Driver perception of steering feel

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Abstract: Steering feel is optimized at a late stage of vehicle development, using prototype vehicles and expert opinion. An understanding of human perception may assist the development of a good 'feel' earlier in the design process. Three psychophysical experiments have been conducted to advance understanding of factors contributing to the feel of steering systems. The first experiment, which investigated the frames of reference for describing the feel (i.e. haptic properties) of a steering wheel, indicated that subjects focused on the steady state force that they applied to the wheel rather than the steady state torque, and on the angle that they turned the wheel rather than the displacement of their hands. In a second experiment, thresholds for detecting changes in both steady state steering-wheel force and steady state steering-wheel angle were determined as about 15 per cent. The rate of growth in the perception of steady state steering-wheel force and steady state steering-wheel angle were determined using magnitude estimation and magnitude production. It was found that, according to Stevens' power law, the sensation of steady state steering-wheel force increases with a power of 1.39 with increased force, whereas the perception of steady state steering-wheel angle increases with a power of 0.93 with increased steering-wheel angle. The implications for steering systems are discussed.

Keywords: steering feel, proprioceptive, haptic feedback

1 INTRODUCTION

Driving a car is a complex task and involves many interactions between the driver and the vehicle through the various controls. Good performance of the system depends on how well a car is able to create the driver's intentions, and how well differences between those intentions and the vehicle's response can be detected by the driver. The steering system is one of the primary controls in a car, allowing the driver to control the direction of the vehicle. The steering system not only allows the driver to control the car but also provides the driver with feedback through haptic (i.e. touch) senses, giving cues to the state of the road–tyre interface.

Forces originating at the road–tyre interface (and related to the road wheel angle, vehicle speed, and road adhesion), present themselves at the steering wheel (subject to kinematic losses through the steering system, and subject to various assist methods in steering systems, e.g. hydraulic and electric power assist) where the driver can interact with them and develop an internal model of the steering properties and the environment.

The relationship between the steering-wheel torque and the steering-wheel angle has been considered a useful means of describing steering feel [**1**]. Various 'metrics' of the relationship are used to define steering feel [**2–5**], and experiments have found that changing the relation between the steering-wheel force and steering-wheel angle can alter the driving experience [**6**]. Knowledge of the way in which haptic stimuli at the steering wheel are perceived by drivers may therefore assist the development of steering-system designs.

The perception of stiffness [**7**] and the perception of viscosity [**8**] seem to come from force, position, and velocity cues. Psychophysiological studies indicate that muscle spindle receptors, cutaneous mechanoreceptors, and joint receptors provide the neural

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inputs used in the perception of the movement and force applied by a limb [**9**].

Psychophysics provides techniques to describe how subjects perceive stimuli. Classic measures include the difference threshold (the minimum change needed to detect a change in a stimulus) and the psychophysical function (the relationship between changes in stimulus magnitude and the perception of those changes). However, the first step in quantifying steering feel using psychophysical methods is to identify what aspects of the haptic feedback at the steering wheel are used by drivers.

Steering torque and steering angle describe the steady state characteristics of steering systems and their relationships have been identified as influencing steering feel [**2–5**]. It seems appropriate to check whether subjects are judging what the experimenter is measuring. It has not been shown whether the properties of steering system should be described in rotational frames of reference (i.e. torque and angle) or translation frames of reference (i.e. force and displacement).

This paper describes three experiments designed to study how drivers perceive the steady state properties of steering wheels. The first experiment investigated whether rotational or translation frames of reference are more intuitive to subjects. It was hypothesized that, if asked to ‘match’ different steering-wheel sizes, either the rotational or the translation frame of reference would be matched more consistently. The second experiment determined difference thresholds for the perception of steering-wheel force and angle, with the hypothesis that Weber’s law would apply for both stimuli. The third experiment investigated the psychophysical scales for the perception of the physical properties at steering wheels by determining relationships between steering-wheel force and the perception of steering-wheel force, and between steering-wheel angle and the perception of steering-wheel angle. It was hypothesized that Stevens’ power law provides an adequate model for describing the psychophysical scales.

2 APPARATUS

A rig was built to simulate the driving position of a 2002 model year Jaguar S-type saloon car as shown in Fig. 1. The framework provided a heel point for subjects and supported a car seat and steering column assembly. The cross-section of a Jaguar S-type steering wheel was used to create the grips of the experimental steering wheel, which was formed by a rapid prototype polymer finished with production quality leather glued and stitched on to the grip.

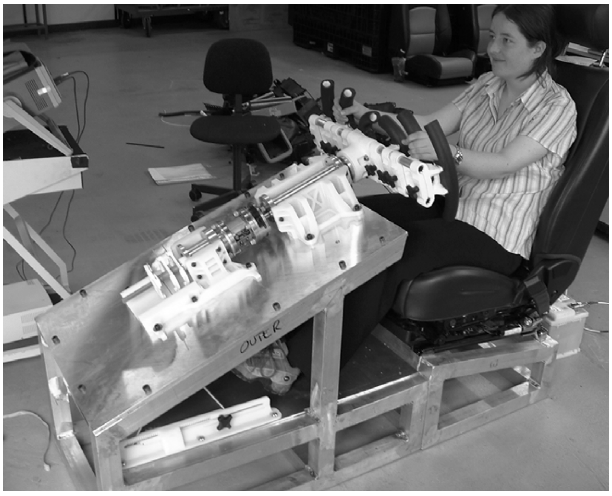

Fig. 1 Test apparatus

Subject posture was constrained by the seat, steering wheel, and heel point. The joint angle at the elbow was monitored and adjusted to 110° for all subjects to ensure that they did not sit too close or too far from the steering wheel.

The steering-column assembly included an optical incremental encoder to measure angle (resolution, 0.044°), a strain gauge torque transducer to measure torque (0.01 N accuracy), bearings to allow the wheel to rotate freely (isotonic control), and a clamp to lock the column in position (isometric control).

3 EXPERIMENTS

Three experiments were performed to investigate the response of the driver to steady state steering-wheel properties and to determine, firstly, the driver frame of reference, secondly, the difference thresholds for the perception of force and angle, and, thirdly, the rate of growth of sensations of force and angle.

The experiments were approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

3.1 Driver’s frame of reference

Frames of reference provide 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). For some tasks, the choice of reference frame may be merely a matter of convenience. In human spatial cognition and navigation the reference frame determines human perception. The haptic perception of steering-wheel position and motion is influenced by the spatial constraint imposed on the wheel, which can only rotate about a column.

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, drivers may use neither allocentric nor egocentric frames of reference and instead may employ some intermediate reference frame as suggested by Kappers [**10**].

This experiment aims to test whether drivers sense steering-wheel force or torque, and whether they sense angle or displacement. The relationships between these properties are

$$T = rF \tag{1}$$

$$x = r\theta \tag{2}$$

To investigate which variable is intuitively used by drivers, it is necessary to uncouple the relationship between rotational and translation frames of reference. This can be achieved by altering the radius of the steering wheel. It was hypothesized that, when asked to 'match' a reference condition using isometric steering wheels (i.e. wheels that do not rotate) with varying radii, subjects would match either the force applied by the hand or the torque applied to the steering wheel. It was similarly hypothesized that, when using isotonic steering wheels (i.e. wheels that rotate without resistance to movement) with varying radii, subjects would match either the displacement of the hand on the steering wheel or the angle through which the steering wheel was turned.

3.1.1 Method

Using the 'method of adjustment' [**11**], subjects 'matched' sensations from a 'reference' steering wheel to a 'test' steering wheel. When grasping the reference wheel, subjects 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. Instructions on the computer monitor then instructed the subjects to move their hands to either the 'small', 'medium', or 'large' steering wheel, and to 'match' the sensation experienced with the reference wheel. Subjects were required to achieve the reference or match within 6 s, and to hold the force or angle for 4 s. Subjects were required to move their hands to the test condition within the 6 s given to achieve the match. The total time for one reference and match trial was 20 s.

Subjects attended two sessions, one with isometric steering wheels and one with isotonic steering wheels. Four reference conditions were presented in each session: 5 N, 15 N, 1.5 N m, and 3 N m with the isometric steering wheels, and 3°, 9°, 10 mm, and 30 mm with the isotonic steering wheels. The forces and distances refer to the forces and distances at the rim of the steering wheel.

For this experiment, 12 male subjects, aged between 18 and 26 years, took part using a within-subjects experimental design where all subjects participated in all conditions. The order of presentation of the reference conditions was balanced across subjects. For six subjects, the first session used the isometric steering wheels; for the other six subjects, the first session used the isotonic steering wheels.

For each reference condition, a total of 18 trials were undertaken: nine trials to account for each combination of three reference wheels and three diameters of test wheel (small, medium, and large) including matching to the same wheel, and a repeat of these nine conditions.

The length of time that subjects were required to hold a force or torque was minimized to prevent fatigue. Typically, subjects took 10 s to reach the desired force or angle. The view of their hands was obscured so that subjects did not receive visual feedback of their position or movement.

3.1.2 Results

The results for a typical subject in the experiment with isometric control are shown in terms of force in Fig. 2, and in terms of torque in Fig. 3. The results for a typical subject in the experiment with isotonic control are shown in terms of angle in Fig. 4 and in terms of displacement in Fig. 5.

Correlation coefficients between the physical magnitudes of the reference condition and the test condition are presented for each subject in Table 1. For isometric control, correlation coefficients were obtained for both torque and force at the steering-wheel rim. For 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, or angle or displacement) is the most efficient engineering term to represent the data.

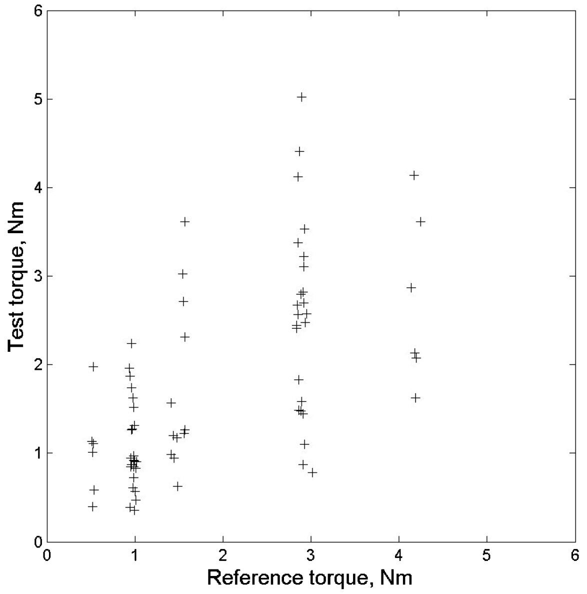

Fig. 2 Relation between steady state reference torque and test torque for isometric control (data from one subject)

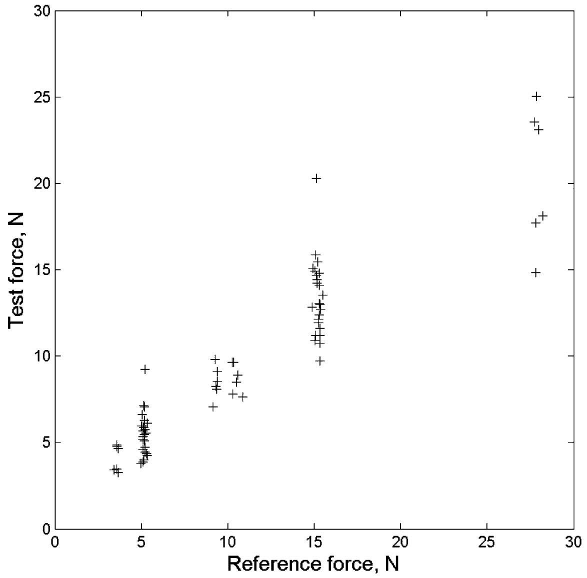

Fig. 3 Relation between steady state reference force and test force for isometric control (data from one subject)

Over the 12 subjects, for 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 isotonic control, the correlation coefficients obtained for angle were significantly higher than those obtained for displacement ($p < 0.01$).

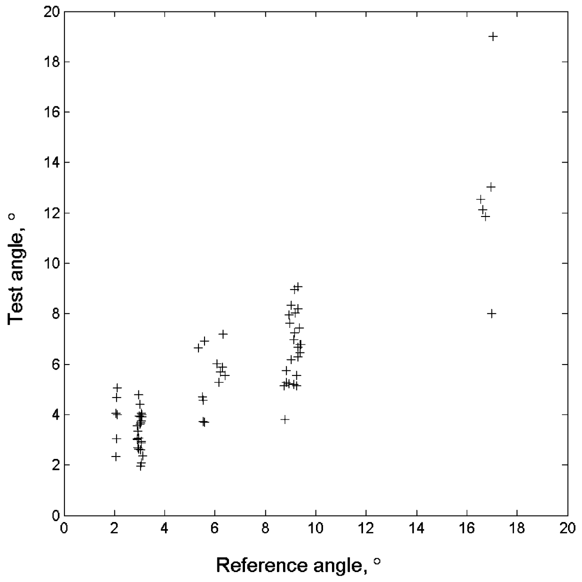

Fig. 4 Relation between steady state reference angle and test angle for isotonic control (data from one subject)

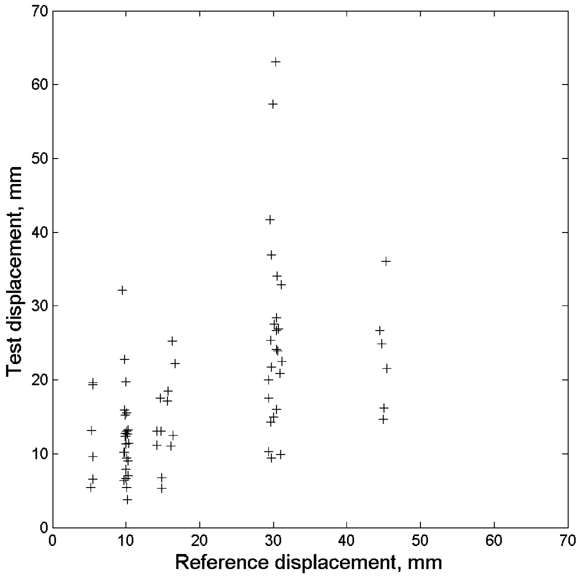

Fig. 5 Relation between steady state reference displacement and test displacement for isotonic control (data from one subject)

3.1.3 Discussion

Lines of best fit to the data had gradients of less than unity for 11 subjects. The single subject that achieved a slope greater than 1.0 did so only for angle data. The effect could have arisen from the reference being presented first (i.e. an order effect). Alternatively, it could indicate that the physical variables do not reflect the parameters adjusted by

Table 1 Spearman's rho correlations coefficients ρ between reference magnitude and test magnitude (all Spearman rho correlation coefficients in the table are significant at $p < 0.01$)

	Correlation coefficient ρ			
	Isometric wheel		Isotonic wheel	
Subject	Torque	Force	Angle	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

the subjects. Regardless of the deviations of references and 'matches' from the 45° line, 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'.

The results suggest that with idealized isometric and isotonic controls, drivers have a better sense of steering-wheel force than steering-wheel torque and a better sense of steering wheel-angle than steering-wheel displacement. It seems that subjects used the forces in their muscles and the angles at the joints of their hands and arms to position the steering wheels.

To judge torque, subjects 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, subjects 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 distance result in less accurate judgements and are not preferred or 'natural'.

3.2 Difference thresholds

A difference threshold is the smallest change in a stimulus required to produce a just noticeable difference in sensation [**11**]. 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

$$\frac{\Delta\phi}{\phi} = c \tag{3}$$

where c is a constant known as the 'Weber fraction', often expressed as a percentage.

Difference thresholds for the perception of force are available in a variety of forms. Jones [**12**] reported the difference threshold as a Weber fraction of 0.07 (7 per cent) for forces generated at the elbow flexor muscles. Difference thresholds for lifted weights have been reported by Laming [**13**] based on an experiment by Fechner [**14**] using weights from 300 to 3000 g, resulting in a Weber fraction of 0.059 (5.9 per cent), and Oberlin [**15**] measured difference thresholds for lifted weights from 50 to 550 g, giving a Weber fraction of 0.043 (4.3 per cent).

Haptic discrimination of finger span with widths varying from 17.7 to 100 mm have been reported as 0.021 (2.1 per cent) by Gaydos [**16**]. Discrimination of elbow movement has been reported as 8 per cent by Jones *et al.* [**17**], while discrimination of sinusoidal movements of the finger studied by Rinker *et al.* [**18**] produced difference thresholds that ranged from 10 per cent to 18 per cent.

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

3.2.1 Method

Difference thresholds were determined with a two-alternative forced-choice procedure using an up-and-down transformed response (UDTR) method [**19**]. Subjects were required to act on the steering wheel to achieve a reference force or reference angle, followed by a test stimulus. The required levels for both actions were presented on a characterless 11-point scale on a computer monitor. The reference stimulus and a test stimulus were presented sequentially, and in random order, to subjects who were required to report which of the two stimuli 'felt greater'. The UDTR method was used with a three-down one-up rule (i.e. three correct responses in a row caused the test stimulus to become closer to the reference stimulus whereas one incorrect response resulted in an increase in the difference between the reference and the test stimulus). The three-up one-down rule means that the difference threshold is observed at a 79.4 per cent correct response level [**19**].

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

For this experiment, 12 male subjects, aged between 18 and 28 years, took part using a within-subjects experimental design. The order of presentation for the reference conditions was balanced across subjects with six subjects starting with isotonic control, and six starting with isometric control.

3.2.2 Results

The median absolute and relative difference thresholds are shown in Table 2. For both force and angle, the absolute difference thresholds increased significantly with increasing magnitude of the reference ($p < 0.01$, Friedman test).

The median absolute and relative difference thresholds for both force and angle are shown in Fig. 6 and Fig. 7 respectively. The median relative difference thresholds tended to decrease (from 16.5 per cent to 11.5 per cent) with increases in the reference force and decrease (from 17.0 per cent to 11.5 per cent) with increases in the reference angle. However, overall, the relative difference thresholds did not differ significantly over the three force references or over the three angle references ($p > 0.4$, Friedman test).

3.2.3 Discussion

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

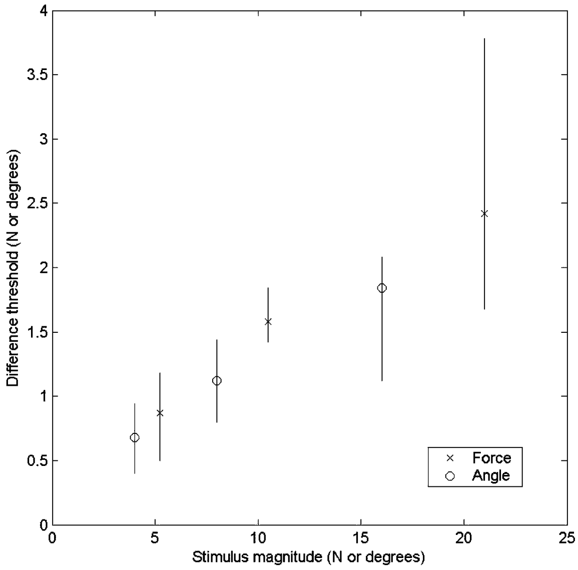

Fig. 6 Absolute difference thresholds for steady state force and angle (medians and interquartile range)

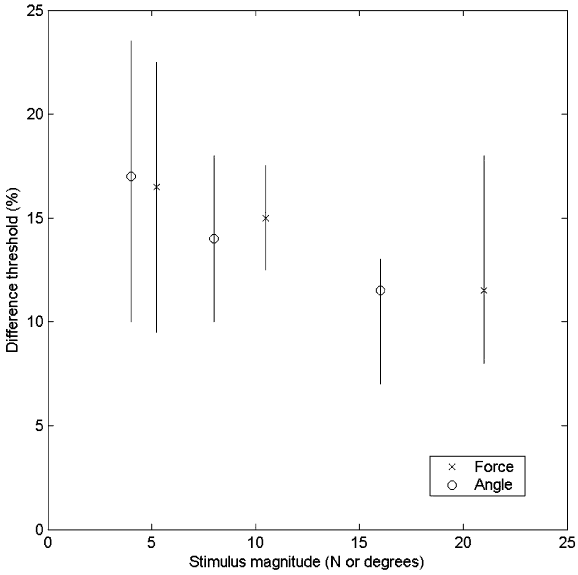

Fig. 7 Relative difference thresholds for steady state force and angle (medians and interquartile range)

Table 2 Median difference thresholds ($N = 12$)

	Threshold values for the following reference values					
	Force			Angle		
Threshold (units)	5.25 N	10.5 N	21 N	4°	8°	16°
Absolute difference threshold (units same as stimuli)	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 mean relative difference thresholds across the magnitudes of the reference stimuli were 15 per cent when detecting changes in force and 14 per cent 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 per cent relative difference threshold was obtained with a correct performance level of 79.4 per cent. Direct comparison with the aforementioned studies of the perception of force are not possible, as correct response levels are not presented in those studies. For the perception of angle, 14 per cent in the present study compares with a difference threshold for limb movement in the range 10–18 per cent (for a 71 per cent correct performance level) according to Rinker *et al.* [**18**], and 8 per cent (for a 71 per cent correct performance level) according to Jones *et al.* [**17**].

3.3 Rate of growth of sensation

The rate of growth of sensation of stimuli has often been determined using Stevens' power law [**20**]

$$\psi = k\phi^n \tag{4}$$

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 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 [**21–24**]. A study of the haptic sensation of finger span by Stevens and Stone [**25**] using widths of 2.3–63.7 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 subjects to make numerical estimations of the perceived magnitudes of sensations, whereas magnitude production requires subjects to adjust the stimulus to produce sensory magnitudes equivalent to given numbers. These methods have systematic biases which Stevens [**20**] called a 'regression effect' [**11**]. The biases are attributed to a tendency for subjects to limit the range of stimuli over which they have control; so with magnitude estimation they limit the range of numbers that they report, and in magnitude production they limit the range of stimuli that they produce. The bias causes magnitude production to yield steeper slopes (i.e. higher values for n) than magnitude estimation.

The third experiment employed both magnitude estimation and magnitude production to develop a scale of perception of steady state steering-wheel force and steady state steering-wheel angle.

3.3.1 Method

For magnitude estimation, a subject 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. Subjects were told that the reference corresponded to 100. A subject then applied 11 different test forces (or angles) by applying a force or angle until the pointer was placed at the middle mark of the 11-point scale. The forces or angles required corresponded to 50 per cent, 60 per cent, 70 per cent, 80 per cent, 90 per cent, 100 per cent, 120 per cent, 140 per cent, 160 per cent, 180 per cent, and 200 per cent of the reference force or angle. For force, these stimuli ranged from 5.25 N to 21 N while, for angle, they ranged from 4.5° to 18°. After the presentation of a test stimulus, a subject was asked to report a number considered to represent the test force (or angle) in proportion to the reference. The presentation order of the test stimuli was randomized. For magnitude production, a subject 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. The subject was told that this corresponded to 100. The scale was removed and a number was displayed instead (50, 60, 70, 80, 90, 100, 120, 140, 160, 180, or 200) and the subject was asked to produce a force (or angle) corresponding to the given number in proportion to the reference. The presentation order of the test stimuli was randomized.

For this experiment, 12 male subjects, aged between 18 and 26 years, took part using a within-subjects experimental design. Subjects attended two sessions with the order of presentation of the force, angle, and magnitude estimation, and magnitude production conditions balanced across subjects.

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 is the slope n given by

$$\log \psi = n \log \phi + \log k \quad (5)$$

3.3.2 Results

Exponents for the rate of growth of sensation were obtained from least-squares regression between the median judgements of the 12 subjects for each test magnitude and the actual test magnitude, with the apparent magnitude assumed to be the dependent variable [**26**]. The calculated exponents 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 subjects, are shown in Figs 8, 9, 10, and 11 for force estimation, force production, angle estimation, and angle production respectively and are compared in Fig. 12.

The Spearman rank order correlation coefficients 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.

3.3.3 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 that this deviation has on the exponent obtained from the median data, an exponent was regressed to all data points from all subjects. 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 subjects were asked to produce a

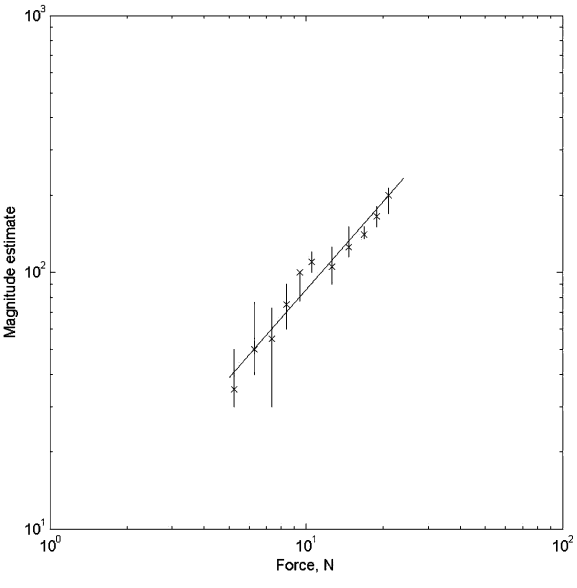

Fig. 8 Rate of growth of apparent force using magnitude estimation. Data from 12 subjects

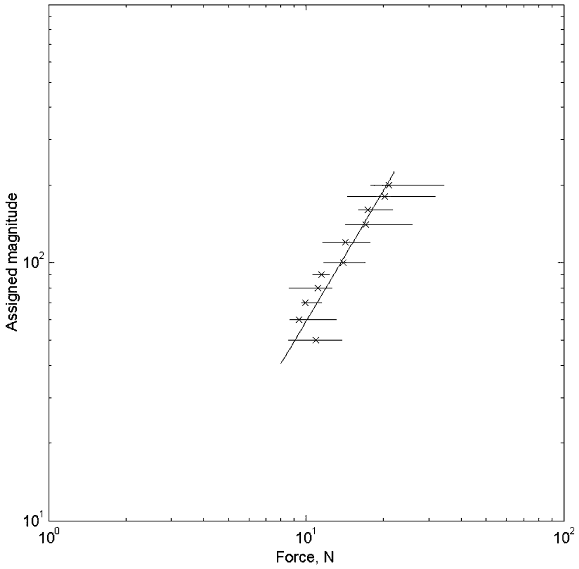

Fig. 9 Rate of growth of apparent force using magnitude production. Data from 12 subjects

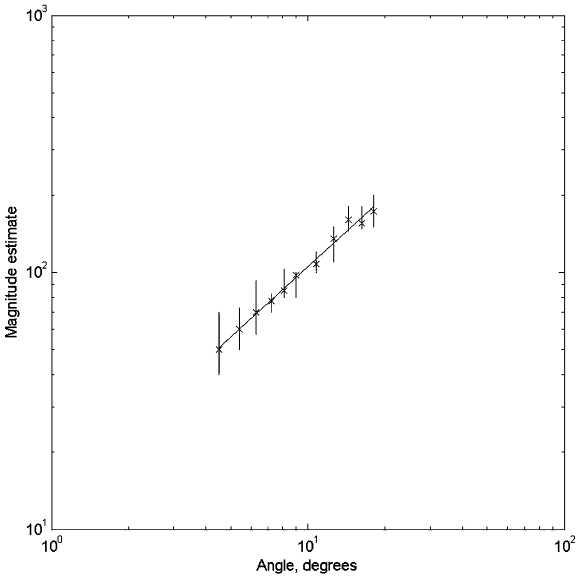

Fig. 10 Rate of growth of apparent angle using magnitude estimation. Data from 12 subjects

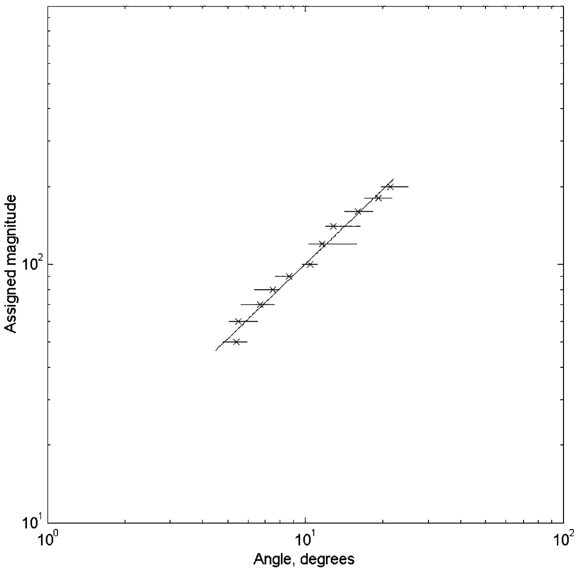

Fig. 11 Rate of growth of apparent angle using magnitude production. Data from 12 subjects

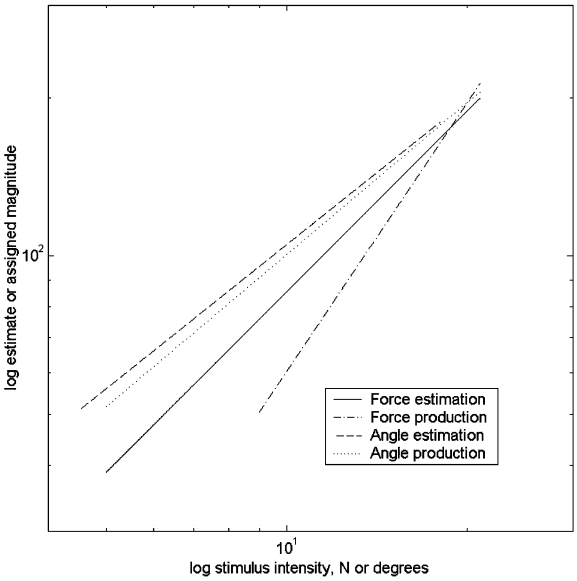

Fig. 12 Rate of growth of apparent force and apparent angle

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 that the exponent for force production (1.70) was higher than it would have been without the two lowest forces. Regression to all the data from all subjects 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. An estimate of the 'unbiased' rate of growth of sensation of apparent force and angle is taken as the geometric mean of the rates of growth for magnitude estimation and magnitude production. 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.

The rate of growth of sensation of steering wheel force lies within the range previously reported for force [**22**]. 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 a 162 per cent 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 per cent increase in the perception of angle.

4 GENERAL DISCUSSION

Although it is desired to optimize 'steering feel', there has been little systematic investigation of what drivers feel, the differences that they can detect, or the way that sensations change with variations in force or angle of turn of steering wheels. The first experiment addressed the appropriate terminology for steering feel, in anticipation of the subsequent two studies. The results of the first study imply that the haptic properties of steering systems in vehicles should take account of the radius of the steering wheel when considering the load applied by the driver. Variations in the steering-wheel radius will scale force perception and change the feel.

The second experiment determined the differences required in steering-wheel force and angle for the differences to be detected. A difference of 15 per cent for force and 14 per cent for angle was required for the difference to be detected 79.4 per cent of the time. Difference thresholds can be described using the theory of signal detection, with no one value for the threshold but values that vary according to the correct response rate. A 'receiver-operating characteristic' (ROC) curve would describe the difference threshold over all response rates. The experiment provided one point on the ROC curve; it would be desirable to measure other points and to construct a full ROC curve so that the relation between the difference threshold and the probability of detecting a difference can be seen.

The conditions in which the difference thresholds were determined may have influenced the thresholds determined. In the present study, subjects 'relaxed' between the force trials and returned the wheel to the centre between the angle trials, representative of successive presentations of individual stimuli rather than incremental changes in force or angle as will occur during driving. Notwithstanding the limitations of the experiment, the results may be useful in various areas. For example, they provide insight into the differences that may be acceptable from asymmetries in a steering system, and the differences acceptable during repeated turns.

The results of the third experiment show that neither the perception of steering wheel force nor the perception of steering wheel angle is ‘linear’. Understanding of how drivers perceive the feedback of steering-wheel force and steering-wheel angle requires recognition that their feel is not linearly related to either the force or the angle.

The studies reported in this paper investigated how the perception of steering-wheel force and steering-wheel angle depend on force and angle respectively. There may be limitations in the application of the findings to vehicle steering systems where the force applied to a steering wheel and the steering wheel-angle vary together. The perception of force or angle may be altered by variations in angle or force respectively. Additionally, auditory, visual, and other somatosensory stimuli present in vehicles but not in this laboratory study may affect the perception of force and angle at a steering wheel.

5 CONCLUSIONS

Steering-wheel force rather than steering-wheel torque, and steering-wheel angle rather than the translational displacement of the hands on the steering wheel, are more efficient descriptors of ‘steering feel’. When judged in successive presentations, the median difference threshold for the perception of steering-wheel force was found to be 15 per cent and the median difference threshold for the perception of steering-wheel angle was 14 per cent. The rate of growth of sensation of steering-wheel force follows a power law function with an exponent of 1.39; so perceptions of steering force increase more rapidly than increases in force. In contrast, the rate of growth of sensation of steering-wheel angle follows a power law with an exponent of 0.93; so perceptions of steering-wheel angle increase less rapidly than increases in steering-wheel angle.

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APPENDIX

Notation

c	Weber constant
F	force (N)
k	scalar constant
r	radius of the steering wheel (m)
T	torque (N m)
x	displacement (m)
n	growth of sensation exponent
$\Delta\phi$	change in stimulus magnitude
θ	angle (deg)
ϕ	stimulus magnitude (N or deg)
ψ	sensation magnitude (relative units)