44	4.83	15.99	25.38
8.99	9.83	29.88	32.68	2.95	3.31	15.48	17.38
8.78	6.24	29.21	11.14	3.09	2.16	16.20	21.09
8.64	10.06	28.71	48.71	2.92	7.28	15.34	26.22
17.10	19.99	30.55	35.72	1.58	2.07	15.37	20.15
17.26	19.59	30.84	65.13	1.64	4.89	15.96	25.66
17.12	30.32	30.58	146.85	1.62	4.35	15.82	15.69
6.24	6.77	30.23	32.81	4.27	2.40	15.38	23.37
5.90	5.26	28.59	17.50	4.13	5.92	14.88	21.33
6.35	3.97	30.77	7.08	4.42	3.67	15.92	19.26
9.15	6.90	30.43	12.34	2.96	3.95	15.55	20.73
8.79	8.31	29.23	40.27	3.11	1.33	16.35	12.99
9.16	8.76	30.44	29.14	2.89	5.69	15.17	20.50
17.17	28.06	30.68	135.92	1.63	2.43	15.88	23.70
17.53	17.10	31.32	30.54	1.60	3.12	15.60	16.38
17.02	16.76	30.41	55.73	1.57	6.47	15.29	23.33

Table F-2: Reference and test magnitudes for Participant 2

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.05	3.29	14.75	15.95	1.02	3.15	9.95	11.36
2.94	4.37	14.26	7.81	0.99	2.23	9.65	11.69
3.07	5.13	14.85	17.04	1.00	1.06	9.76	10.30
3.07	3.83	10.20	12.73	1.01	1.11	3.64	10.85
3.05	8.39	10.15	40.62	1.01	2.18	3.64	7.86
3.09	7.13	10.26	12.73	1.00	2.04	3.60	10.70
3.04	5.03	5.43	8.99	1.04	2.78	5.45	10.03
3.00	6.05	5.36	20.11	1.01	1.48	5.31	7.78
2.98	4.66	5.32	22.59	1.03	1.42	5.39	13.87
3.05	5.74	14.79	10.25	1.01	3.46	9.90	12.48
3.00	5.34	14.52	25.87	1.00	1.97	9.76	10.36
2.99	7.63	14.50	25.36	0.99	1.09	9.68	10.59
3.07	5.61	10.19	27.15	1.02	1.89	3.69	6.80
3.02	5.95	10.04	10.63	1.05	0.86	3.77	8.41
2.98	3.31	9.92	11.01	0.99	1.66	3.57	8.72
3.03	5.45	5.42	9.73	1.05	1.68	5.54	8.82
3.14	7.03	5.60	23.37	1.02	1.27	5.36	12.41
3.08	6.43	5.51	31.14	1.00	3.29	5.27	11.84
9.17	7.74	44.39	37.51	2.98	7.46	29.03	26.88
8.71	8.99	42.18	16.07	2.97	5.17	28.97	27.15
9.14	7.96	44.25	26.46	3.09	2.96	30.14	28.92
9.19	7.72	30.57	25.68	3.06	1.78	11.03	17.41
9.24	6.99	30.72	33.85	2.97	3.14	10.72	11.32
9.04	8.72	30.07	15.58	2.88	3.03	10.39	15.89
9.32	10.25	16.65	18.31	2.99	3.26	15.69	11.73
9.33	9.72	16.67	32.32	2.92	3.02	15.32	15.84
9.34	7.96	16.68	38.55	2.94	1.71	15.41	16.72
9.01	10.29	43.63	18.39	2.91	7.68	28.43	27.67
9.01	9.11	43.63	44.13	2.94	5.14	28.72	26.96
8.99	8.57	43.53	28.49	2.91	2.61	28.42	25.44
8.92	8.79	29.67	42.57	3.07	3.92	11.05	14.13
9.15	10.67	30.41	19.06	3.00	1.97	10.80	19.21
9.27	8.88	30.82	29.51	3.06	3.14	11.02	16.48
8.99	13.52	16.07	24.16	2.94	3.04	15.41	15.96
8.94	13.18	15.98	43.81	2.98	1.92	15.63	18.75
9.11	11.48	16.27	55.62	3.03	5.69	15.92	20.52
2.08	2.39	10.07	11.57	0.55	3.01	5.33	10.85
2.13	6.40	10.33	11.43	0.55	2.22	5.35	11.63
2.06	4.85	9.98	16.12	0.56	0.93	5.48	9.03
3.07	3.43	10.20	11.41	1.47	1.33	5.30	13.02
3.07	4.26	10.20	20.63	1.44	3.60	5.20	12.96
3.04	5.34	10.09	9.53	1.50	2.62	5.39	13.73
5.59	4.40	9.99	7.85	1.02	3.41	5.36	12.29

5.60	8.09	10.00	26.90	1.04	2.42	5.48	12.68
5.59	5.53	9.98	26.77	1.00	1.06	5.24	10.33
2.07	4.89	10.04	8.73	0.54	4.37	5.27	15.76
2.06	4.33	9.97	20.98	0.56	2.47	5.42	12.96
2.11	4.71	10.21	15.67	0.57	0.93	5.55	9.08
3.03	3.44	10.07	16.66	1.45	2.44	5.21	8.80
3.01	3.45	10.00	6.17	1.50	1.08	5.41	10.57
3.09	6.09	10.27	20.26	1.45	2.44	5.24	12.81
5.75	3.82	10.27	6.83	0.99	2.32	5.20	12.20
5.74	6.75	10.26	22.44	0.97	0.72	5.08	7.02
5.70	5.38	10.19	26.06	1.01	3.13	5.31	11.27
6.27	6.66	30.38	32.26	1.60	4.25	15.58	15.32
5.92	9.29	28.69	16.60	1.59	3.23	15.50	16.95
6.22	11.99	30.14	39.85	1.65	1.97	16.06	19.21
9.18	8.13	30.53	27.01	4.33	2.28	15.59	22.25
8.99	9.50	29.88	46.03	4.38	4.62	15.79	16.66
8.93	10.78	29.70	19.27	4.51	2.96	16.25	15.54
16.26	14.35	29.06	25.64	3.03	4.43	15.90	15.98
16.18	15.07	28.91	50.11	3.08	3.47	16.19	18.21
16.23	10.23	29.00	49.53	2.91	1.90	15.27	18.53
6.32	12.63	30.62	22.57	1.62	4.38	15.77	15.78
6.35	6.66	30.77	32.24	1.60	3.20	15.61	16.81
6.13	9.84	29.67	32.71	1.62	1.89	15.79	18.47
8.94	14.32	29.72	69.35	4.35	4.74	15.69	17.09
9.08	11.64	30.19	20.80	4.40	1.78	15.87	17.41
9.05	7.80	30.10	25.93	4.34	3.06	15.63	16.06
16.93	17.02	30.26	30.40	3.05	4.16	16.00	21.83
16.79	18.64	29.99	61.96	2.98	1.56	15.64	15.18
16.17	17.70	28.89	85.72	2.94	4.78	15.44	17.24

Table F-3: Reference and test magnitudes for Participant 3

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.04	4.05	5.44	19.63	0.98	0.92	3.54	4.83
2.92	3.05	5.22	5.44	0.95	0.96	3.42	3.48
2.97	3.92	5.31	13.03	0.98	0.36	3.55	3.52
3.10	2.35	10.30	11.38	0.95	1.87	9.26	9.84
3.05	3.95	10.14	13.14	0.94	1.95	9.19	7.03
2.91	3.53	9.66	6.31	0.96	0.84	9.32	8.24
3.07	3.74	14.85	6.68	1.01	0.57	5.28	5.52
3.03	3.61	14.69	17.50	0.98	1.63	5.14	5.88
3.05	3.90	14.77	12.97	0.99	0.97	5.19	5.07
3.06	4.01	5.46	19.41	1.01	0.89	3.64	3.19
3.06	2.91	5.47	9.66	0.98	0.90	3.55	4.70
3.03	3.67	5.42	6.55	1.01	0.48	3.62	4.64
3.06	2.60	10.19	12.62	0.95	0.87	9.29	8.47
2.94	3.05	9.77	10.14	0.95	2.24	9.28	8.06
3.07	2.11	10.20	3.77	0.96	1.72	9.34	9.05
3.06	2.95	14.82	5.28	0.99	0.72	5.18	7.03
2.93	2.70	14.19	13.06	0.99	1.52	5.19	5.47
2.92	3.34	14.14	11.09	1.01	0.84	5.28	4.40
8.78	3.81	15.68	18.47	2.86	1.49	10.30	7.84
9.14	6.96	16.33	12.43	2.93	2.48	10.56	8.94
8.75	5.12	15.64	17.04	2.91	0.86	10.49	8.44
8.92	5.21	29.67	25.21	2.85	3.37	27.79	17.68
9.18	7.24	30.51	24.07	2.86	4.12	27.87	14.84
8.93	7.95	29.68	14.21	2.84	2.42	27.74	23.57
9.28	8.22	44.96	14.68	2.88	1.48	15.10	14.46
9.25	5.12	44.82	24.81	2.91	3.10	15.30	11.17
9.18	8.02	44.46	26.66	2.84	2.44	14.92	12.81
9.12	5.21	16.30	25.21	2.86	2.67	10.29	9.64
9.29	6.67	16.60	22.19	2.87	1.83	10.35	9.63
9.00	6.17	16.09	11.02	3.01	0.79	10.83	7.70
9.34	6.79	31.05	32.86	2.85	2.56	27.81	25.01
9.38	6.77	31.19	22.50	2.88	5.05	28.07	18.21
8.81	5.76	29.29	10.29	2.87	4.40	27.99	23.08
9.30	9.09	45.02	16.23	2.91	1.45	15.27	14.12
9.36	7.46	45.34	36.13	2.92	3.56	15.31	12.84
9.38	6.47	45.44	21.52	2.91	2.81	15.28	14.77
5.32	6.65	9.50	32.20	1.41	0.98	5.08	5.16
5.57	3.72	9.96	6.64	1.41	1.56	5.09	5.63
5.54	3.73	9.89	12.42	1.45	0.94	5.24	9.22
3.01	1.95	10.02	9.44	0.52	1.04	5.08	5.44
2.95	3.08	9.80	10.23	0.53	1.96	5.13	7.05
2.98	4.41	9.92	7.88	0.54	0.59	5.22	5.76
2.09	3.05	10.11	5.45	0.98	0.61	5.16	5.96

2.07	2.30	10.01	11.15	0.99	1.31	5.22	4.71
2.09	4.68	10.14	15.55	0.96	1.26	5.05	6.62
5.50	4.69	9.82	22.72	1.48	1.17	5.35	4.21
5.52	4.57	9.86	15.19	1.44	1.20	5.20	6.30
5.59	6.90	10.00	12.33	1.49	0.63	5.38	6.12
2.99	2.63	9.95	12.72	0.52	0.39	5.09	3.83
2.97	4.79	9.88	15.92	0.53	1.10	5.19	3.96
3.08	3.88	10.24	6.94	0.51	1.13	5.02	5.94
2.12	5.07	10.28	9.06	0.95	0.40	4.99	3.86
2.05	4.05	9.94	19.62	0.97	1.26	5.08	4.54
2.13	3.98	10.31	13.24	0.99	0.85	5.18	4.44
16.72	11.84	29.87	57.33	4.13	2.87	14.87	15.07
17.04	19.03	30.44	34.00	4.17	4.15	15.04	14.94
16.55	12.55	29.57	41.73	4.20	2.08	15.12	20.30
8.95	7.63	29.76	36.95	1.56	2.31	15.25	12.14
8.83	5.28	29.35	17.55	1.55	3.00	15.09	10.81
9.01	8.36	29.97	14.94	1.57	1.23	15.31	11.99
6.14	5.23	29.75	9.34	2.90	1.58	15.23	15.45
6.29	5.88	30.48	28.47	2.91	3.23	15.28	11.63
6.05	6.01	29.32	19.97	2.88	2.78	15.14	14.61
16.97	13.03	30.31	63.09	4.26	3.62	15.36	13.03
16.97	8.00	30.32	26.60	4.19	2.16	15.09	11.36
16.64	12.16	29.72	21.73	4.19	1.63	15.08	15.86
9.21	5.55	30.62	26.89	1.56	1.30	15.24	12.66
9.32	6.27	30.99	20.85	1.57	3.60	15.34	12.98
9.14	8.90	30.40	15.91	1.55	2.72	15.16	14.27
6.41	5.54	31.06	9.90	2.92	1.11	15.31	10.78
6.22	5.68	30.11	27.50	2.93	2.70	15.37	9.74
6.33	7.19	30.65	23.91	2.95	2.58	15.48	13.56

Table F-4: Reference and test magnitudes for Participant 4

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.01	5.17	14.57	25.04	0.98	2.05	5.13	7.38
3.02	7.75	14.64	13.85	1.02	1.25	5.36	12.24
2.96	4.31	14.35	14.32	1.00	0.85	5.25	4.45
2.97	4.47	9.88	14.87	0.98	1.14	3.55	4.11
2.96	3.34	9.83	16.16	0.98	1.11	3.55	5.84
2.98	7.51	9.91	13.41	0.96	0.72	3.45	7.06
3.03	3.33	5.41	5.95	0.98	1.76	9.58	6.33
3.00	5.59	5.36	27.06	1.00	1.94	9.78	10.19
3.06	5.20	5.47	17.29	0.97	1.02	9.49	9.99
2.98	5.18	14.43	17.24	0.99	1.06	5.17	5.56
2.92	3.56	14.16	17.27	0.99	0.77	5.19	7.54
3.07	7.05	14.89	12.60	0.97	1.23	5.08	4.42
3.02	2.55	10.03	8.49	0.99	0.62	3.56	3.24
2.92	2.83	9.70	5.06	0.98	0.55	3.54	1.99
3.01	3.06	10.01	14.80	0.98	0.51	3.52	4.96
2.97	5.85	5.30	28.33	0.97	0.80	9.42	7.77
2.93	5.37	5.23	17.85	0.97	1.85	9.50	6.68
3.05	2.88	5.45	5.15	0.99	0.88	9.66	4.60
8.63	8.25	41.78	39.95	2.93	2.54	15.37	9.14
8.71	9.98	42.17	17.84	2.97	2.17	15.60	21.17
8.70	8.69	42.15	28.89	2.95	2.94	15.48	15.46
8.62	8.61	28.66	28.63	3.07	2.82	11.05	10.17
8.67	5.80	28.82	28.09	2.95	2.36	10.62	12.38
8.96	14.55	29.78	25.99	2.91	0.97	10.49	9.51
8.99	8.25	16.06	14.73	2.90	4.12	28.31	14.84
8.48	6.22	15.15	30.11	2.94	3.34	28.70	17.51
9.05	9.34	16.18	31.04	2.90	2.41	28.33	23.50
8.67	7.60	41.97	25.28	2.97	2.79	15.61	14.66
8.84	8.04	42.82	38.96	2.96	2.26	15.55	22.03
8.73	11.66	42.27	20.84	2.93	3.14	15.36	11.33
9.01	9.27	29.94	30.81	2.91	2.99	10.47	15.72
8.85	8.16	29.43	14.58	2.96	2.42	10.65	8.72
8.63	5.68	28.68	27.53	3.04	1.91	10.95	18.61
8.86	4.37	15.83	21.17	2.89	2.40	28.20	23.37
8.90	10.47	15.90	34.82	2.86	3.27	27.93	11.80
8.85	9.66	15.81	17.27	2.87	4.14	28.04	21.76
2.04	4.11	9.89	19.92	0.98	2.17	5.16	7.82
2.02	4.80	9.79	8.57	0.98	0.59	5.15	5.80
2.06	5.68	9.98	18.87	0.98	0.56	5.13	2.97
2.88	4.35	9.58	14.45	1.44	1.43	5.19	5.16
2.93	4.52	9.73	21.91	1.45	1.18	5.22	6.18
3.07	13.72	10.19	24.50	1.42	0.99	5.13	9.68
5.46	7.28	9.76	13.01	0.53	2.06	5.13	7.41

5.42	6.12	9.68	29.62	0.53	1.73	5.12	9.06
5.50	5.19	9.82	17.25	0.53	0.27	5.19	2.60
2.04	2.70	9.89	8.97	0.95	1.07	5.01	5.64
2.05	3.88	9.91	18.78	0.96	0.30	5.04	2.97
2.13	10.18	10.33	18.18	1.00	1.00	5.26	3.60
2.95	4.34	9.81	14.42	1.46	1.03	5.26	5.39
2.96	9.92	9.85	17.73	1.49	1.39	5.37	5.02
2.94	5.54	9.78	26.84	1.44	0.56	5.17	5.50
5.35	7.23	9.57	35.01	0.52	0.55	5.11	5.37
5.38	6.21	9.61	20.64	0.54	1.26	5.26	4.53
5.55	8.74	9.92	15.62	0.55	0.62	5.33	3.28
5.96	7.15	28.87	34.61	2.93	4.63	15.38	16.70
5.94	9.87	28.79	17.64	2.93	1.84	15.41	17.98
6.27	5.51	30.38	18.31	2.97	2.53	15.62	13.29
8.67	9.69	28.84	32.21	4.30	3.96	15.50	14.27
8.59	6.96	28.57	33.69	4.28	2.92	15.41	15.33
8.69	7.31	28.91	13.06	4.34	1.74	15.65	16.97
16.02	14.63	28.63	26.14	1.60	2.80	15.56	10.10
16.14	8.65	28.84	41.89	1.62	2.07	15.84	10.87
16.03	12.49	28.64	41.52	1.58	1.84	15.46	17.98
6.03	7.15	29.21	23.77	2.96	2.28	15.55	11.97
5.99	6.68	28.99	32.35	2.96	1.90	15.53	18.49
5.94	15.20	28.76	27.17	2.95	4.90	15.50	17.66
8.73	9.40	29.02	31.25	4.36	2.95	15.70	15.50
8.55	12.34	28.41	22.05	4.30	3.98	15.48	14.32
8.72	8.95	29.01	43.37	4.31	2.09	15.54	20.35
16.17	9.69	28.88	46.93	1.61	1.49	15.70	14.50
16.00	12.03	28.60	39.99	1.60	3.28	15.60	11.83
16.57	13.21	29.60	23.60	1.57	2.64	15.34	13.86

Table F-5: Reference and test magnitudes for Participant 5

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.90	2.04	9.63	9.88	0.99	1.85	9.64	9.73
2.89	3.45	9.60	6.16	0.98	1.27	9.52	12.37
3.10	2.03	10.31	6.74	0.98	3.30	9.57	11.89
2.83	3.43	13.70	11.42	0.99	0.51	3.57	4.97
2.91	5.02	14.11	8.97	1.02	1.66	3.67	8.71
2.95	3.07	14.28	14.89	0.96	1.72	3.45	6.21
3.01	3.00	5.37	14.51	0.97	1.94	5.09	7.00
3.02	2.71	5.39	4.85	1.05	1.36	5.51	13.24
2.81	3.00	5.02	9.98	0.97	1.08	5.12	5.67
2.85	4.70	9.49	8.40	0.99	2.57	9.70	9.28
3.07	2.44	10.20	11.83	0.99	2.03	9.67	10.68
3.09	2.13	10.26	7.08	1.00	0.88	9.75	8.59
3.09	2.74	14.96	13.27	0.94	0.89	3.39	4.66
2.82	2.96	13.68	5.29	0.95	1.18	3.42	4.27
2.94	3.93	14.24	13.07	0.98	0.43	3.51	4.20
3.08	4.77	5.51	15.85	0.96	0.50	5.01	4.85
2.92	2.20	5.21	10.66	0.97	1.03	5.07	5.43
3.02	3.41	5.40	6.09	0.95	0.13	5.00	0.47
9.24	4.75	30.70	23.03	2.88	6.82	28.10	35.78
8.92	6.63	29.65	11.85	3.09	4.07	30.11	39.68
8.86	5.85	29.45	19.45	3.08	9.36	30.01	33.71
9.06	11.57	43.87	38.46	2.93	3.29	10.56	32.11
9.21	6.78	44.61	12.12	2.88	2.52	10.39	13.23
9.21	8.70	44.59	42.12	2.84	3.26	10.24	11.74
9.44	4.73	16.87	22.91	3.00	3.50	15.74	12.63
8.86	9.09	15.83	16.24	3.10	2.56	16.28	25.00
9.40	7.42	16.80	24.68	2.94	3.34	15.42	17.54
8.62	7.22	28.67	12.90	2.89	3.60	28.18	12.96
9.29	5.81	30.87	28.16	2.94	3.68	28.66	19.33
8.71	8.20	28.94	27.27	2.97	2.81	28.98	27.43
8.83	9.66	42.76	46.77	2.93	2.29	10.55	12.02
9.30	8.28	45.03	14.80	3.06	3.00	11.02	10.82
9.44	10.38	45.74	34.50	2.91	1.55	10.50	15.13
8.62	6.61	15.40	21.96	2.91	2.90	15.28	28.30
8.80	6.29	15.73	30.45	2.91	4.97	15.26	26.07
9.16	11.95	16.37	21.35	3.02	2.93	15.87	10.57
3.09	2.39	10.27	11.60	0.51	1.68	5.00	8.81
2.84	4.56	9.45	8.14	0.54	0.89	5.25	8.68
3.07	3.10	10.21	10.32	0.53	1.30	5.21	4.68
1.98	3.83	9.59	12.73	1.39	1.24	5.01	12.07
2.10	7.92	10.17	14.15	1.48	0.78	5.33	4.09
1.97	3.24	9.52	15.67	1.50	1.65	5.41	5.95
5.75	6.30	10.27	30.52	0.98	1.34	5.12	4.83

5.46	8.69	9.75	15.52	0.98	0.61	5.13	5.98
5.50	4.19	9.83	13.94	1.01	1.44	5.32	7.58
2.89	5.96	9.60	10.64	0.54	1.66	5.26	5.97
3.02	3.01	10.02	14.57	0.55	1.45	5.35	7.61
2.91	3.63	9.68	12.06	0.56	0.35	5.42	3.42
1.98	3.53	9.57	17.08	1.46	0.91	5.26	4.80
2.10	5.39	10.17	9.63	1.42	1.59	5.13	5.73
2.04	3.25	9.87	10.82	1.46	1.32	5.25	12.92
5.80	3.97	10.36	13.20	1.02	0.46	5.35	4.47
5.80	4.39	10.37	21.27	0.99	1.17	5.20	6.15
5.58	7.76	9.97	13.87	1.00	1.03	5.24	3.72
8.58	6.96	28.53	33.72	1.60	2.78	15.65	14.62
8.68	7.07	28.84	12.63	1.69	1.97	16.47	19.20
9.32	8.05	30.99	26.77	1.62	3.18	15.84	11.46
6.46	6.32	31.28	21.02	4.32	2.29	15.56	22.32
5.90	7.30	28.56	13.04	4.37	2.76	15.73	14.49
6.38	7.27	30.91	35.20	4.52	3.82	16.29	13.78
16.74	15.74	29.91	76.21	3.00	3.46	15.73	12.45
16.84	16.27	30.09	29.07	3.01	1.53	15.78	14.89
15.95	16.27	28.50	54.10	2.92	3.00	15.33	15.75
9.08	12.57	30.17	22.45	1.66	3.53	16.21	12.71
9.41	8.32	31.29	40.31	1.64	3.20	15.97	16.79
8.98	9.07	29.85	30.15	1.69	1.86	16.46	18.19
6.27	7.04	30.38	34.09	4.21	3.18	15.19	16.71
6.31	9.55	30.56	17.07	4.52	3.81	16.28	13.73
6.24	8.63	30.20	28.71	4.35	3.32	15.68	32.39
17.06	13.60	30.48	45.22	3.04	2.86	15.98	27.88
16.93	12.81	30.25	62.04	3.10	2.78	16.30	14.60
17.05	15.49	30.47	27.68	2.90	4.20	15.24	15.12

Table F-6: Reference and test magnitudes for Participant 6

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.90	5.71	14.04	10.20	0.96	1.62	3.44	15.84
3.10	4.00	15.02	19.36	0.97	1.45	3.49	5.23
3.10	5.22	15.00	17.37	1.01	1.15	3.64	6.02
3.10	3.57	10.30	6.37	0.96	1.12	9.36	10.94
3.04	3.37	10.11	11.20	0.96	1.99	9.39	10.43
3.05	4.46	10.14	21.61	1.00	2.07	9.78	7.46
3.04	5.75	5.43	10.28	1.02	2.11	5.34	7.60
3.06	6.23	5.46	20.70	0.99	1.20	5.18	11.72
3.04	5.06	5.43	24.52	1.02	1.78	5.37	9.33
3.03	7.01	14.69	23.31	1.05	1.59	3.79	8.34
3.07	5.27	14.85	25.54	1.02	1.03	3.67	10.00
2.94	6.24	14.26	11.14	0.98	1.26	3.55	4.55
3.04	4.11	10.10	13.65	0.98	1.08	9.51	10.57
3.08	7.15	10.25	12.77	0.97	1.83	9.46	9.62
3.06	4.59	10.16	22.21	1.01	1.92	9.88	6.92
3.08	4.53	5.50	21.92	1.01	1.87	5.29	6.74
2.94	4.46	5.24	14.81	1.00	1.74	5.24	9.12
3.07	4.58	5.49	8.19	1.00	1.51	5.25	14.70
9.07	10.57	43.91	18.88	2.87	1.83	10.33	17.86
9.18	10.70	44.48	51.83	3.00	3.73	10.82	13.43
8.81	12.45	42.68	41.38	3.02	3.82	10.88	20.05
8.91	16.36	29.64	29.23	3.02	2.76	29.50	26.90
9.46	10.89	31.44	36.22	2.92	5.24	28.46	27.53
8.64	13.42	28.73	64.98	3.07	7.51	29.96	27.05
9.24	15.12	16.51	27.02	3.06	6.28	16.04	22.64
9.12	12.88	16.29	42.83	3.08	3.15	16.16	30.68
9.44	12.64	16.87	61.24	2.99	3.10	15.70	16.29
8.63	11.11	41.81	36.95	3.06	3.61	11.02	18.98
9.21	11.86	44.59	57.45	3.05	2.87	10.98	27.96
8.67	13.72	41.98	24.51	3.02	4.26	10.90	15.37
9.00	11.52	29.92	38.29	2.88	3.69	28.09	36.04
8.75	15.44	29.09	27.59	3.01	5.68	29.36	29.85
9.19	11.87	30.55	57.48	3.11	7.27	30.38	26.19
9.20	11.52	16.43	55.82	2.94	6.27	15.45	22.60
9.38	9.97	16.77	33.14	2.99	4.01	15.70	21.06
9.37	10.29	16.74	18.39	2.90	3.52	15.24	34.34
2.09	4.98	10.10	8.89	1.40	1.62	5.04	15.82
2.12	3.11	10.26	15.09	1.48	2.05	5.35	7.39
2.14	3.65	10.36	12.13	1.42	1.84	5.11	9.65
2.92	5.15	9.71	9.21	0.54	0.70	5.28	6.84
3.08	4.80	10.23	15.96	0.53	1.36	5.21	7.13
3.05	4.16	10.13	20.14	0.55	1.56	5.36	5.63
5.78	4.69	10.32	8.38	0.98	1.81	5.14	6.52

5.77	5.18	10.31	17.23	0.94	0.92	4.93	9.01
5.79	3.81	10.34	18.44	0.95	1.64	5.00	8.63
2.10	4.71	10.16	15.65	1.48	1.91	5.35	10.01
2.12	3.67	10.27	17.79	1.42	1.00	5.13	9.73
2.05	5.81	9.93	10.38	1.40	2.19	5.06	7.91
2.88	4.24	9.56	14.11	0.55	0.69	5.37	6.74
2.92	9.51	9.70	16.99	0.52	1.31	5.08	6.88
3.04	5.62	10.10	27.21	0.54	1.89	5.28	6.80
5.78	5.44	10.33	26.34	0.97	2.28	5.11	8.22
5.75	8.67	10.27	28.84	0.98	2.00	5.12	10.48
5.72	6.51	10.22	11.63	0.99	0.96	5.18	9.37
6.39	8.57	30.96	15.32	4.21	2.56	15.16	24.93
6.41	7.13	31.07	34.54	4.54	4.38	16.36	15.80
6.28	10.82	30.43	35.98	4.46	4.18	16.05	21.93
9.42	12.26	31.31	21.91	1.67	1.74	16.27	16.95
9.43	10.45	31.36	34.75	1.60	2.64	15.63	13.88
9.09	12.69	30.21	61.44	1.66	3.03	16.15	10.91
17.35	19.86	30.99	35.49	3.02	3.33	15.83	12.00
16.67	14.46	29.79	48.07	2.90	1.83	15.25	17.86
17.07	14.19	30.49	68.72	2.87	3.16	15.09	16.59
6.35	7.84	30.73	26.07	4.33	2.99	15.60	15.69
6.38	9.17	30.89	44.40	4.17	2.90	15.03	28.29
6.42	11.69	31.10	20.88	4.42	4.49	15.94	16.20
8.88	11.88	29.54	39.49	1.58	1.72	15.40	16.79
8.96	11.83	29.79	21.13	1.56	3.37	15.24	17.67
9.36	9.94	31.13	48.17	1.65	5.19	16.07	18.70
17.50	9.88	31.27	47.87	2.89	3.97	15.17	14.30
16.87	13.11	30.14	43.57	2.87	3.17	15.05	16.66
17.23	16.57	30.79	29.60	2.92	2.14	15.32	20.83

Table F-7: Reference and test magnitudes for Participant 7

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.79	4.59	9.28	8.20	0.99	0.48	5.20	4.72
2.95	1.01	9.81	4.90	0.97	0.42	5.08	1.50
3.01	2.39	10.02	7.96	0.99	0.63	5.20	3.28
2.90	3.98	14.04	7.12	0.98	2.90	9.59	10.46
2.93	3.19	14.20	10.59	0.95	0.83	9.29	8.07
2.91	3.13	14.11	15.16	0.95	1.69	9.25	8.87
3.06	3.27	5.46	15.84	1.01	1.04	3.62	10.13
3.03	2.96	5.41	5.29	1.00	1.10	3.61	3.96
3.10	3.37	5.53	11.22	0.99	0.39	3.56	2.04
3.02	2.18	10.03	10.55	0.98	0.93	5.13	9.05
3.03	3.00	10.06	9.99	1.03	0.49	5.41	1.75
3.08	3.92	10.24	7.01	0.99	0.71	5.21	3.72
3.06	5.38	14.82	9.61	0.99	0.70	9.69	6.84
2.92	2.68	14.13	12.96	0.94	1.49	9.19	7.81
3.05	3.52	14.78	11.71	1.01	0.91	9.84	3.27
3.04	2.83	5.43	13.71	1.01	0.37	3.65	1.94
2.94	3.04	5.25	5.42	0.99	0.98	3.56	3.54
3.02	4.38	5.39	14.55	0.98	0.86	3.52	8.36
9.10	5.67	30.27	10.14	2.88	1.38	15.14	13.48
8.68	4.38	28.87	21.20	3.01	1.97	15.82	7.09
8.67	8.85	28.84	29.41	2.91	3.01	15.30	15.79
8.60	12.43	41.67	22.20	2.86	5.56	27.93	20.02
8.67	10.17	41.99	33.80	2.94	2.93	28.67	28.57
8.70	6.92	42.15	33.53	2.93	2.23	28.53	11.70
9.40	8.59	16.80	41.61	2.99	3.48	10.79	33.99
9.13	7.25	16.31	12.96	3.12	3.81	11.24	13.72
8.65	7.81	15.46	25.96	3.01	2.05	10.83	10.75
8.85	7.90	29.43	38.25	2.88	3.08	15.10	30.06
9.21	8.33	30.61	27.71	2.84	2.68	14.93	9.66
8.65	7.75	28.75	13.85	2.96	2.96	15.56	15.55
8.47	8.66	41.02	15.47	2.93	3.08	28.57	30.03
9.12	8.70	44.18	42.13	2.93	3.54	28.58	18.58
8.85	9.34	42.84	31.07	2.84	2.19	27.67	7.89
8.67	6.82	15.50	33.05	3.06	2.58	11.02	13.54
9.30	8.49	16.62	15.17	3.08	3.05	11.10	11.00
8.88	7.24	15.87	24.08	2.88	3.13	10.37	30.53
3.05	2.37	10.14	4.23	0.97	0.02	5.10	0.24
2.98	1.23	9.92	5.94	0.98	-0.06	5.17	-0.21
3.04	1.42	10.11	4.73	0.93	0.22	4.87	1.17
2.05	2.01	9.95	3.59	0.49	0.56	4.81	2.00
2.15	2.45	10.41	8.15	0.53	0.32	5.15	3.12
2.04	1.99	9.89	9.63	0.51	1.61	4.96	8.43
5.62	2.66	10.04	12.91	1.48	0.64	5.35	6.25

5.28	4.84	9.44	8.64	1.47	1.58	5.28	5.70
5.38	3.48	9.62	11.59	1.39	0.89	5.02	4.68
3.05	2.60	10.14	12.60	0.99	0.60	5.18	5.87
2.99	2.80	9.93	9.32	1.03	1.78	5.43	6.41
3.04	4.45	10.09	7.95	1.01	1.20	5.29	6.32
2.03	4.79	9.83	8.57	0.52	0.34	5.09	3.34
2.04	2.30	9.90	11.15	0.51	0.87	5.02	4.59
2.07	3.27	10.03	10.86	0.53	1.56	5.19	5.64
5.77	1.59	10.30	7.68	1.47	0.55	5.30	2.91
5.65	5.84	10.10	10.44	1.38	0.59	4.97	2.14
5.65	3.99	10.09	13.27	1.42	0.17	5.13	1.61
8.75	7.98	29.10	14.25	2.85	0.65	14.96	6.36
9.18	3.76	30.52	18.23	2.95	3.74	15.46	13.49
8.65	5.74	28.77	19.09	2.93	2.45	15.39	12.87
5.84	6.49	28.30	11.60	1.57	3.91	15.35	14.08
5.86	6.64	28.40	22.07	1.59	1.47	15.50	14.30
5.98	4.86	28.98	23.52	1.59	1.86	15.55	9.75
16.18	6.01	28.91	29.11	4.29	1.25	15.45	12.17
15.93	12.64	28.47	22.58	4.27	4.06	15.38	14.63
16.63	7.91	29.72	26.30	4.27	2.63	15.37	13.81
8.72	5.25	29.00	25.42	2.98	1.23	15.65	12.01
8.80	7.91	29.25	26.30	2.99	5.26	15.68	18.96
8.60	15.88	28.59	28.37	3.03	3.38	15.90	17.72
5.94	16.97	28.75	30.33	1.64	1.45	15.98	14.13
6.09	4.28	29.52	20.71	1.59	3.13	15.51	16.41
5.95	8.89	28.82	29.54	1.59	4.86	15.50	17.53
15.98	4.67	28.56	22.61	4.28	3.45	15.44	18.10
16.64	16.38	29.73	29.26	4.30	4.34	15.49	15.65
15.93	8.75	28.47	29.10	4.27	1.17	15.38	11.46

Table F-8: Reference and test magnitudes for Participant 8

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.92	5.40	9.72	17.94	0.99	1.22	3.57	6.42
3.05	4.81	10.15	23.28	0.96	1.34	3.45	13.03
2.91	4.00	9.68	7.15	1.00	1.35	3.61	4.87
3.08	4.71	14.94	15.65	0.98	1.71	5.15	6.15
3.07	4.63	14.85	8.27	0.99	1.44	5.18	7.54
2.92	4.76	14.12	23.04	0.96	1.78	5.03	17.34
3.07	5.45	5.49	9.73	0.97	2.36	9.43	8.52
3.07	4.02	5.48	19.45	0.97	2.36	9.47	12.37
3.04	3.17	5.43	10.55	0.98	1.55	9.54	15.15
2.95	5.24	9.80	9.37	1.00	1.18	3.61	11.53
3.02	6.25	10.03	20.79	1.03	1.10	3.73	5.78
2.92	6.26	9.70	30.33	0.96	1.64	3.46	5.92
2.99	5.80	14.48	28.11	1.00	2.10	5.27	20.46
3.03	4.75	14.68	8.48	1.03	1.97	5.38	10.36
2.88	7.78	13.97	25.86	1.01	1.86	5.29	6.72
2.90	5.58	5.19	18.57	0.97	2.41	9.45	8.68
3.08	4.90	5.50	23.74	0.97	2.60	9.50	13.68
2.99	5.19	5.35	9.26	1.00	1.71	9.74	16.64
9.37	10.69	31.14	35.54	2.89	2.86	10.43	15.02
8.67	10.34	28.83	50.10	2.89	2.13	10.40	20.77
8.92	15.18	29.66	27.12	2.94	3.85	10.58	13.88
8.93	13.88	43.26	46.15	2.99	4.19	15.67	15.09
8.74	9.28	42.31	16.59	2.97	3.24	15.58	16.98
9.18	13.26	44.48	64.23	2.96	2.75	15.56	26.79
9.24	11.92	16.51	21.29	3.06	5.35	29.87	19.29
8.95	9.90	16.00	47.93	2.88	5.04	28.14	26.48
8.82	10.28	15.76	34.18	2.94	3.23	28.66	31.47
8.72	13.19	28.99	23.57	3.03	2.50	10.91	24.42
8.81	11.14	29.29	37.05	3.07	5.37	11.06	28.19
8.68	10.66	28.86	51.64	2.90	6.04	10.44	21.77
8.67	9.11	41.98	44.11	3.03	2.83	15.89	27.56
8.63	14.68	41.81	26.23	3.11	2.84	16.31	14.89
8.64	11.58	41.85	38.51	2.98	4.92	15.64	17.72
8.68	9.06	15.52	30.12	2.89	5.91	28.22	21.29
8.74	9.85	15.61	47.70	2.93	4.92	28.60	25.81
8.79	10.77	15.70	19.24	3.00	3.19	29.31	31.15
3.05	4.01	10.15	13.33	1.42	2.30	5.12	12.09
2.86	3.12	9.50	15.10	1.41	1.68	5.09	16.35
2.99	7.25	9.95	12.95	1.41	2.52	5.10	9.07
2.07	4.18	10.02	13.90	1.00	3.60	5.25	12.97
2.08	6.41	10.06	11.46	0.98	1.45	5.12	7.59
2.07	4.78	10.01	23.15	1.00	1.87	5.24	18.24
5.33	6.37	9.52	11.37	0.52	2.97	5.11	10.69

5.70	8.89	10.19	43.08	0.53	2.39	5.18	12.53
5.75	7.55	10.28	25.09	0.53	0.62	5.17	6.01
3.07	12.27	10.21	21.92	1.43	1.30	5.16	12.66
2.98	5.86	9.91	19.50	1.40	1.68	5.03	8.80
2.96	6.46	9.82	31.30	1.39	1.87	5.01	6.73
2.08	4.87	10.06	23.58	0.96	1.75	5.05	17.04
2.12	8.48	10.28	15.14	0.96	1.28	5.05	6.73
2.13	7.20	10.30	23.93	0.98	1.99	5.14	7.19
5.45	8.17	9.74	27.18	0.53	1.78	5.21	6.41
5.65	11.99	10.09	58.08	0.54	1.82	5.28	9.57
5.57	10.44	9.96	18.66	0.53	0.93	5.16	9.03
9.01	9.57	29.95	31.82	4.32	4.79	15.58	25.16
8.68	9.06	28.86	43.88	4.36	2.93	15.70	28.54
8.55	6.38	28.44	11.39	4.48	6.11	16.16	22.00
5.94	8.38	28.78	27.87	3.01	5.38	15.82	19.39
5.97	11.04	28.90	19.72	3.09	3.56	16.22	18.70
6.23	10.65	30.17	51.56	2.97	3.53	15.57	34.42
17.51	19.29	31.29	34.46	1.67	4.19	16.30	15.11
16.97	12.76	30.33	61.79	1.59	3.89	15.48	20.44
17.13	15.65	30.61	52.03	1.62	2.47	15.78	24.07
8.64	14.01	28.72	25.03	4.47	3.43	16.11	33.45
9.06	12.28	30.11	40.84	4.47	5.40	16.10	28.36
8.65	11.35	28.76	54.96	4.38	4.60	15.80	16.57
5.95	7.83	28.81	37.91	3.08	3.15	16.16	30.72
6.03	12.05	29.20	21.52	3.04	4.01	15.94	21.05
6.36	7.96	30.81	26.45	3.01	6.34	15.80	22.83
16.41	13.15	29.33	43.73	1.58	6.69	15.41	24.10
16.84	17.23	30.09	83.46	1.61	5.30	15.71	27.80
16.55	16.47	29.57	29.42	1.57	2.43	15.31	23.67

Table F-9: Reference and test magnitudes for Participant 9

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.03	3.20	14.66	5.71	0.99	0.51	3.58	4.99
3.05	2.00	14.77	6.66	1.02	0.82	3.68	4.30
2.87	1.80	13.92	8.72	1.01	0.99	3.65	3.57
2.91	2.79	5.20	4.98	0.98	0.80	5.15	4.22
3.07	2.60	5.49	8.66	1.02	1.27	5.38	4.57
2.93	3.82	5.24	18.52	0.99	0.43	5.17	4.22
3.08	4.49	10.24	14.92	0.96	0.87	9.39	8.52
2.91	2.54	9.68	4.53	0.99	1.61	9.63	8.44
3.06	2.08	10.18	10.08	0.99	3.27	9.67	11.80
3.01	2.15	14.59	10.42	1.03	1.25	3.70	4.52
2.96	3.94	14.36	7.05	1.01	1.12	3.63	5.91
3.08	2.71	14.91	9.01	1.01	0.35	3.63	3.37
2.97	1.93	5.31	6.42	1.00	0.71	5.28	3.73
3.01	2.54	5.38	12.30	0.99	1.53	5.21	5.51
3.03	2.15	5.42	3.84	0.99	0.64	5.20	6.24
3.01	2.65	9.99	8.80	0.97	1.07	9.47	5.64
2.91	2.52	9.67	12.19	1.00	1.90	9.75	6.86
2.94	2.08	9.77	3.72	0.99	0.95	9.70	9.29
8.78	6.90	42.55	12.33	3.02	0.62	10.87	6.09
9.22	6.13	44.66	20.39	2.94	1.70	10.58	8.92
8.75	8.97	42.40	43.42	2.96	2.80	10.68	10.10
8.62	6.67	15.40	11.91	3.11	2.58	16.33	13.55
8.63	9.15	15.42	30.42	3.00	3.63	15.75	13.08
8.64	8.67	15.44	42.00	3.08	1.37	16.16	13.40
8.91	9.23	29.63	30.68	2.98	2.22	29.10	21.61
8.75	6.45	29.09	11.53	2.97	4.13	28.96	21.69
8.64	6.08	28.73	29.45	2.98	6.70	29.07	24.15
8.60	8.10	41.65	39.25	3.02	3.72	10.88	13.41
8.63	12.54	41.81	22.41	3.07	2.23	11.06	11.72
8.94	7.22	43.30	23.99	3.01	0.97	10.86	9.46
8.63	5.41	15.41	17.98	2.92	2.51	15.34	13.20
8.64	8.53	15.43	41.34	2.94	3.79	15.43	13.66
8.80	6.72	15.72	12.00	2.95	1.18	15.50	11.49
8.75	9.61	29.10	31.95	2.95	4.37	28.79	22.93
8.71	6.79	28.95	32.88	2.94	6.21	28.66	22.39
8.73	3.70	29.01	6.60	3.03	2.56	29.54	24.97
1.98	2.01	9.58	3.59	1.43	0.60	5.17	5.89
2.10	2.36	10.16	7.85	1.44	1.30	5.18	6.83
2.08	1.42	10.06	6.87	1.46	1.24	5.25	4.47
5.47	2.54	9.77	4.53	0.98	1.14	5.13	5.97
5.36	5.46	9.57	18.14	1.02	1.60	5.35	5.76
5.43	4.90	9.70	23.74	1.00	0.51	5.26	4.94
3.10	2.66	10.30	8.83	0.54	0.48	5.26	4.71

2.96	3.12	9.84	5.58	0.54	0.95	5.26	5.00
3.09	2.70	10.26	13.08	0.55	1.49	5.38	5.35
2.07	2.08	10.01	10.09	1.45	1.57	5.21	5.64
2.13	3.07	10.31	5.49	1.48	1.16	5.35	6.09
2.07	1.71	10.02	5.69	1.40	0.71	5.05	6.94
5.59	3.82	9.98	12.71	0.98	1.18	5.14	6.22
5.61	4.76	10.03	23.06	1.01	1.56	5.29	5.63
5.47	3.71	9.78	6.63	1.02	0.47	5.34	4.58
3.03	2.96	10.09	9.85	0.54	1.17	5.25	6.17
3.01	3.05	9.99	14.78	0.54	1.52	5.27	5.49
3.07	3.28	10.22	5.87	0.53	0.73	5.21	7.14
6.29	5.84	30.48	10.44	4.28	0.16	15.44	1.57
6.21	7.02	30.08	23.34	4.40	2.08	15.84	10.93
6.22	6.02	30.12	29.17	4.49	3.72	16.19	13.42
16.70	14.72	29.84	26.31	3.07	3.05	16.11	16.02
16.33	14.79	29.17	49.19	3.02	4.69	15.83	16.91
16.08	12.96	28.73	62.76	3.05	1.36	16.00	13.31
8.76	6.78	29.11	22.55	1.58	1.46	15.44	14.21
8.69	9.59	28.90	17.13	1.62	2.45	15.83	12.88
8.70	5.47	28.93	26.49	1.60	3.35	15.58	12.08
5.87	5.77	28.44	27.94	4.41	3.48	15.90	12.53
6.33	5.12	30.66	9.15	4.27	2.87	15.40	15.07
6.19	6.26	30.00	20.81	4.42	1.27	15.94	12.41
16.36	19.26	29.24	64.03	3.11	2.91	16.32	15.30
15.96	10.98	28.51	53.18	2.97	4.23	15.60	15.24
16.37	12.13	29.24	21.68	3.00	1.13	15.76	11.07
8.87	7.07	29.48	23.49	1.57	1.87	15.33	9.83
8.70	8.27	28.94	40.07	1.59	3.13	15.54	11.27
9.07	9.49	30.14	16.95	1.61	1.69	15.66	16.45

Table F-10: Reference and test magnitudes for Participant 10

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
2.99	4.20	5.34	20.32	1.02	3.35	9.99	12.08
2.79	5.34	4.98	17.77	0.97	0.86	9.49	8.43
3.01	2.98	5.38	5.33	0.97	1.46	9.50	7.65
2.89	3.01	13.98	14.58	1.03	0.72	5.41	7.01
3.08	2.80	14.90	9.32	1.01	1.65	5.31	5.93
2.93	2.84	14.20	5.08	0.95	1.23	4.99	6.48
3.02	5.24	10.04	17.40	1.00	0.85	3.61	4.46
2.96	4.15	9.83	7.41	0.94	0.55	3.38	5.37
2.98	3.69	9.91	17.86	1.02	1.13	3.68	4.08
3.01	3.27	5.37	10.88	0.97	2.26	9.46	8.13
2.89	2.90	5.16	5.18	0.97	0.75	9.46	7.35
2.94	5.11	5.26	24.73	0.99	1.27	9.69	6.65
3.05	4.14	14.77	20.05	0.99	0.96	5.22	9.34
3.06	4.27	14.84	7.63	1.02	1.32	5.33	6.92
3.11	3.99	15.05	13.26	1.00	2.47	5.25	8.92
2.93	3.91	9.76	12.99	0.99	0.87	3.58	3.14
2.91	5.27	9.67	9.41	0.94	1.05	3.40	5.52
2.95	3.18	9.81	15.38	0.95	0.88	3.44	8.57
8.89	4.67	15.88	22.61	3.01	7.59	29.40	27.35
9.22	9.72	16.46	32.33	2.95	3.34	28.81	32.59
8.93	13.62	15.96	24.34	3.00	5.69	29.27	29.86
8.85	11.92	42.85	57.73	3.15	2.88	16.55	28.11
8.88	7.31	42.99	24.29	2.95	4.10	15.51	14.76
8.92	11.11	43.18	19.86	2.99	3.40	15.72	17.83
9.17	10.79	30.49	35.88	3.05	2.48	10.99	13.02
8.85	12.06	29.43	21.55	2.97	2.40	10.69	23.38
9.05	8.64	30.08	41.83	2.94	3.13	10.59	11.28
8.72	9.43	15.57	31.36	2.85	4.67	27.80	16.82
8.56	12.81	15.29	22.88	2.93	2.40	28.57	23.45
8.70	6.00	15.55	29.07	2.95	3.34	28.77	17.51
8.63	9.38	41.79	45.44	2.97	2.77	15.59	27.06
8.64	6.47	41.87	11.55	3.03	3.71	15.91	19.48
8.58	7.11	41.55	23.64	2.92	4.41	15.33	15.88
8.69	11.37	28.90	37.80	2.83	3.69	10.20	13.29
8.63	4.38	28.68	7.83	2.97	2.74	10.69	14.36
8.70	11.04	28.93	53.47	2.93	3.08	10.55	30.07
5.85	7.85	10.45	38.01	0.55	1.26	5.36	4.54
5.29	9.47	9.46	31.49	0.53	0.58	5.14	5.69
5.27	6.97	9.41	12.46	0.53	0.76	5.17	4.00
2.03	3.68	9.82	17.82	1.01	0.51	5.31	5.02
2.13	3.79	10.30	12.61	1.02	2.12	5.36	7.65
2.06	4.08	9.98	7.29	0.98	0.86	5.13	4.52
2.91	3.46	9.69	11.50	1.43	1.14	5.16	5.97

2.91	7.12	9.69	12.72	1.49	1.03	5.35	10.07
2.98	4.02	9.90	19.45	1.40	2.19	5.05	7.90
5.47	4.79	9.77	15.91	0.52	2.41	5.07	8.67
5.33	5.18	9.53	9.25	0.52	0.80	5.08	7.85
5.42	5.74	9.69	27.80	0.54	1.04	5.24	5.48
2.12	3.01	10.26	14.56	1.00	0.45	5.25	4.38
2.00	7.36	9.67	13.15	0.97	0.87	5.11	4.55
2.00	5.41	9.66	18.00	1.00	1.71	5.27	6.16
3.06	4.60	10.18	15.30	1.43	0.85	5.16	3.07
2.92	3.44	9.71	6.14	1.38	1.03	4.98	5.43
2.86	4.86	9.51	23.51	1.45	0.74	5.23	7.18
16.23	13.47	28.99	65.25	1.64	2.92	16.00	10.54
16.12	13.97	28.80	46.43	1.57	1.35	15.31	13.19
16.05	15.19	28.67	27.15	1.59	2.40	15.47	12.59
5.96	6.81	28.87	32.98	3.08	2.66	16.16	25.92
5.85	5.35	28.32	17.78	3.01	2.69	15.81	9.69
5.94	5.84	28.79	10.43	2.96	3.03	15.53	15.90
8.66	11.35	28.79	37.74	4.49	3.22	16.19	16.93
8.60	6.93	28.58	12.38	4.46	2.52	16.07	24.54
8.53	7.25	28.37	35.11	4.35	4.25	15.69	15.31
16.55	11.38	29.57	37.82	1.67	3.20	16.26	11.52
16.01	14.61	28.61	26.10	1.57	1.46	15.36	14.19
16.07	15.77	28.71	76.36	1.61	2.79	15.71	14.64
6.14	8.45	29.74	40.92	2.86	2.17	15.01	21.16
5.95	8.66	28.80	15.47	3.12	2.62	16.36	13.78
5.84	7.76	28.31	25.79	3.02	4.01	15.85	14.47
8.57	9.42	28.48	31.31	4.30	3.77	15.51	13.58
8.62	6.69	28.67	11.96	4.27	4.40	15.39	23.10
8.66	6.35	28.79	30.75	4.43	2.67	15.96	26.04

Table F-11: Reference and test magnitudes for Participant 11

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.10	4.07	10.31	7.28	0.98	0.77	5.15	4.07
2.99	3.27	9.94	15.82	1.00	1.86	5.26	6.72
2.91	2.88	9.68	9.56	0.99	0.59	5.22	5.73
3.04	3.94	14.71	7.04	1.02	0.29	3.66	2.88
3.04	3.76	14.73	12.50	0.99	0.95	3.55	4.99
2.91	3.21	14.11	15.57	1.01	1.11	3.64	3.98
2.98	4.07	5.33	13.52	1.01	0.87	9.85	8.44
2.94	3.84	5.24	6.86	1.00	2.16	9.76	7.79
2.97	3.14	5.31	15.21	0.98	1.87	9.57	9.81
3.02	3.81	10.03	6.81	0.97	1.32	5.08	4.75
3.05	2.19	10.15	10.59	1.03	0.94	5.39	4.94
3.05	3.16	10.13	10.50	1.01	0.60	5.31	5.83
2.92	2.99	14.12	9.93	0.99	0.26	3.58	2.53
3.05	3.53	14.79	17.10	0.99	0.80	3.57	4.22
2.97	5.27	14.40	9.41	1.02	1.52	3.67	5.49
2.87	4.37	5.12	7.80	1.01	2.63	9.84	13.80
2.89	2.77	5.17	13.40	0.99	2.59	9.65	9.35
3.02	2.62	5.39	8.70	1.01	1.14	9.82	11.08
9.15	8.54	30.41	15.26	2.94	2.61	15.44	13.70
9.12	4.85	30.34	23.47	3.00	3.44	15.76	12.41
8.98	5.05	29.86	16.78	3.04	1.53	15.94	14.92
8.72	8.82	42.25	15.76	3.09	1.12	11.12	10.97
9.15	7.71	44.30	25.62	2.97	2.04	10.70	10.72
9.40	4.50	45.53	21.79	2.97	3.11	10.70	11.19
9.23	6.82	16.49	22.67	2.92	2.76	28.51	26.95
8.80	7.22	15.73	12.91	2.96	6.06	28.92	21.83
9.23	3.95	16.48	19.12	3.08	4.09	30.08	21.49
8.63	8.89	28.69	15.88	2.96	4.79	15.53	17.27
8.66	4.81	28.80	23.31	2.96	2.78	15.53	14.60
8.88	6.03	29.51	20.04	2.97	2.07	15.58	20.17
9.35	5.36	45.30	17.82	3.04	1.30	10.94	12.64
9.32	6.38	45.16	30.88	3.01	3.00	10.84	15.73
8.75	9.12	42.39	16.29	2.92	3.34	10.52	12.05
8.57	8.00	15.31	14.29	2.91	3.53	28.34	18.53
9.07	5.03	16.21	24.34	2.98	7.37	29.07	26.56
9.29	8.06	16.59	26.80	3.00	2.65	29.30	25.86
2.97	1.23	9.86	2.19	1.01	1.12	5.32	5.86
2.93	1.30	9.76	6.29	1.05	1.66	5.51	5.97
2.99	2.42	9.95	8.04	1.00	0.75	5.24	7.35
2.10	2.15	10.19	3.84	1.51	0.50	5.43	4.89
2.08	2.91	10.06	9.66	1.45	1.31	5.24	6.89
2.08	2.27	10.07	11.01	1.47	2.08	5.30	7.50
5.55	3.35	9.91	11.14	0.51	0.64	5.00	6.23
5.73	3.61	10.23	6.45	0.54	2.83	5.23	10.19
5.65	2.99	10.09	14.50	0.52	2.09	5.11	10.99
3.00	4.64	9.99	8.29	1.01	2.25	5.33	8.12
3.00	2.96	9.96	14.35	0.97	1.52	5.07	7.97
2.89	2.33	9.60	7.75	0.97	0.85	5.07	8.27
2.12	4.02	10.29	13.38	1.44	0.56	5.17	5.50
2.10	2.55	10.16	12.34	1.42	1.19	5.12	6.22
2.12	3.75	10.25	6.69	1.47	1.74	5.29	6.27

5.48	3.89	9.79	6.94	0.53	1.45	5.16	7.60
5.76	2.52	10.29	12.19	0.52	2.42	5.11	8.71
5.36	3.75	9.58	12.46	0.50	0.57	4.86	5.58
8.89	7.03	29.56	12.56	2.89	2.55	15.17	13.38
8.80	4.21	29.25	20.38	2.98	4.97	15.64	17.90
8.87	6.83	29.50	22.71	2.97	1.31	15.61	12.81
6.42	6.69	31.09	11.96	4.49	1.37	16.19	13.34
6.21	4.59	30.08	15.25	4.55	2.87	16.41	15.06
6.41	5.57	31.07	26.97	4.53	4.57	16.31	16.46
16.05	7.88	28.67	26.20	1.59	1.71	15.56	16.72
16.87	9.37	30.15	16.74	1.63	5.19	15.93	18.71
16.47	7.68	29.42	37.21	1.59	2.71	15.52	14.25
8.61	6.69	28.63	11.96	2.98	5.26	15.67	18.95
8.87	5.13	29.49	24.84	3.07	3.03	16.13	15.91
9.00	5.50	29.93	18.27	3.07	1.60	16.14	15.59
6.34	5.38	30.71	17.89	4.47	1.61	16.11	15.71
6.31	5.38	30.57	26.07	4.30	3.49	15.48	18.33
6.29	8.68	30.49	15.52	4.37	3.92	15.75	14.11
16.43	11.28	29.36	20.15	1.58	3.46	15.45	18.16
16.02	7.06	28.62	34.21	1.62	4.70	15.76	16.94
16.60	16.04	29.65	53.33	1.57	1.49	15.29	14.55

Table F-12: Reference and test magnitudes for Participant 12

Angle (°)		Displacement (mm)		Torque (N.m)		Force (N)	
Ref	Match	Ref	Match	Ref	Match	Ref	Match
3.03	3.05	5.42	10.15	1.01	1.13	3.62	4.07
2.99	3.65	5.34	17.70	0.94	0.73	3.38	7.11
3.01	3.09	5.37	5.52	0.97	1.13	3.50	5.95
2.92	2.84	9.70	5.07	0.96	1.13	5.06	5.95
2.88	3.51	9.57	17.01	1.00	0.72	5.25	7.02
2.93	3.82	9.73	12.69	0.99	1.22	5.21	4.41
2.90	3.09	14.04	10.27	0.95	3.26	9.24	11.74
2.92	3.71	14.15	6.63	0.99	1.16	9.68	11.28
3.00	5.24	14.51	25.36	0.98	1.53	9.56	8.02
3.02	4.36	5.40	21.12	0.95	1.50	3.44	7.89
3.05	1.91	5.46	3.42	0.98	0.91	3.52	8.92
3.06	3.20	5.47	10.63	0.97	1.69	3.48	6.07
3.08	3.56	10.25	17.24	0.98	2.49	5.17	8.97
3.07	2.24	10.21	4.00	0.96	1.68	5.04	8.82
2.92	3.80	9.70	12.62	0.98	0.57	5.16	5.57
3.05	4.20	14.78	20.36	0.97	1.01	9.42	9.88
3.09	3.93	14.96	13.06	0.99	2.22	9.67	11.65
2.91	4.19	14.09	7.48	1.02	2.87	9.98	10.35
9.33	9.46	16.67	31.44	2.91	2.65	10.47	9.53
9.04	8.71	16.15	42.19	2.91	1.29	10.47	12.57
9.39	8.42	16.78	15.04	2.98	1.97	10.75	10.34
8.66	7.73	28.78	13.81	2.95	2.48	15.47	13.00
9.06	8.25	30.13	39.96	3.01	1.83	15.79	17.90
8.91	9.16	29.61	30.44	3.04	2.71	15.94	9.78
9.37	8.92	45.40	29.66	2.89	8.08	28.18	29.12
9.32	10.21	45.13	18.24	2.91	2.14	28.37	20.92
8.73	9.25	42.28	44.79	2.89	6.14	28.24	32.26
8.94	8.37	15.97	40.53	2.93	3.16	10.58	16.59
8.86	10.88	15.83	19.45	2.99	1.81	10.77	17.66
8.75	9.61	15.63	31.95	2.98	3.52	10.72	12.68
8.88	8.19	29.52	39.66	2.92	4.21	15.30	15.17
9.39	7.92	31.21	14.15	2.93	3.22	15.40	16.92
8.84	9.44	29.39	31.40	2.91	1.92	15.26	18.77
8.75	12.81	42.39	62.02	2.91	3.23	28.38	31.51
9.34	8.84	45.24	29.38	2.91	4.29	28.36	22.54
9.40	10.17	45.52	18.17	2.89	7.17	28.18	25.83
5.46	4.13	9.76	13.73	1.44	1.74	5.19	6.28
5.72	4.99	10.21	24.15	1.45	0.62	5.22	6.08
5.73	7.52	10.23	13.43	1.48	1.17	5.32	6.12
3.01	3.17	10.01	5.66	0.99	1.07	5.19	5.61
3.05	3.69	10.15	17.86	0.99	0.81	5.20	7.91
3.04	3.74	10.12	12.42	0.98	1.95	5.12	7.01
2.05	1.74	9.92	5.80	0.55	1.70	5.40	6.13

2.00	1.73	9.70	3.09	0.54	0.67	5.28	6.51
2.11	2.22	10.22	10.74	0.55	1.29	5.36	6.76
5.42	8.28	9.68	40.10	1.46	1.21	5.25	6.34
5.52	5.75	9.86	10.28	1.41	0.75	5.09	7.28
5.64	5.60	10.07	18.60	1.46	1.55	5.27	5.59
3.03	4.02	10.07	19.46	0.99	1.92	5.22	6.93
3.03	3.41	10.06	6.09	1.00	1.34	5.24	7.06
3.09	3.85	10.26	12.80	1.02	0.87	5.38	8.45
2.10	2.59	10.18	12.56	0.55	0.55	5.39	5.39
2.08	2.23	10.07	7.42	0.54	0.92	5.26	4.83
2.09	1.65	10.13	2.95	0.53	2.25	5.15	8.11
16.17	14.57	28.88	48.45	4.31	4.10	15.53	14.77
16.28	15.01	29.08	72.72	4.31	2.29	15.54	22.32
17.13	19.20	30.60	34.31	4.39	3.25	15.81	17.04
8.95	15.24	29.75	27.22	2.96	3.30	15.56	17.35
9.30	6.86	30.93	33.22	2.99	1.83	15.68	17.83
8.82	11.49	29.32	38.19	2.88	3.48	15.13	12.55
6.18	5.27	29.94	17.51	1.62	3.30	15.79	11.88
6.16	5.14	29.82	9.19	1.60	1.66	15.57	16.18
6.17	6.29	29.90	30.48	1.60	2.78	15.59	14.61
16.12	19.13	28.80	92.63	4.43	3.06	15.96	16.07
16.21	17.52	28.97	31.31	4.47	2.02	16.10	19.72
16.12	12.53	28.80	41.67	4.36	4.00	15.71	14.40
9.13	10.13	30.37	49.05	3.09	4.24	16.23	15.26
9.16	9.73	30.47	17.38	3.03	3.33	15.91	17.49
8.83	9.95	29.37	33.10	3.03	1.60	15.91	15.64
6.32	9.15	30.61	44.31	1.58	1.51	15.42	14.74
6.10	5.99	29.56	19.91	1.59	2.49	15.51	13.06
6.31	7.94	30.54	14.18	1.60	3.01	15.62	10.84

F.2 Raw data from Chapter 5: Sensitivity to steering wheel force and steering wheel angle

Table F-13: Difference threshold test magnitudes for 5.25 N reference

Trial number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
2	5.46	5.46	5.46	5.25	5.25	5.46	5.46	5.25	5.25	5.46	5.46	5.25
3	5.67	5.46	5.46	5.25	5.25	5.46	5.67	5.25	5.46	5.46	5.67	5.46
4	5.67	5.46	5.67	5.04	5.46	5.67	5.67	5.04	5.46	5.46	5.67	5.46
5	5.67	5.67	5.88	5.04	5.46	5.67	5.88	5.25	5.46	5.25	5.67	5.46
6	5.46	5.88	5.88	5.25	5.46	5.88	5.88	5.46	5.25	5.46	5.46	5.67
7	5.67	5.88	6.09	5.25	5.25	6.09	5.88	5.67	5.25	5.67	5.46	5.88
8	5.67	6.09	6.3	5.46	5.46	6.09	6.09	5.88	5.25	5.67	5.46	5.88
9	5.67	6.3	6.51	5.46	5.67	6.09	6.3	5.88	5.46	5.67	5.25	6.09
10	5.88	6.3	6.51	5.46	6.09	5.88	6.3	5.88	5.46	5.46	5.46	6.09
11	5.88	6.3	6.72	5.67	6.3	6.09	6.3	5.67	5.67	5.46	5.46	6.09
12	5.88	6.09	6.72	5.67	6.51	6.3	6.09	5.67	5.88	5.46	5.67	5.88
13	5.67	6.09	6.93	5.67	6.51	6.3	6.09	5.67	5.88	5.25	5.67	6.09
14	5.67	6.09	6.93	5.46	6.51	6.3	6.09	5.88	5.88	5.25	5.67	6.09
15	5.88	6.3	6.93	5.46	6.3	6.09	6.3	5.88	5.67	5.46	5.46	6.09
16	5.88	6.3	6.72	5.67	6.3	6.09	6.3	5.88	5.67	5.46	5.67	6.3
17	5.88	6.3	6.72	5.88	6.3	6.3	6.51	6.09	5.67	5.46	5.67	6.51
18	6.09	6.51	6.72	5.88	6.09	6.51	6.72	6.09	5.46	5.25	5.67	6.51
19	6.09	6.51	6.51	5.88	6.09	6.51	6.72	6.3	5.46	5.25	5.46	6.51
20	6.09	6.51	6.51	6.09	6.09	6.51	6.72	6.3	5.46		5.46	6.3
21	5.88	6.72	6.51	6.09	5.88	6.3	6.51	6.3	5.67		5.46	6.3
22	5.88	6.72	6.3	6.09	5.88	6.3	6.72	6.09	5.67			6.3
23	5.88	6.72	6.51	5.88	5.88	6.3	6.72	6.09	5.88			6.09
24		6.51	6.51		5.67	6.09	6.72	6.09	5.88			6.09
25		6.72	6.51		5.67	6.09	6.51		5.88			6.3
26		6.72	6.3		5.67		6.51		5.67			6.3
27		6.72	6.3		5.88		6.51		5.67			6.51
28		6.93	6.3		5.88				5.67			6.51
29		6.93	6.51		6.09							6.51
30		6.93	6.51		6.195							6.3
31		6.72	6.51		6.3							6.3
32		6.72	6.72		6.51							
33		6.72	6.72		6.51							
34		6.93	6.72		6.72							
35		6.93	6.51		6.72							
36		6.93	6.51		6.72							
37		6.72			6.51							

Table F-14: Difference threshold test magnitudes for 10.5 N reference

Trial Number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
2	10.5	10.92	10.5	10.5	10.92	10.5	10.92	10.5	10.92	10.5	10.92	10.5
3	10.5	10.92	10.5	10.92	11.34	10.5	10.92	10.92	10.92	10.92	10.92	10.5
4	10.08	11.34	10.92	11.34	11.76	10.08	10.92	10.92	10.92	10.92	10.92	10.92
5	10.5	11.34	11.34	11.34	11.76	10.5	11.34	11.34	10.5	10.92	10.5	10.92
6	10.5	11.34	11.34	11.34	11.76	10.92	11.34	11.76	10.5	10.5	10.92	10.92
7	10.5	10.92	11.76	10.92	11.34	11.34	11.34	12.18	10.5	10.92	10.92	11.34
8	10.92	10.92	11.76	10.92	11.34	11.76	11.76	12.6	10.08	10.92	10.92	11.76
9	10.92	10.92	11.76	11.34	11.34	12.18	12.18	12.6	10.08	11.34	11.34	12.18
10	11.34	10.5	11.34	11.34	10.92	12.18	12.18	12.6	10.5	11.34	11.76	12.6
11	11.34	10.92	11.76	11.34	11.34	12.6	12.6	12.18	10.92	11.76	11.76	13.02
12	11.76	10.92	11.76	11.76	11.34	13.02	12.6	12.18	11.34	11.76	11.76	13.02
13	12.18	10.92	11.76	11.76	11.76	13.02	12.6	12.18	11.34	12.18	12.18	13.02
14	12.18	11.34	12.18	11.76	12.18	13.02	12.18	11.76	11.34	12.18	12.18	12.6
15	12.18	11.76	12.18	12.18	12.18	12.6	12.6	12.18	10.92	12.18	12.18	12.6
16	11.76	11.76	12.18	12.18	12.18	12.6	13.02	12.18	10.92	12.6	11.76	12.6
17	11.76	11.76	11.76	12.18	11.76	13.02	13.02	12.18	10.92	12.6	11.76	12.18
18	11.76	12.18	11.76	11.76	11.76	13.02	13.44	11.76	11.34	12.6	12.18	12.18
19	11.34	12.18	11.76	12.18	11.76	13.02	13.44	11.76	11.34	12.18	12.18	12.18
20	11.34	12.18	12.18	12.18	11.34	12.6	13.44	11.76	11.76	12.18	12.18	11.76
21	11.76	12.6	12.18	12.6	11.34		13.02	11.34	11.76	12.18	11.76	11.76
22	11.76	12.6	12.18	12.6	10.92		13.44	11.76	12.18	12.6		12.18
23	11.76	12.6	11.76	12.6	10.92		13.44	12.18	12.18	12.6		12.6
24	12.18	12.18	12.18	12.18	11.34		13.44	12.6	12.18	12.6		13.02
25	12.18	12.18	12.6	12.18	11.34		13.02	12.6	11.76	12.18		13.02
26	12.18	12.18	12.6	12.18	11.76		13.02	12.6				13.44
27	11.76	12.6	12.6	11.76	11.76		13.02	13.02				13.44
28	11.76	12.6	12.18	11.76	11.76		12.6	13.02				13.44
29	11.76	12.6	12.18	11.76	11.34		12.6	13.02				13.02
30	12.18	12.18		11.34			12.6	12.6				13.02
31	12.18	12.18					12.18	12.6				13.02
32	12.6	12.18					12.18	12.6				12.6
33	12.6	11.76					12.18	12.18				12.6
34	12.6						11.76	12.18				12.6
35	12.18						11.76	12.18				12.18
36	12.18											12.18
37	12.18											12.6
38	11.76											12.6
39	11.76											12.6
40	11.76											12.18
41	11.34											12.18
42	11.34											12.18
43	11.34											11.76
44	11.76											11.76

45	11.76	11.76
46	11.76	11.34
47		11.34
48		11.34
49		10.92
50		10.92

Table F-15: Difference threshold test magnitudes for 21 N reference

Trial number	1	2	3	4	5	6	7	8	9	10	11	12
1	21.00	21	21	21	21	21	21	21	21	21	21	21
2	21.00	21	21	21.84	21.84	21	21	21	21.84	21.84	21.84	21
3	21.84	21.84	21	22.68	21.84	21	21	21.84	21.84	22.68	21.84	21
4	21.84	21.84	21.84	22.68	21.84	20.16	20.16	21.84	22.68	22.68	22.68	21.84
5	21.84	22.68	22.68	23.52	21	21	21	22.68	22.68	23.52	22.68	21.84
6	21.00	23.52	22.68	23.52	21.84	21.84	21	22.68	22.68	23.52	23.52	22.68
7	21.84	23.52	22.68	23.52	22.68	22.68	21	22.68	23.52	23.52	23.52	22.68
8	22.68	23.52	21.84	24.36	22.68	22.68	21.84	21.84	23.52	22.68	23.52	22.68
9	22.68	22.68	22.68	24.36	22.68	23.52	22.68	21.84	23.52	22.68	22.68	21.84
10	23.52	22.68	23.52	24.36	21.84	24.36	22.68	21.84	22.68	23.52	22.68	22.68
11	23.52	22.68	23.52	25.2	21.84	25.2	22.68	21	22.68	23.52	22.68	22.68
12	23.52	21.84	24.36	25.2	22.68	26.04	23.52	21.84	22.68	23.52	21.84	22.68
13	22.68	22.68	24.36	25.2	23.52	26.04	23.52	21.84	21.84	24.36	22.68	21.84
14	23.52	22.68	24.36	24.36	23.52	26.04	23.52	22.68	21.84	24.36	23.52	21.84
15	24.36	22.68	25.2	24.36	23.52	25.2	22.68	22.68	21.84	24.36	24.36	22.68
16	24.36	21.84	26.04	24.36	22.68	25.2	22.68	23.52	22.68	23.52	25.2	22.68
17	25.20	22.68	26.04	23.52	23.52	25.2	22.68	24.36	23.52	23.52	26.04	22.68
18	25.20	22.68	26.04	24.36	23.52	24.36	21.84	24.36	23.52	23.52	26.04	21.84
19	25.20	23.52	25.2	25.2	24.36	24.36	21.84	24.36	23.52	22.68	26.88	21.84
20	24.36	23.52	25.2	25.2	24.36	25.2	22.68	23.52	24.36	22.68	26.88	
21	24.36	23.52	25.2	25.2	25.2	25.2	22.68	23.52	25.2	22.68	26.88	
22	24.36	22.68	24.36	24.36	25.2	25.2	22.68	23.52	25.2	21.84	26.04	
23	23.52		24.36	24.36	25.2	24.36	21.84	22.68	26.04	21.84	26.04	
24	23.52		24.36	25.2		24.36	21.84	22.68	26.04	22.68	26.04	
25	23.52		25.2	25.2		24.36		22.68	26.88	22.68	25.2	
26	22.68		25.2	25.2		23.52		23.52	26.88	22.68	26.04	
27	23.52		25.2	24.36		23.52		23.52	26.88	23.52	26.04	
28	23.52		24.36	24.36		23.52		23.52	26.04	23.52	26.04	
29	23.52		24.36	24.36		22.68		22.68	26.04	23.52	25.2	
30	22.68		25.2	23.52		22.68		22.68	26.04	22.68	25.2	
31	22.68		25.2			22.68			25.2	22.68	25.2	
32	22.68		25.2			21.84			25.2		24.36	
33	21.84		26.04						25.2		24.36	
34	21.84		26.04						24.36			
35	21.84		26.04						24.36			
36									25.2			
37									25.2			
38									25.2			
39									24.36			
40									24.36			

Table F-16: Difference threshold test magnitudes for 4 degree reference

Trial number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	4	4	4	4	4	4	4	4	4	4	4	4
2	4	4	4.16	4	4	4	4.16	4	4.16	4.16	4	4
3	4.16	4.16	4.32	4	4	4	4.16	4.16	4.32	4.16	4	4.16
4	4.32	4.16	4.48	3.84	4.16	4.16	4.32	4.32	4.32	4.16	4.16	4.16
5	4.32	4.16	4.48	4	4.32	4.32	4.32	4.48	4.32	4.32	4.32	4.16
6	4.48	4	4.48	4.16	4.48	4.32	4.48	4.48	4.16	4.32	4.32	4.32
7	4.48	4	4.64	4.16	4.64	4.48	4.64	4.48	4.16	4.32	4.48	4.32
8	4.48	4	4.64	4.32	4.64	4.48	4.64	4.64	4.16	4.16	4.48	4.48
9	4.64	4.16	4.64	4.32	4.64	4.48	4.8	4.8	4	4.16	4.48	4.48
10	4.64	4.16	4.8	4.48	4.48	4.64	4.8	4.96	4	4.16	4.64	4.48
11	4.64	4.16	4.8	4.48	4.48	4.8	4.96	5.12	4	4.32	4.64	4.32
12	4.48	4.32	4.8	4.48	4.48	4.96	4.96	5.12	3.84	4.32	4.64	4.48
13	4.48	4.48	4.64	4.32	4.32	5.12	4.96	5.28	4	4.32	4.48	4.48
14	4.64	4.64	4.64	4.32	4.48	5.12	4.8	5.28	4.16	4.16	4.48	4.48
15	4.64	4.8	4.64	4.48	4.48	5.12	4.8	5.44	4.16	4.16	4.48	4.64
16	4.64	4.8	4.48	4.48	4.48	5.28	4.8	5.44	4.32	4.16	4.32	4.64
17	4.48	4.8	4.48	4.48	4.32	5.44	4.64	5.44	4.32	4.32	4.32	4.64
18	4.64	4.64	4.48	4.32	4.32	5.44	4.8	5.28	4.32	4.48	4.48	4.8
19	4.64	4.8	4.64	4.48	4.48	5.44	4.96	5.28	4.48	4.48	4.48	4.8
20	4.8	4.8	4.64	4.48	4.48	5.28	5.12	5.28	4.64	4.48	4.48	4.96
21	4.8	4.8	4.64	4.64	4.48	5.28	5.12	5.12	4.64	4.32	4.32	4.96
22	4.8	4.64	4.48	4.64	4.32	5.28	5.12	5.12	4.64	4.32	4.32	4.96
23	4.64		4.64	4.64		5.12	4.96	5.28	4.48	4.32	4.48	4.8
24	4.64		4.8	4.8		5.12	5.12	5.44	4.64		4.48	4.96
25	4.64		4.8	4.8		5.12	5.12	5.44	4.64		4.48	4.96
26			4.8	4.8		5.28	5.12	5.44	4.64		4.32	4.96
27			4.96	4.96		5.28	4.96	5.6	4.48			4.8
28			5.12	5.12		5.28		5.6				4.8
29			5.12	5.12		5.12		5.6				4.8
30			5.12	5.28		5.12		5.44				4.64
31			4.96	5.28		5.12		5.44				4.64
32			4.96	5.28		4.96		5.44				
33			4.96	5.44		4.96		5.28				
34			5.12	5.44		4.96		5.28				
35				5.44		4.8		5.28				
36						4.8		5.12				
37						4.8		5.12				
38						4.64		5.28				
39						4.8		5.28				
40						4.96		5.28				
41						4.96		5.12				
42						5.12		5.12				
43						5.28		5.12				
44						5.28		4.96				

45	5.44	4.96
46	5.6	4.96
47	5.76	
48	5.76	
49	5.76	
50	5.6	
51	5.6	
52	5.6	
53	5.44	
54	5.44	
55	5.44	
56	5.28	
57	5.28	
58	5.28	
59	5.12	

Table F-17: Difference threshold test magnitudes for 8 degree reference

Trial number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	8	8	8	8	8	8	8	8	8	8	8	8
2	8	8.32	8	8	8.32	8.32	8	8	8.32	8.32	8.32	8.32
3	8.32	8.64	8	8.32	8.32	8.32	8.32	8	8.32	8.64	8.32	8.64
4	8.32	8.96	7.68	8.64	8.32	8.32	8.32	7.68	8.64	8.64	8.64	8.64
5	8.64	8.96	8	8.64	8	8	8.32	7.68	8.64	8.64	8.96	8.64
6	8.64	8.96	8	8.96	8	8	8.64	7.68	8.64	8.32	8.96	8.32
7	8.96	9.28	8	8.96	8.32	8	8.96	7.36	8.32	8.64	8.96	8.32
8	8.96	9.28	8.32	8.96	8.64	8.32	8.96	7.68	8.64	8.64	9.28	8.64
9	8.96	9.28	8.64	9.28	8.64	8.64	8.96	8	8.64	8.64	9.28	8.96
10	8.64	8.96	8.64	9.28	8.64	8.64	8.64	8	8.96	8.32	9.6	8.96
11	8.96	8.96	8.96	9.28	8.96	8.96	8.96	8.32	8.96	8.32	9.6	8.96
12	8.96	8.96	9.28	8.96	8.96	9.28	8.96	8.32	8.96	8.32	9.92	8.64
13	8.96	8.64	9.28	8.96	9.28	9.28	9.28	8.64	8.64	8	9.92	8.96
14	8.64	8.64	9.28	9.28	9.6	9.6	9.28	8.96	8.64	8	9.92	8.96
15	8.64	8.96	8.96	9.6	9.92	9.92	9.28	8.96	8.64	8	9.6	8.96
16	8.64	8.96	8.96	9.6	9.92	9.92	9.6	9.28	8.32	8.32	9.6	8.64
17	8.96	8.96	8.96	9.6	9.92	9.92	9.6	9.28	8.32	8.32	9.6	8.64
18	8.96	8.64	8.64	9.28	9.6	9.6	9.6	9.28	8.64	8.32	9.28	8.64
19	8.96	8.96	8.64	9.28	9.6	9.6	9.28	9.6	8.64	8	9.28	
20	9.28	8.96	8.32	9.28	9.6	9.6	9.28	9.6	8.96	8	9.28	
21	9.6	8.96	8.32	8.96	9.28	9.92	9.28	9.6	9.28		9.6	
22	9.6	8.64	8.32	9.28	9.6	9.92	8.96	9.28	9.28		9.6	
23	9.6	8.64	8.64	9.28	9.6	10.24	8.96	9.28	9.28		9.6	
24	9.28	8.96	8.64	9.28	9.6	10.56	8.96	9.28	8.96		9.28	
25	9.28	9.28	8.96	8.96	9.28	10.56	8.64	8.96	8.96		9.6	
26	9.28	9.6	8.96	8.96	9.28	10.88	8.64	8.96	8.96		9.6	
27		9.6	9.28	8.96		11.2	8.96	8.96	8.64		9.92	
28		9.6	9.28			11.52	8.96	8.64			10.24	
29		9.28	8.96			11.52	9.28	8.64			10.24	
30		9.6	8.96			11.84	9.28	8.96			10.24	
31		9.6	8.96			11.84	9.28	9.28			9.92	
32		9.6	8.64			11.84	8.96	9.6				
33		9.28				11.52		9.6				
34		9.28				11.52		9.92				
35		9.28						9.92				
36		8.96						9.92				
37		8.96						9.6				
38		8.96										
39		9.28										
40		9.28										
41		9.28										

Table F-18: Difference threshold test magnitudes for 16 degree reference

Trial number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	16	16	16	16	16	16	16	16	16	16	16	16
2	16	16.64	16	16.64	16.64	16.64	16	16	16	16.64	16.64	16.64
3	16.64	16.64	16	16.64	17.28	16.64	16.64	16.64	16.64	17.28	16.64	17.28
4	17.28	16.64	15.36	16.64	17.28	17.28	16.64	16.64	16.64	17.28	16.64	17.28
5	17.28	16	16	17.28	17.28	17.28	16.64	16.64	17.28	17.28	17.28	17.28
6	17.28	16.64	16.64	17.28	17.92	17.28	16	16	17.92	17.92	17.28	16.64
7	16.64	16.64	16.64	17.28	17.92	17.92	16	16.64	17.92	17.92	17.28	17.28
8	16.64	17.28	16.64	16.64	17.92	17.92	16	17.28	17.92	17.92	16.64	17.28
9	17.28	17.92	17.28	17.28	17.28	17.92	15.36	17.92	18.56	18.56	16.64	17.28
10	17.28	17.92	17.28	17.28	17.92	17.28	16	17.92	18.56	18.56	17.28	16.64
11	17.28	17.92	17.28	17.28	17.92	17.28	16	17.92	18.56	18.56	17.28	17.28
12	16.64	18.56	16.64	16.64	18.56	17.28	16	17.28	19.2	17.92	17.92	17.28
13	16.64	18.56	16.64	16.64	18.56	16.64	16.64	17.28	19.2	18.56	17.92	17.28
14	17.28	18.56	16.64	17.28	18.56	17.28	16.64	17.92	19.2	18.56	18.56	17.92
15	17.28	17.92	17.28	17.28	17.92	17.28	16.64	18.56	19.84	18.56	18.56	17.92
16	17.92	17.92	17.28	17.92	17.92	17.28	16	18.56	19.84	17.92	18.56	17.92
17	17.92	18.56	17.28	18.56	17.92	16.64	16.64	18.56	19.84	17.92	17.92	17.28
18	17.92	18.56	16.64	18.56	17.28	17.28	16.64	17.92	19.2	17.92	17.92	17.28
19	17.28	18.56	17.28	18.56	17.92	17.92	17.28	17.92	19.2	17.28	18.56	17.28
20	17.28	17.92	17.28	19.2	17.92	17.92	17.28	17.92	19.2	17.28	18.56	16.64
21	17.28	18.56	17.28	19.2	17.92	17.92	17.28		19.84	17.28	18.56	16.64
22		18.56	16.64	19.84	18.56	17.28	16.64		19.84	17.92	17.92	16.64
23		18.56	16.64	20.48	18.56		16.64		19.84	17.92	17.92	16
24		19.2	17.28	20.48	18.56		16.64		19.2	17.92	17.92	16
25		19.84	17.92	20.48	17.92		16		19.2	17.28	17.28	
26		19.84		19.84	17.92		16		19.2		17.28	
27		19.84		19.84	17.92				18.56		17.28	
28		19.2		19.84	17.28				19.2		16.64	
29		19.2		20.48					19.2			
30		19.84		20.48					19.2			
31		19.84		20.48					18.56			
32		19.84		19.84					18.56			
33		19.2		19.84					18.56			
34		19.84		19.84					17.92			
35		19.84							17.92			

F.3 Raw data from Chapter 6: Scaling steering wheel force and steering wheel angle

Table F-19: Force magnitude estimates for 12 participants (where 100 = 10.5 N)

Test magnitude	Sub 1	2	3	4	5	6	7	8	9	10	11	12
50	30	70	25	30	50	50	30	60	40	25	30	50
60	80	60	30	75	40	85	100	50	50	40	50	30
70	30	80	30	50	70	70	60	80	20	25	80	40
80	90	90	60	60	80	150	70	80	30	50	60	90
90	100	130	100	70	100	95	70	70	120	80	100	100
100	120	110	90	100	130	110	120	100	100	120	100	120
120	150	120	100	85	110	200	90	140	90	100	120	90
140	150	120	120	90	170	140	100	130	160	100	120	150
160	150	140	120	140	140	320	100	150	170	150	140	120
180	175	160	160	180	150	250	150	180	200	130	170	125
200	200	170	200	200	200	300	150	180	250	170	150	250

Table F-20: Force magnitude production for 12 participants (in N)

Test magnitude (N)	Sub 1	2	3	4	5	6	7	8	9	10	11	12
5.3	9.5	13.6	10.4	14.4	12.8	14.3	7.3	7.3	11.5	5.6	8.9	21.5
6.3	9.1	13.9	7.0	15.2	9.2	16.8	12.2	2.6	12.8	9.6	8.9	7.9
7.4	9.6	12.0	9.6	11.1	13.0	12.7	11.3	2.8	9.7	9.7	10.2	7.5
8.4	11.4	21.1	11.3	14.8	11.0	10.8	11.9	1.8	8.9	7.4	7.8	28.5
9.5	11.5	13.4	11.5	18.1	11.8	10.8	10.8	4.8	11.9	6.5	10.3	19.8
10.5	11.7	17.0	11.7	15.8	10.4	17.9	15.4	12.5	10.9	17.0	11.8	20.4
12.6	11.1	14.8	11.1	29.3	12.0	23.9	13.7	11.7	15.5	16.0	11.5	22.6
14.7	9.0	28.2	16.3	44.1	12.2	25.1	45.5	10.7	16.4	17.7	14.8	21.4
16.8	15.2	23.9	16.2	20.9	13.0	14.0	33.7	19.0	17.7	17.1	16.5	24.8
18.9	13.9	47.6	16.4	41.4	13.8	25.6	36.7	14.0	20.3	20.2	14.6	30.1
21.0	18.3	52.5	19.8	52.5	15.8	29.5	33.7	16.8	12.6	22.1	18.9	35.6

Table F-21: Angle magnitude estimates for 12 participants (where 100 = 9 degrees)

Test magnitude	Sub 1	2	3	4	5	6	7	8	9	10	11	12
50	50	50	40	70	40	70	25	80	30	50	40	70
60	50	80	60	50	50	50	70	60	70	100	60	80
70	40	100	70	100	70	130	50	90	60	50	70	60
80	100	80	70	80	60	70	75	80	60	75	90	120
90	70	100	90	120	120	110	80	100	80	80	70	80
100	80	100	80	70	100	110	100	120	100	95	80	90
120	100	120	100	100	100	100	90	120	120	115	140	125
140	110	140	110	110	150	140	90	150	160	130	130	175
160	175	160	110	180	180	160	130	200	150	130	150	200
180	150	180	120	150	160	300	120	180	150	140	180	175
200	175	220	130	150	200	250	150	200	170	150	160	175

Table F-22: Angle magnitude production for 12 participants (in degrees)

Test magnitude (°)	1	2	3	4	5	6	7	8	9	10	11	12
4.5	4.8	4.7	6.8	5.4	3.4	6.6	5.5	5.7	5.4	4.7	5.0	10.5
5.4	7.6	5.5	5.5	5.2	4.4	6.9	4.7	4.8	5.5	6.4	5.5	17.5
6.3	6.7	5.1	7.2	5.2	3.8	5.8	8.6	6.6	6.4	7.5	7.7	16.3
7.2	8.8	6.5	7.6	6.9	5.0	8.3	7.3	6.1	7.7	5.6	7.8	12.7
8.1	8.7	7.6	15.3	7.7	8.6	8.8	8.7	8.8	6.5	7.5	8.6	9.2
9.0	10.3	9.3	12.4	10.9	9.4	10.7	11.9	9.9	9.1	9.9	10.8	17.0
10.8	9.5	11.1	21.9	15.8	6.3	12.1	15.9	10.4	10.9	14.2	10.2	20.9
12.6	11.5	12.2	23.9	14.6	9.5	19.0	15.5	12.2	18.8	13.5	11.6	12.1
14.4	14.7	16.0	33.7	16.1	13.5	13.6	18.6	13.1	18.1	16.4	14.5	25.2
16.2	13.3	19.2	45.8	20.3	20.9	15.0	24.1	16.1	17.9	19.2	17.2	26.3
18.0	24.2	21.4	48.0	29.5	15.6	20.8	21.6	19.3	21.3	19.9	19.5	27.4

F.4 Raw data from Chapter 7: Stiffness profile sensitivity

Table F-23: Difference threshold measurements for 12 participants. Reference stiffness profile *n* = 0.5 (values in the table refer to the exponent of the test stiffness profile)

Trial number	Sub 1	2	3	4	5	6	7	8	9	10	11	12
1	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
2	0.54	0.54	0.52	0.52	0.54	0.54	0.54	0.52	0.54	0.54	0.54	0.52
3	0.54	0.56	0.52	0.52	0.54	0.56	0.54	0.54	0.54	0.56	0.56	0.52
4	0.56	0.58	0.52	0.54	0.56	0.58	0.56	0.56	0.54	0.58	0.58	0.54
5	0.58	0.58	0.52	0.54	0.58	0.6	0.56	0.58	0.54	0.58	0.58	0.56
6	0.58	0.58	0.54	0.56	0.6	0.62	0.56	0.58	0.56	0.58	0.6	0.58
7	0.6	0.6	0.54	0.58	0.62	0.64	0.58	0.6	0.56	0.6	0.6	0.6
8	0.6	0.62	0.54	0.58	0.62	0.66	0.58	0.62	0.58	0.6	0.62	0.62
9	0.62	0.64	0.52	0.6	0.64	0.68	0.58	0.64	0.58	0.62	0.62	0.62
10	0.62	0.64	0.52	0.6	0.64	0.68	0.6	0.66	0.6	0.64	0.64	0.62
11	0.64	0.64	0.54	0.62	0.64	0.68	0.6	0.66	0.62	0.64	0.64	0.6
12	0.66	0.62	0.54	0.62	0.66	0.7	0.6	0.68	0.62	0.66	0.64	0.6
13	0.66	0.64	0.54	0.62	0.66	0.72	0.62	0.7	0.62	0.68	0.62	0.6
14	0.66	0.64	0.52	0.64	0.66	0.74	0.62	0.72	0.6	0.68	0.62	0.62
15	0.64	0.66	0.54	0.66	0.68	0.76	0.62	0.74	0.62	0.7	0.64	0.62
16	0.64	0.66	0.52	0.68	0.68	0.78	0.6	0.76	0.62	0.7	0.66	0.62
17	0.66	0.66	0.54	0.68	0.7	0.78	0.6	0.78	0.62	0.7	0.66	0.6
18	0.66	0.68	0.54	0.7	0.7	0.78	0.6	0.78	0.64	0.68	0.66	0.62
19	0.66	0.68	0.54	0.7	0.7	0.76	0.62	0.8	0.66	0.68	0.64	0.64
20	0.64	0.68	0.56	0.7	0.72	0.78	0.62	0.8	0.68	0.68	0.66	0.66
21	0.66	0.66	0.56	0.68	0.74	0.78	0.64	0.82	0.7	0.66	0.66	0.68
22	0.66	0.66	0.56	0.68	0.76	0.78	0.66	0.82	0.7	0.68	0.66	0.7
23	0.66	0.64	0.54	0.68	0.76	0.8	0.66	0.84	0.72	0.68	0.64	0.7
24	0.68	0.64	0.54	0.66	0.78	0.82	0.66	0.84	0.72	0.68	0.64	0.7
25	0.68	0.66	0.56	0.66	0.8	0.84	0.64	0.84	0.74	0.66	0.64	0.72
26	0.7	0.68	0.56	0.68	0.8	0.86	0.64	0.86	0.76	0.68	0.62	0.74
27	0.72	0.68	0.56	0.68	0.8	0.86	0.64	0.86	0.76	0.68	0.62	0.76
28	0.74	0.68	0.54	0.7	0.78	0.88	0.62	0.86	0.78	0.68	0.62	0.78
29	0.74	0.7	0.54	0.72	0.8	0.9	0.62	0.84	0.78	0.7	0.64	0.8
30	0.74	0.7	0.54	0.74	0.8	0.92	0.62	0.84	0.78	0.72	0.66	0.82
31	0.76	0.7	0.56	0.76	0.82	0.94	0.6	0.86	0.8	0.72	0.66	0.84
32	0.76	0.68	0.56	0.76	0.84	0.94	0.62	0.88	0.8	0.74	0.68	0.86
33	0.76	0.68	0.58	0.78	0.84	0.94	0.62	0.9	0.82	0.74	0.68	0.88
34	0.78	0.7	0.58	0.8	0.84	0.96	0.62	0.9	0.82	0.76	0.7	0.9
35	0.78	0.7	0.6	0.8	0.82	0.96	0.6	0.9	0.82	0.78	0.7	0.9
36	0.78	0.72	0.62	0.8	0.84	0.96	0.62	0.9	0.84	0.78	0.72	0.9
37	0.76	0.72	0.64	0.78	0.84	0.94	0.62	0.88	0.84	0.8	0.72	0.88
38	0.76	0.72	0.64	0.8	0.84	0.96	0.62	0.9	0.84	0.8	0.72	0.9
39	0.76	0.74	0.64	0.8	0.82	0.98	0.64	0.9	0.86	0.8	0.7	0.9
40	0.78	0.76	0.62	0.8	0.82	1	0.64	0.9	0.86	0.78	0.7	0.92
41	0.8	0.76	0.62	0.78	0.84	1	0.66	0.88	0.86	0.78	0.7	0.94
42	0.8	0.76	0.62	0.8	0.84	1	0.68	0.9	0.84	0.78	0.68	0.94

43	0.8	0.78	0.6	0.82	0.86	0.98	0.7	0.9	0.86	0.8	0.7	0.96
44	0.82	0.78	0.6	0.84	0.86	0.98	0.72	0.9	0.88	0.82	0.7	0.98
45	0.82	0.78	0.58	0.84	0.88	0.98	0.72	0.88	0.88	0.82	0.7	0.98
46	0.82	0.8	0.58	0.84	0.88	0.96	0.74	0.9	0.88	0.82	0.72	1
47	0.8	0.82	0.58	0.86	0.9	0.98	0.74	0.92	0.9	0.8	0.72	1
48	0.82	0.82	0.56	0.88	0.9	1	0.74	0.92	0.9	0.82	0.74	1.02
49	0.82	0.82	0.58	0.9	0.9	1	0.76	0.92	0.9	0.84	0.74	1.04
50	0.84	0.8	0.58	0.9	0.88	1.02	0.76	0.9	0.88	0.86	0.76	1.04
51	0.84	0.82	0.58	0.9	0.88	1.02	0.78	0.9	0.9	0.86	0.76	1.04
52	0.86	0.82	0.56	0.88	0.88	1.02	0.8		0.9	0.86	0.76	1.02
53	0.88	0.82	0.56	0.9	0.86	1	0.8		0.9	0.84	0.74	1.04
54	0.9	0.8	0.56	0.9	0.88	1	0.8		0.88		0.74	1.06
55	0.9	0.8	0.58	0.92	0.9	1	0.78		0.88			1.06
56	0.9	0.8	0.58	0.92	0.9	0.98	0.8		0.88			1.08
57	0.88		0.6	0.92	0.9	0.98	0.82		0.86			1.1
58	0.88		0.62	0.94	0.88	0.98	0.82		0.88			1.12
59	0.88		0.62	0.94	0.88	0.96	0.84		0.9			1.14
60			0.64	0.94	0.88	0.98	0.84		0.92			1.16
61			0.66	0.96	0.86	1	0.84		0.92			1.18
62			0.66	0.96	0.86	1	0.82		0.92			1.18
63			0.66	0.98	0.86	1.02			0.9			1.18
64			0.64	0.98		1.02			0.9			1.2
65			0.64	0.98		1.04						1.2
66			0.64	0.96		1.04						1.2
67			0.62			1.04						1.18
68			0.62			1.02						1.18
69			0.62			1.02						
70						1.02						
71						1						
72						1						
73						1						
74						0.98						

Table F-24: Difference threshold measurements for 12 participants. Reference stiffness profile $n = 0.8$ (values in the table refer to the exponent of the test stiffness profile)

Trial number	1	2	3	4	5	6	7	8	9	10	11	12
1	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
2	0.84	0.84	0.84	0.82	0.84	0.84	0.84	0.82	0.84	0.82	0.82	0.84
3	0.86	0.84	0.84	0.82	0.86	0.86	0.86	0.82	0.86	0.82	0.82	0.84
4	0.86	0.84	0.86	0.84	0.86	0.86	0.86	0.84	0.88	0.84	0.84	0.86
5	0.88	0.82	0.88	0.84	0.88	0.88	0.88	0.84	0.9	0.84	0.84	0.86
6	0.9	0.82	0.88	0.84	0.9	0.9	0.9	0.86	0.92	0.86	0.86	0.86
7	0.92	0.82	0.9	0.82	0.9	0.92	0.92	0.88	0.94	0.88	0.88	0.84
8	0.92	0.84	0.9	0.82	0.92	0.94	0.94	0.9	0.96	0.88	0.9	0.84
9	0.94	0.84	0.92	0.84	0.92	0.94	0.94	0.9	0.98	0.88	0.92	0.86
10	0.96	0.86	0.94	0.86	0.94	0.96	0.96	0.92	1	0.86	0.92	0.86
11	0.98	0.88	0.94	0.86	0.94	0.96	0.96	0.94	1	0.88	0.92	0.88
12	1	0.9	0.94	0.88	0.96	0.96	0.96	0.94	1	0.9	0.9	0.88
13	1.02	0.92	0.92	0.88	0.96	0.98	0.98	0.96	0.98	0.9	0.9	0.88
14	1.02	0.92	0.94	0.9	0.98	1	1	0.96	0.98	0.9	0.92	0.9
15	1.02	0.92	0.96	0.9	1	1	1	0.98	1	0.88	0.94	0.9
16	1.04	0.94	0.96	0.9	1.02	1.02	1.02	1	1.02	0.9	0.94	0.92
17	1.04	0.96	0.96	0.88	1.04	1.04	1.04	1	1.04	0.9	0.94	0.94
18	1.06	0.98	0.94	0.9	1.04	1.04	1.04	1	1.06	0.9	0.96	0.94
19	1.08	0.98	0.94	0.92	1.06	1.06	1.06	0.98	1.06	0.92	0.98	0.96
20	1.1	1	0.94	0.92	1.06	1.08	1.06	1	1.08	0.94	0.98	0.98
21	1.1	1	0.92	0.94	1.08	1.08	1.08	1.02	1.1	0.96	0.98	1
22	1.1	1	0.92	0.96	1.08	1.08	1.08	1.02	1.12	0.98	1	1.02
23	1.08	0.98	0.94	0.96	1.1	1.1	1.08	1.02	1.12	0.98	1.02	1.02
24	1.08	0.98	0.94	0.98	1.12	1.12	1.1	1.04	1.12	0.98	1.04	1.04
25	1.08	0.98	0.94	1	1.12	1.12	1.12	1.06	1.1	0.96	1.04	1.04
26	1.06	1	0.92	1.02	1.14	1.12	1.12	1.08	1.12	0.98	1.06	1.04
27	1.06	1	0.92	1.02	1.14	1.1	1.12	1.08	1.14	1	1.06	1.02
28	1.06	1	0.92	1.02	1.14	1.12	1.1	1.1	1.16	1.02	1.08	1.04
29	1.04	0.98	0.9	1	1.12	1.12	1.12	1.1	1.16	1.02	1.1	1.04
30	1.04	1	0.92	1	1.12	1.14	1.12	1.12	1.18	1.04	1.1	1.06
31	1.04	1.02	0.94	1	1.12	1.16	1.14	1.12	1.18	1.04	1.1	1.08
32	1.02	1.02	0.94	0.98	1.1	1.18	1.16	1.14	1.18	1.04	1.08	1.1
33	1.04	1.02	0.94	1	1.12	1.18	1.18	1.16	1.16	1.02	1.1	1.12
34	1.06	1.04	0.92	1.02	1.12	1.2	1.18	1.18	1.16	1.04	1.12	1.14
35	1.08	1.04	0.94	1.04	1.12	1.2	1.2	1.2	1.16	1.06	1.12	1.14
36	1.08	1.04	0.96	1.06	1.14	1.2	1.2	1.2	1.18	1.08	1.12	1.16
37	1.1	1.02	0.96	1.06	1.16	1.22	1.2	1.22	1.18	1.1	1.1	1.18
38	1.1	1.02	0.98	1.06	1.16	1.22	1.22	1.22	1.18	1.1	1.1	1.18
39	1.12	1.02	0.98	1.08	1.16	1.24	1.22	1.24	1.2	1.1	1.12	1.18
40	1.12	1	0.98	1.08	1.18	1.24	1.24	1.26	1.2	1.12	1.14	1.2
41	1.14	1.02	1	1.08	1.18	1.26	1.24	1.28	1.22	1.12	1.16	1.22
42	1.14	1.04	1.02	1.1	1.18	1.28	1.26	1.28	1.24	1.12	1.18	1.22
43	1.14	1.06	1.02	1.1	1.2	1.28	1.28	1.28	1.26	1.1	1.18	1.24
44	1.12	1.06	1.04	1.12	1.22	1.28	1.28	1.3	1.28		1.18	1.24

45	1.14	1.06	1.06	1.14	1.22	1.3	1.28	1.32	1.3	1.16	1.24
46	1.16	1.04	1.06	1.16	1.24	1.32	1.3	1.32	1.32	1.16	1.26
47	1.16		1.06	1.18	1.26	1.32	1.32	1.32	1.32	1.16	1.26
48	1.18		1.08	1.18	1.26	1.34	1.32	1.3	1.32	1.14	1.26
49	1.2		1.08	1.2	1.26	1.34	1.34	1.3	1.34	1.14	1.24
50	1.2		1.08	1.2	1.28	1.34	1.34	1.3	1.36	1.14	1.24
51	1.2		1.06	1.2	1.3	1.32	1.34	1.28	1.38	1.16	1.26
52	1.18		1.06	1.18	1.3	1.32	1.32	1.3	1.38	1.16	1.26
53	1.18		1.06	1.2	1.32	1.34	1.32	1.3	1.38	1.18	1.26
54	1.18		1.04	1.22	1.32	1.34	1.34	1.32	1.36	1.2	1.24
55	1.16		1.04	1.22	1.32	1.36	1.34	1.32	1.36	1.2	1.26
56	1.16		1.04	1.22	1.34	1.38	1.36	1.32	1.38	1.2	1.26
57	1.16		1.02	1.24	1.34	1.38	1.38	1.34	1.4	1.18	1.28
58	1.14			1.26	1.34	1.38	1.38	1.36	1.4	1.18	1.3
59	1.16			1.26	1.36	1.4	1.38	1.36	1.4	1.18	1.3
60	1.16			1.28	1.36	1.4	1.4	1.36	1.38	1.16	1.3
61	1.18			1.3	1.38	1.4	1.4	1.38	1.38		1.28
62	1.18			1.3	1.4	1.38	1.4	1.38	1.38		
63	1.18			1.3	1.4	1.38	1.38	1.4	1.36		
64	1.16			1.28	1.4	1.38	1.38	1.42	1.36		
65	1.16				1.38	1.36	1.38	1.44	1.36		
66	1.16				1.4	1.36	1.36	1.44	1.34		
67	1.18				1.42	1.38	1.36	1.44			
68	1.2				1.42	1.4	1.38	1.42			
69	1.2				1.42	1.42	1.4	1.44			
70	1.22				1.44	1.44	1.42	1.44			
71	1.24				1.44	1.44	1.44	1.46			
72	1.26				1.46	1.44	1.44	1.48			
73	1.26				1.48	1.42	1.44	1.5			
74	1.26				1.48	1.42	1.44	1.52			
75	1.28				1.5	1.42	1.42	1.54			
76	1.28				1.5	1.4	1.42	1.56			
77	1.3				1.5	1.42	1.42	1.56			
78	1.32				1.52	1.44	1.4	1.56			
79	1.32				1.52	1.44	1.42	1.54			
80	1.34				1.52	1.46	1.44	1.54			
81	1.34				1.54	1.48	1.44	1.56			
82	1.36				1.56	1.48	1.46	1.58			
83	1.38				1.56	1.48	1.48	1.58			
84	1.4				1.56	1.5	1.48	1.58			
85	1.4				1.54	1.52	1.48	1.56			
86	1.4				1.54	1.52	1.5				
87	1.42				1.54	1.52	1.52				
88	1.42				1.52	1.54	1.52				
89	1.44				1.52	1.56	1.52				
90	1.44				1.54	1.56	1.54				
91	1.44				1.54	1.56	1.56				
92	1.42				1.54	1.54	1.56				
93	1.42				1.52	1.54	1.56				
94	1.42				1.54		1.54				

95	1.4	1.54	1.54
96	1.4	1.54	
97	1.4	1.52	
98	1.38	1.52	
99	1.38	1.52	
100	1.38	1.5	
101	1.36		
102	1.36		
103	1.36		
104	1.34		
105	1.34		
106	1.34		
107	1.32		
108	1.32		
109	1.32		
110	1.3		
111	1.3		
112	1.3		
113	1.28		
114	1.28		

F.5 Raw data from Chapter 8: Linear feel

Table F-25: Linear feel experiment responses (value in the table is the more linear stimuli of the pair, values represent the exponent, *n*)

Subject	0.315 or 0.4	0.315 or 0.5	0.315 or 0.63	0.315 or 0.8	0.315 or 1.0	0.315 or 1.25	0.4 or 0.5	0.4 or 0.63	0.4 of 0.8	0.4 or 1.0	0.4 or 1.25	0.5 or 0.63	0.5 or 0.8	0.5 or 1.0	0.5 or 1.25	0.63 or 0.8	0.63 or 1.0	0.63 or 1.25	0.8 or 1.0	0.8 or 1.25	1.0 or 1.25
1	0.4	0.5	0.63	0.315	0.315	0.315	0.5	0.63	0.4	0.4	0.4	0.63	0.8	0.5	0.5	0.63	0.63	0.63	0.8	0.8	1.25
2	0.315	0.5	0.63	0.8	0.315	1.25	0.5	0.63	0.4	1.0	1.25	0.5	0.5	0.5	1.25	0.8	0.63	1.25	1.0	0.8	1.0
3	0.4	0.5	0.315	0.8	1.0	1.25	0.4	0.63	0.4	1.0	1.25	0.63	0.8	1.0	1.25	0.8	1.0	1.25	1.0	0.8	1.25
4	0.4	0.5	0.315	0.8	1.0	1.25	0.4	0.63	0.8	1.0	0.4	0.63	0.8	0.5	1.25	0.63	0.63	0.63	0.8	0.8	1.25
5	0.4	0.5	0.63	0.8	1.0	0.315	0.4	0.63	0.4	1.0	1.25	0.63	0.8	0.5	1.25	0.8	0.63	1.25	0.8	1.25	1.0
6	0.4	0.5	0.63	0.8	1.0	0.315	0.5	0.63	0.4	0.4	0.4	0.63	0.5	0.5	0.5	0.8	0.63	0.63	0.8	1.25	1.0
7	0.4	0.5	0.63	0.8	0.315	0.315	0.5	0.4	0.8	0.4	0.4	0.5	0.8	0.5	0.5	0.8	1.0	1.25	0.8	0.8	1.25
8	0.4	0.5	0.315	0.315	0.315	1.25	0.4	0.4	0.4	1.0	1.25	0.63	0.5	0.5	0.5	0.8	1.0	0.63	1.0	0.8	1.25
9	0.4	0.315	0.315	0.315	0.315	0.315	0.5	0.4	0.4	0.4	0.4	0.63	0.8	0.5	0.5	0.8	0.63	1.25	1.0	0.8	1.25
10	0.315	0.5	0.315	0.315	0.315	1.25	0.4	0.4	0.8	1.0	0.4	0.63	0.5	1.0	1.25	0.8	0.63	1.25	1.0	0.8	1.0
11	0.315	0.5	0.63	0.8	1.0	1.25	0.5	0.63	0.8	1.0	1.25	0.63	0.8	1.0	1.25	0.63	1.0	1.25	1.0	0.8	1.0
12	0.315	0.315	0.315	0.8	0.315	1.25	0.5	0.63	0.8	1.0	0.4	0.63	0.8	0.5	0.5	0.8	1.0	1.25	1.0	0.8	1.0
13	0.4	0.5	0.63	0.8	1.0	0.315	0.4	0.63	0.4	1.0	0.4	0.63	0.5	1.0	0.5	0.8	0.63	0.63	0.8	0.8	1.25
14	0.315	0.315	0.63	0.315	1.0	0.315	0.5	0.63	0.8	0.4	0.4	0.63	0.8	1.0	0.5	0.8	1.0	1.25	1.0	0.8	1.25
15	0.4	0.5	0.63	0.315	1.0	1.25	0.5	0.63	0.4	1.0	1.25	0.5	0.5	1.0	1.25	0.8	0.63	0.63	0.8	0.8	1.0
16	0.315	0.315	0.63	0.8	0.315	1.25	0.5	0.4	0.8	1.0	1.25	0.5	0.8	0.5	0.5	0.63	1.0	1.25	0.8	0.8	1.0
17	0.4	0.5	0.63	0.8	1.0	1.25	0.4	0.63	0.8	1.0	1.25	0.63	0.5	1.0	1.25	0.8	1.0	1.25	0.8	0.8	1.0
18	0.315	0.5	0.63	0.315	1.0	0.315	0.4	0.4	0.8	1.0	0.4	0.63	0.5	0.5	0.5	0.8	0.63	0.63	1.0	1.25	1.25
19	0.4	0.5	0.63	0.8	1.0	0.315	0.4	0.63	0.8	0.4	0.4	0.5	0.5	1.0	1.25	0.63	1.0	0.63	0.8	0.8	1.0
20	0.4	0.315	0.315	0.315	0.315	1.25	0.4	0.63	0.4	0.4	0.4	0.63	0.5	0.5	0.5	0.8	0.63	0.63	0.8	0.8	1.0
21	0.4	0.5	0.63	0.8	0.315	0.315	0.4	0.4	0.8	1.0	0.4	0.5	0.8	1.0	0.5	0.63	1.0	0.63	1.0	0.8	1.0

F.6 Raw data from Chapter 9: Preferred feel

Table F-26: Preferred feel experiment judgements (value in the table is the preferred stimuli of the pair, and represents the exponent, *n*)

Subject	0.25 or 0.315	0.25 or 0.4	0.25 or 0.5	0.25 or 0.63	0.25 or 0.8	0.25 or 1.0	0.315 or 0.4	0.315 or 0.5	0.315 of 0.63	0.315 or 0.8	0.315 or 1.0	0.4 or 0.5	0.4 or 0.63	0.4 or 0.8	0.4 or 1.0	0.5 or 0.63	0.5 or 0.8	0.5 or 1.0	0.63 or 0.8	0.63 or 1.0	0.8 or 1.0
1	0.315	0.4	0.5	0.63	0.8	1.0	0.315	0.5	0.63	0.8	1.0	0.4	0.63	0.8	1.0	0.5	0.8	1.0	0.8	1.0	0.8
2	0.25	0.25	0.25	0.25	0.25	0.25	0.315	0.5	0.315	0.8	0.315	0.5	0.4	0.4	0.4	0.63	0.5	0.5	0.63	0.63	0.8
3	0.315	0.25	0.5	0.63	0.25	1.0	0.315	0.5	0.315	0.315	0.315	0.4	0.63	0.4	1.0	0.5	0.8	0.5	0.63	1.0	0.8
4	0.315	0.25	0.5	0.63	0.25	0.25	0.315	0.5	0.315	0.315	0.315	0.4	0.63	0.4	0.4	0.5	0.5	0.5	0.63	0.63	0.8
5	0.25	0.4	0.5	0.63	0.8	1.0	0.4	0.5	0.63	0.8	1.0	0.5	0.63	0.4	0.4	0.5	0.5	0.5	0.8	0.63	0.8
6	0.25	0.4	0.5	0.25	0.25	0.25	0.4	0.315	0.63	0.315	0.315	0.5	0.63	0.8	1.0	0.63	0.5	1.0	0.8	1.0	1.0
7	0.315	0.4	0.5	0.25	0.8	0.25	0.4	0.5	0.315	0.315	0.315	0.5	0.4	0.4	0.4	0.63	0.5	0.5	0.63	0.63	0.8
8	0.315	0.4	0.25	0.25	0.25	1.0	0.315	0.5	0.315	0.8	0.315	0.4	0.63	0.8	0.4	0.5	0.5	0.5	0.63	0.63	0.8
9	0.315	0.25	0.25	0.63	0.25	1.0	0.4	0.5	0.315	0.315	0.315	0.5	0.63	0.4	0.4	0.63	0.5	0.5	0.8	1.0	0.8
10	0.315	0.25	0.5	0.63	0.25	1.0	0.315	0.5	0.63	0.8	1.0	0.5	0.4	0.8	1.0	0.5	0.8	0.5	0.63	0.63	1.0
11	0.25	0.4	0.5	0.25	0.8	1.0	0.315	0.5	0.315	0.315	0.315	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.63	0.63	0.8
12	0.315	0.4	0.5	0.63	0.8	1.0	0.4	0.5	0.63	0.8	0.315	0.5	0.63	0.8	0.4	0.5	0.5	0.5	0.8	1.0	0.8
13	0.315	0.4	0.5	0.25	0.8	1.0	0.4	0.5	0.315	0.8	0.315	0.4	0.4	0.8	1.0	0.63	0.8	0.5	0.63	1.0	1.0
14	0.315	0.4	0.5	0.25	0.8	0.25	0.315	0.5	0.63	0.315	0.315	0.5	0.4	0.8	0.4	0.5	0.8	0.5	0.63	0.63	0.8
15	0.315	0.4	0.5	0.25	0.25	0.25	0.315	0.5	0.63	0.315	1.0	0.5	0.63	0.4	0.4	0.5	0.5	1.0	0.63	0.63	1.0
16	0.315	0.25	0.5	0.63	0.8	1.0	0.315	0.5	0.63	0.8	1.0	0.5	0.63	0.8	1.0	0.5	0.8	0.5	0.63	1.0	1.0
17	0.315	0.4	0.25	0.63	0.25	1.0	0.315	0.5	0.63	0.8	0.315	0.4	0.63	0.4	0.4	0.5	0.5	0.5	0.8	0.63	0.8
18	0.315	0.4	0.25	0.63	0.8	1.0	0.315	0.5	0.63	0.8	1.0	0.5	0.63	0.8	0.4	0.5	0.5	1.0	0.63	0.63	0.8
19	0.25	0.25	0.25	0.25	0.25	0.25	0.4	0.315	0.315	0.315	0.315	0.4	0.63	0.8	0.4	0.5	0.5	0.5	0.63	0.63	0.8
20	0.315	0.4	0.5	0.63	0.8	1.0	0.4	0.315	0.315	0.8	1.0	0.5	0.63	0.4	1.0	0.63	0.8	0.5	0.63	0.63	0.8
21	0.25	0.25	0.5	0.63	0.25	1.0	0.4	0.5	0.63	0.315	0.315	0.5	0.4	0.4	1.0	0.5	0.63	0.5	0.63	0.63	1.0

Table F-27: Raw data from free choice preferred stiffness profile. Reference exponent *n* = 0.45 (values represent force in N)

Angle (°)	Sub 1	2	3	4	5	6	7	8	9	10	11	12
0.4	1.6	2.1	1.3	1.9	0.7	1.2	2.1	1.2	2.1	1.9	1.6	1.8
0.8	2.2	2.8	1.9	2.7	1.4	1.9	2.7	1.9	2.6	2.4	2.2	2.6
1.2	2.7	3.3	2.4	3.2	2.0	2.4	3.2	2.3	3.0	2.8	2.5	3.0
1.6	3.1	3.6	2.8	3.6	2.4	2.9	3.6	2.6	3.3	3.2	3.0	3.3
2	3.4	3.9	3.1	4.0	2.8	3.3	4.0	3.0	3.8	3.6	3.3	3.6
3	4.1	4.4	3.8	4.5	3.5	4.0	4.7	3.6	4.4	4.1	3.9	4.2
4	4.7	4.8	4.2	5.0	3.9	4.6	5.2	4.2	4.9	4.7	4.3	4.8
5	5.2	5.1	4.8	5.4	4.4	5.0	5.5	4.6	5.5	5.2	4.9	5.3
6	5.6	5.6	5.3	5.8	4.9	5.5	5.8	5.1	5.9	5.6	5.1	5.8
7	6.0	6.0	5.7	6.2	5.2	5.9	6.1	5.4	6.3	6.0	5.4	6.2
8	6.4	6.4	6.0	6.5	5.7	6.3	6.4	5.8	6.7	6.4	5.7	6.5
9	6.7	6.7	6.5	6.9	5.9	6.7	6.7	6.2	7.1	6.7	5.8	6.7
10	7.1	7.1	6.7	7.2	6.3	7.1	7.1	6.6	7.3	7.1	6.1	7.1
11	7.4	7.4	7.0	7.6	6.6	7.4	7.4	6.7	7.6	7.4	6.3	7.4
12	7.7	7.7	7.3	7.8	6.9	7.7	7.7	7.1	7.8	7.7	6.4	7.7
13	7.9	7.9	7.6	7.9	7.3	7.9	7.9	7.3	8.2	7.9	6.5	7.9
14	8.2	8.2	7.8	8.2	7.5	8.2	8.2	7.6	8.5	8.2	6.7	8.2
15	8.5	8.5	8.2	8.5	7.8	8.5	8.5	7.8	8.7	8.5	6.8	8.5
16	8.7	8.7	8.4	8.7	8.0	8.7	8.7	8.0	9.0	8.7	6.9	8.7
17	9.0	9.0	8.7	9.0	8.5	9.0	9.0	8.2	9.3	9.0	7.2	9.0
18	9.3	9.2	9.0	9.2	8.8	9.2	9.2	8.5	9.6	9.2	7.5	9.2
19	9.6	9.4	9.2	9.4	9.1	9.4	9.4	8.7	9.8	9.4	7.6	9.4
20	9.8	9.7	9.4	9.7	9.3	9.7	9.7	8.9	10.0	9.7	8.0	9.7
21	10.1	9.9	9.6	9.9	9.6	9.9	9.9	9.1	10.2	9.9	8.4	9.9

22	10.3	10.1	9.8	10.1	9.9	10.2	10.1	9.4	10.4	10.1	8.7	10.1
23	10.5	10.3	10.0	10.3	10.0	10.4	10.3	9.6	10.6	10.3	9.0	10.2
24	10.6	10.5	10.2	10.5	10.3	10.6	10.5	9.8	10.7	10.5	9.4	10.3
25	10.7	10.7	10.4	10.7	10.7	10.8	10.7	10.3	11.0	10.7	9.6	10.5
26	10.9	10.9	10.5	10.9	10.9	11.0	10.9	10.6	11.2	10.9	10.0	10.5
27	11.1	11.1	10.9	11.1	11.1	11.2	11.1	10.8	11.3	11.1	10.4	10.7
28	11.2	11.2	11.1	11.2	11.2	11.4	11.2	11.0	11.4	11.2	10.9	10.9
29	11.4	11.4	11.3	11.4	11.4	11.5	11.4	11.2	11.4	11.4	11.2	11.2
30	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6

Table F-28: Raw data from free choice preferred stiffness profile. Reference exponent $n = 1$ (values represent force in N)

Angle (°)	Sub 1	2	3	4	5	6	7	8	9	10	11	12
0.4	1.1	2.0	0.9	0.9	0.1	0.9	2.1	1.4	0.7	2.1	0.9	0.8
0.8	1.9	2.6	1.5	1.0	0.3	1.5	3.0	1.8	1.0	3.0	1.5	1.4
1.2	2.2	3.3	2.2	1.4	0.4	1.8	3.8	2.1	1.4	3.5	1.9	1.7
1.6	2.5	3.8	2.4	1.5	0.6	2.2	4.1	2.7	1.6	3.9	2.4	2.0
2	2.9	4.1	3.0	1.7	0.7	2.5	4.6	2.9	2.0	3.9	2.7	2.3
3	3.4	4.8	3.6	2.0	1.1	3.1	5.7	3.2	2.2	4.4	3.3	2.8
4	3.8	5.4	3.9	2.5	1.5	3.6	6.7	3.6	2.7	4.6	3.7	3.3
5	4.1	5.7	4.2	2.7	1.8	3.9	6.9	3.8	3.0	4.9	4.1	3.4
6	4.4	5.9	4.5	3.3	2.2	4.1	7.2	4.0	3.5	5.1	4.3	3.9
7	4.6	6.0	4.8	3.7	2.6	4.5	7.5	4.3	4.1	5.5	4.5	4.3
8	4.5	6.4	5.1	4.0	2.9	4.9	7.7	4.6	4.7	5.7	4.7	4.5
9	4.9	6.5	5.2	4.4	3.3	4.9	7.8	4.8	5.2	5.7	4.8	4.8
10	5.0	6.9	5.3	4.7	3.7	5.2	7.9	5.2	5.4	5.7	5.2	5.0
11	5.3	6.9	5.6	5.1	4.0	5.4	8.1	5.5	5.8	5.9	5.5	5.2
12	5.3	7.0	5.9	5.6	4.4	5.7	8.1	5.7	6.3	6.1	5.7	5.6
13	5.5	7.2	6.2	5.8	4.8	5.9	8.2	5.7	6.6	6.2	6.0	5.9
14	5.6	7.5	6.3	6.3	5.1	6.3	8.4	6.0	7.0	6.5	6.3	6.1
15	5.7	7.8	6.7	6.5	5.5	6.6	8.7	6.2	7.4	6.8	6.7	6.3
16	6.0	7.8	7.0	6.9	5.8	6.7	8.7	6.5	7.6	7.2	6.9	6.5
17	6.1	7.9	7.4	7.4	6.2	7.0	8.9	6.6	8.0	7.5	7.1	6.9
18	6.3	8.1	7.7	7.7	6.4	7.3	9.1	6.9	8.4	7.8	7.3	6.9
19	6.6	8.5	8.1	8.2	6.9	7.4	9.3	7.4	8.7	8.3	7.5	7.4
20	6.9	8.6	8.3	8.3	7.4	7.5	9.3	7.7	9.1	8.5	7.9	7.3
21	7.1	9.1	8.7	8.8	7.6	7.7	9.5	8.1	9.4	8.6	8.1	7.7
22	7.5	9.1	9.0	9.1	8.1	8.1	9.7	8.4	9.6	8.9	8.4	8.1
23	7.7	9.4	9.3	9.4	8.6	8.5	9.9	8.7	9.8	9.2	8.7	8.2

24	8.0	9.6	9.5	9.6	8.9	8.8	10.1	9.0	10.0	9.3	9.1	8.5
25	8.3	9.9	9.7	9.8	9.2	9.2	10.2	9.3	10.2	9.4	9.3	8.9
26	8.9	10.0	10.0	9.9	9.4	9.6	10.4	9.5	10.4	9.8	9.8	9.3
27	9.5	10.2	10.4	10.1	9.8	9.9	10.7	9.9	10.5	10.0	10.1	9.6
28	10.1	10.5	10.5	10.3	10.1	10.3	10.9	10.3	10.7	10.5	10.4	10.3
29	10.5	10.8	10.8	10.7	10.5	10.7	11.1	10.5	10.9	10.8	10.7	10.7
30	11.0	11.0	11.0	11.0	11.0	11.0	11.3	11.0	11.0	11.0	11.0	11.0