# A study of the human ability to detect road surface type based on steering wheel vibration feedback.

**J. Giacomin * and Y.J. Woo**

**Department of Mechanical Engineering**
**The University of Sheffield**
**Mappin Street, Sheffield, S1 3JD**

*** Corresponding Author**
**Tel 0114-222-7781 Fax 0114-222-7890 e-mail j.a.giacomin@sheffield.ac.uk**

**Abstract**

A study was performed to investigate the human ability to detect road surface type based on the associated steering wheel vibration feedback. Tangential direction acceleration time histories measured during road testing of a single mid-sized European automobile were used as the basis for the study. Scaled and frequency filtered copies of two base stimuli were presented to test subjects in a laboratory setting during two experiments which each involved 25 participants. *Theory of signal detection (TSD)* was adopted as the analytical framework and the results were summarised by means of the detectability index *d'* and as *receiver operating curve (ROC)* points. The results of the experiment to investigate the effect of scaling suggested monotonic relationships between stimulus level and detection for both road surfaces. Detection of the tarmac surface improved with reductions in acceleration level while the opposite was true of the cobblestone surface. The *ROC* points for both surfaces were characterised by gradual increases in detection as a function of acceleration level, obtaining hit rates of nearly 100% at optimum. The results of the experiment to investigate the effect of frequency bandwidth suggested a monotonically increasing relationship between detectability and the bandwi\dth of the vibration stimuli. Detection of both road surfaces improved with increases in bandwidth. Average hit rates exceeded 80% for stimuli covering the frequency range from 0 to 80 Hz. Human detection of road surface type appears to depend on the long term memory model, or cognitive interpretation mechanism, associated with each surface. The complexity of the measured response suggests the need to categorise and classify incoming data before an optimal choice of feedback stimuli can be made in automotive steering systems.

**Keywords:** human, perception, vehicle, steering, vibration, detection

## 1. Introduction

Road vehicle drivers are regularly exposed to vibrational stimuli. These stimuli are normally considered to be sources of discomfort and methods for analysing the *noise, vibration and harshness (NVH)* properties of road vehicles are in regular use [1]. The points of contact through which the driver perceives vehicle vibration include the floor panel, pedals, the gearshift lever, the seat and the steering wheel. Of these, the steering wheel is a particularly important source of feedback due to great sensitivity of the skin tactile receptors of the hand [2-4] and due to the lack of intermediate structures such as shoes and clothing which can act to attenuate the transmission of vibrational stimuli to the driver.

Steering vibration can reach frequencies of up to 300 Hz during driving [5] and vibrational modes of the wheel and column can produce large resonant peaks in the steering wheel power spectrum at frequencies from 20 to 50 Hz [6]. The design of the steering system components has been the subject of several studies [7,8] and the human subjective response to hand-arm steering vibration has also been investigated in terms of both the perceived sensation [5] and the induced fatigue [9]. While further research is required, much is currently known about the discomfort associated with steering vibration.

A less well understood topic is the question of the information transmitted to the driver by means of the steering vibration. With the advent of electronically assisted steering and “by-wire” technologies [10] the question of what stimuli should reach the driver assumes great importance. All current methodologies for estimating vibrational comfort, whether hand-arm or whole-body, and whether based on the use of frequency weightings [11,12] or customer correlations [13], are defined in such a way as to suggest that a uniform reduction in vibrational level is accompanied by a uniform reduction in discomfort. Stated alternatively, less vibration is better. This may not be appropriate in the case of information since scenarios can be imagined in which an increase in vibration level might help clarify the nature of the road surface or of the vehicle dynamic state. Vehicle steering wheel vibration may contain clues regarding the road surface type, the presence of water or snow, tyre slip or the dynamic state of subsystems such as the engine, the main suspensions, the steering and the brakes. Retention, or even improvement, of this information may be important for customer satisfaction and for active road safety.

The perceptual and cognitive role to assign to machines has been the subject of much research. Studies have shown that the global performance of a coupled person-machine system can be improved when certain low level perceptual and cognitive functions are assigned to the machine [14-17]. One useful approach in such cases is represented by information theoretic methods. Since the work of Shannon [18], researchers have applied measures of *information entropy* to problems in human behaviour and control [19,20]. The premise of such approaches is that a communication channel can be analysed in terms of the symbols used, and that the probability of occurrence of the symbols can be used as a metric of information flow. In recent years such information measures have begun to be applied to problems of automotive person-machine integration [20] and a future availability of generalised information measures might offer the prospect of judging vehicle vibrational stimuli in terms of both human comfort and information content (see Figure 1).

In order to begin to investigate the relationship between steering vibration and the human recognition of the road surface, a preliminary study [21] was performed by the authors to determine the effect of the steering wheel acceleration level on the human recognition of road surface type in terms of percent correct recognition. The study described here investigates, instead, how the human recognition of road surface type improves or degrades as a function of both the level and the frequency bandwidth of the steering acceleration signal. Tangential direction acceleration time histories measured during road testing of a single mid-sized European automobile were used as the basis for the study. Scaled and frequency filtered copies of the base stimuli were presented to test subjects in a laboratory setting, and their ability to correctly identify the road surface was measured. *Theory of signal detection (TSD)* was adopted as the analytical framework for the analysis.

**2. Theory of Signal Detection (TSD)**

Tanner and Swets [22] have proposed a model of human behaviour in detection situations which is based on statistical decision theory. Central to the model is the assumption that humans, animals or machines perform detection tasks against a background of external environmental noise and of internal noise related to the workings of the sensory and decisional processes. The model, referred to as *Theory of Signal Detection (TSD)*, consists of Gaussian probability distributions representing the internal sensory responses to the background noise (*N distribution*), and to the combination of background noise plus signal (*SN distribution*) as illustrated in Figure 2. In any detection scenario a criterion location along the internal response axis will be adopted by the receiver. Whenever the internal response is greater than this criterion value, detection will be presumed, while no signal is considered to have been detected in cases when the internal response is less than the chosen criterion value. For internal responses which exceed the criterion value, however, both correct identification hits and false alarms are possible given the statistical nature of the task. Each individual chooses a criterion value such that a specific ratio of hits to false alarms is achieved which he or she considers appropriate to the given identification scenario. Table 1 presents the 2x2 decision matrix associated with the identification task of the human, animal or machine observer.
Figure 2 also illustrates the concept of detectability index *d',* which is a commonly used metric of the ease or difficulty of detection. The detectability index *d’* is taken to be the ratio of the separation between the centres of the two distributions, and their spread. The detection task is easier for cases characterised by large separations and/or small variances. For experimental protocols in

which the test subjects are requested to provide a simple “yes” or “no” response, the detectability index *d’* can be estimated from the experimentally determined hit rates and false alarm rates by means of the associated Z score values using the relations below.

$$Z_n = 1.0 - p(\mathit{false\,alarms})$$
$$Z_{sn} = 1.0 - p(hit)$$
$$d' = Z_n - Z_{sn} \qquad (1)$$

*TSD* has been successfully applied in numerous psychophysical applications [22,23]. The detectability index *d’* was chosen for use in the current study as a suitable metric of test subject ability to correctly identify road surface type. A further method from *TSD* which was used in the current study was the concept of *receiver operating characteristic (ROC)* curve. *ROC* curves are obtained by plotting hit rates against the accompanying false alarm rates, with each experimental condition or test subject providing a single data point. When the receiver (test subject) chooses a low criterion value, then both the hit rate and the false alarm rate will be large, leading to a data point in the upper right corner of the *ROC* graph. When instead the receiver chooses a high criterion value the data point will result near the origin. The placement of the *ROC* data points provides a convenient representation of detection performance.

## 3. Two Experiments in the Human Recognition of Road Surface Type

### 3.1 Test Stimuli

Tangential direction steering wheel acceleration time histories were measured using a single mid-sized European automobile (an Audi A4) which was driven over eight different road surfaces. Measurements were performed on the wheel in the tangential direction so as to provide motion data along the operational axis of the steering system. While substantial vertical and fore-and-aft direction motions can occur in current road vehicles, induced motions along these directions are not necessary for the operation of the steering system, and thus may change substantially in the future as “by-wire” steering systems are introduced. Since only a single axis of vibration could be reproduced experimentally in the current study, the tangential direction was selected as the most representative and useful in light of possible future developments in automotive steering technology.

In order to measure the tangential direction motion, an accelerometer was mounted rigidly to the wheel by means of a mounting clamp which guaranteed adequate coupling stiffness to frequencies in excess of 400 Hz. A two minute recording was performed at a sampling rate of 512 Hz using anti-aliasing filters while driving over each surface at a single representative speed. The roads were chosen to be representative of UK driving conditions and were intended to provide vibration stimuli which varied in terms of their stationarity [24], vibration level and spectral energy distributions.

Data analysis suggested that four of the eight roads provided data sets which were widely separated and distinct in their statistical properties. The roads, presented in Figure 3, were a tarmac surface, a cobblestone surface, a concrete surface and a wide, low, bump. The root mean square (r.m.s.) acceleration values of the stimuli were 0.048 $m/s^2$ for the tarmac surface, 0.271 $m/s^2$ for the cobblestone, 0.092 $m/s^2$ for the concrete and 0.249 $m/s^2$ for the bump. The kurtosis values for the same stimuli, which are dimensionless, were 3.00 for the tarmac surface, 3.25 for the cobblestone surface, 3.83 for the concrete surface and 10.76 for the bump. A ten second segment was extracted from each of the four data sets to serve as test stimuli. The segments were selected such that the r.m.s. value, kurtosis value and power spectral density were statistically close to those of the complete recording. Figure 4 presents the time history segments while Figure 5 presents the associated power spectral densities.

In order to investigate the possible effect of vibration level on human identification of road surface type, each of the four steering wheel time histories was multiplied by each of five different scale values. Scale factors of 0.6, 0.8, 1.0, 4.0 and 7.0 were chosen so as to construct test stimuli which were higher than the threshold of human perception of hand-arm vibration stimuli [2] and lower than maximal steering acceleration values encountered in road vehicles. The mathematical operation of scaling was chosen so as to not affect spectral or phase relationships. The use of five multiplication factors produced a total of 20 test stimuli.

In order to investigate the possible effect of the frequency bandwidth of the acceleration stimuli on the human identification of road surface type, each of the four original steering wheel time histories was low-pass filtered by means of digital butterworth filters [25]. For each of the original signals, five frequency bandwidths of 0-20 Hz, 0-40 Hz, 0-60 Hz, 0-80 Hz and 0-100 Hz were achieved, producing a total of 20 test stimuli. The r.m.s. levels of all test stimuli are presented in Table 2.

### 3.2 Test Facility

All tests were performed using the steering wheel rotational vibration simulator shown in Figure 6. The system consists of a 325mm diameter aluminum wheel attached to a steel shaft which is mounted on two bearings. The shaft is connected to an electrodynamic shaker by means of a stinger-rod. Table 3 presents the principal geometric characteristics of the rig, which were chosen based on data from a small European automobile. The seat is fully adjustable in terms of horizontal position and back-rest inclination as in the original vehicle. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker driven by PA100 power amplifier. The imparted tangential acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel and was amplified by means of an Entran MSC6 signal-conditioning unit. Control and data acquisition were performed by means of the LMS EMON software system coupled to a DIFA SCADASIII electronic frontend unit. The software permitted the fixing of safety cutoff limits for the test acceleration, which were set to 20.0 $m/s^2$ peak acceleration. A hardware unit was also used which incorporated both a manual shutdown and an emergency soft-stop condenser circuit.

The steering wheel rig had a first resonance frequency of 350 Hz. When loaded by a human hand-arm system and tested under sinusoidal excitation at frequencies of 4.0, 8.0, 16.0, 31.5, 63.0, 125 and 250 Hz at amplitudes of 0.2, 2.0 and 20.0 $m/s^2$ r.m.s. the bench was characterised by a maximum total harmonic distortion (THD) of 15% at 4 Hz and 20 $m/s^2$. With both increasing frequency and decreasing amplitude the THD dropped to a minimum of 0.002% at 250 Hz and 0.2 $m/s^2$. During the tests which measured the tangential direction THD, a linear fore-and-aft direction acceleration measurement was also performed at the same point on the rigid wheel. Fore-and-aft acceleration was found to be no greater than -50 dB with respect to the tangential acceleration in all cases measured. The safety features of the rig and the chosen test acceleration levels conform to the health and safety recommendations outlined by British Standards Institution BS7085 [26].

### 3.3 Test Protocol

Two experiments were performed to investigate, separately, the effects of steering acceleration level and steering acceleration bandwidth on the human identification of road surface type. The two experiments shared a common protocol, the only difference being the stimuli applied. Each of the experiments was divided into two sessions, with the tarmac surface being the subject of the first session and the cobblestone surface the subject of the second. In each session the road surface in question was displayed on a board in front of the subject. In each session the test stimuli consisted of 13 repetitions of each of the 5 scaled, or bandpass filtered, stimuli from the displayed road surface plus a further 15 stimuli chosen randomly from the stimuli sets of the other three road surfaces. Each participant therefore performed 80 identifications in a session, for a total of 160 identifications in a complete experiment. Due to the large number of identifications each subject was asked to perform only a single experiment (both sessions). In each session the order of presentation of the stimuli was randomised for each participant in order to reduce learning or fatigue effects.

Before commencing testing each participant was asked to remove any articles of heavy clothing such as coats, and to remove watches and jewellery. He or she was then asked to adjust the seat so as to achieve a driving posture which was as similar as possible to the one normally adopted in their own vehicle. He or she was next asked to grip the steering wheel using both hands, applying the grip strength that would be used when driving on a winding country road. The participant was then asked to fix eyes on the board directly in front of the simulator which displayed photographs of the road surface as seen from both a distance (as during driving) and close up (from approximately 1 meter).

Upon commencing testing each participant was presented each of the steering acceleration stimuli in random order. Each 10-second stimulus was separated by a 5 second gap during which time the participant indicated whether he or she considered the vibration to have been produced by the displayed road surface. The participant was asked to indicate the response by stating “yes” or “no”. Participants were requested to provide their best estimate and to respond even if uncertain. The vehicle speed associated with each stimulus was not provided, and no feedback was provided regarding whether identification had been correct or incorrect. For each scale factor or frequency bandwidth the hit rate was taken to be the proportion of “yes” responses obtained from the stimuli which were actually from the presented road surface. The false alarm rate was taken to be the proportion of “yes” responses obtained from the stimuli which were not derived from the road surface which was being presented.

Considering all activities performed from the moment the participant entered the laboratory, the total time to perform a single session was approximately 25 minutes. A complete experiment consisted of two sessions which were performed on consecutive days, the order of the sessions (tarmac or cobblestone) being randomised. The participants were instructed that they could interrupt a session at any point if they should wish. The test facility and protocol were reviewed and found to meet the University of Sheffield guidelines for good research practice.

**3.4 Test Subjects**

25 Sheffield University staff and students participated in each experiment. Upon arriving in the laboratory each was issued an information and consent form and was provided an explanation of the experimental methods and the laboratory safety features. Sex, age, height, and weight data were then collected, and the participant was requested to state whether he or she had any physical or mental condition which might effect perception of hand-arm vibration, and whether he or she had ingested coffee within the 2 hours previous to arriving in the laboratory. The subjects who participated in the stimulus level experiment consisted of 23 males and 2 females, and had a mean age of 28.7 years, a mean height of 1.77 m and a mean mass of 73.8 kg. The subjects who participated in the stimulus bandwidth experiment consisted of 21 males and 4 females, and had a mean age of 31.7 years, a mean height of 1.75 m and a mean mass of 69.9 kg. No participant declared any condition which might effect the perception of hand-arm vibration, and none declared having ingested coffee prior to their tests.

## 4 Results

### 4.1 Experiment to investigate the effect of stimuli acceleration level

Figure 7 presents the detectability index *d'* values determined from the hit and false alarm rates obtained from the tarmac and cobblestone sessions. Since the experiment contained stimuli which had been scaled to five different amplitude levels, the *d'* values were calculated from the hit and the false alarm rates of each group of stimuli sharing the same scale factor. For the two road surfaces the results suggest monotonic relationships between stimulus level and detection. Interestingly, both sets of results suggest that optimal detection does not occur at the natural stimulus scale measured in the road vehicle. Further, detection varied inversely for the two stimuli sets. Detection of the tarmac surface improved with reductions in stimuli level while the opposite was true of the cobblestone surface which was characterised by a nearly 100% hit rate at the highest scale factor tested. A further point of interest is that for both stimuli, extreme scaling in the inappropriate direction leads to false alarm rates which are greater than the hit rates, as evidenced by the negative values of the detectably index *d'*.

Figures 8 and 9 present the *receiver operating characteristic* points obtained for each of the 25 test participants for the tarmac and cobblestone surfaces respectively. The plots contain less than 25 individual points due to the occasional outcome of more than one subject having produced identical hit and false alarm rates. Both figures suggest progressive change in human detection with scale factor. Average hits rates of greater than 80% were obtained for scale factors less than unity in the case of the tarmac surface, and for scale factors greater than unity in the case of the cobblestone surface. The tarmac stimuli produced a large number of false alarms at large scale factors, suggesting a difficulty on the part of the test subjects to associate these vibration levels with the surface within the context of the modern vehicles they drive. On the contrary, the results for the cobblestone stimuli show large, uncorrelated, scatter at the lowest scale factors, suggesting that the subjective response may have consisted of pure guesses at these amplitudes.

### 4.2 Experiment to investigate the effect of stimuli frequency bandwidth

Figure 10 presents the detectability index *d'* values determined from the hit and false alarm rates obtained from the experiment which investigated the effect of stimulus frequency bandwidth on human detection. As in the case of the scaling experiment, the *d'* values were calculated from the hit and the false alarm rates of each group of stimuli sharing the same frequency bandwidth. The results for both sets of stimuli suggest a monotonically increasing relationship between detectability and bandwidth. Detection of both road surfaces improved with increases in the bandwidth of the vibratory stimuli.

Figure 11 presents the *receiver operating characteristic points* obtained for the 25 test participants for the cobblestone surface stimuli, which can be considered representative of both data sets. The figure suggests a progressive change in detectability with bandwidth. Average hit rates exceeded 80% for stimuli covering the frequency range from 0 to 80 Hz. The results suggest that the long term memory model used by average drivers to judge road surface type contains information about oscillatory frequencies in excess of 60 Hz. While qualitatively similar, the small differences between the two data sets suggest that the energy content associated with the higher frequencies was more important towards correct identification of the cobblestone surface than of the tarmac surface.

**5 Discussion**

Several aspects of the problem of human detection of road surface type can be hypothesised based on the experimental results. A first aspect is that detection of road surface type was not found to be strictly optimal at the natural vibration level encountered in the road vehicle. In a previous study by the authors [21] the human detection of road surface type by means of steering wheel vibration was found to follow one of three general patterns: improve with increasing vibration amplitude, degrade with increasing vibration amplitude, or degrade with any change (greater or lesser) away from the natural vibration level measured in the road vehicle. The road surface types used in the current study illustrate the first two, not necessarily intuitive, patterns. In fact, detection was found to be optimal at extreme scale factors distant from the vibration level of the original stimuli. Further, the automobile used to provide the stimuli for the current experiments can be considered an average European saloon with average mechanical characteristics, thus the vibrational stimuli were not unusually low or unusually high in level. This aspect of the detection problem may be of some relevance to the designers of traditional and “by-wire” steering systems since careful consideration appears to be necessary when choosing the target level of steering feedback for each driving condition.

A second aspect of the problem of human detection of road surface type that can be hypothesised based on the experimental results is the importance towards correct detection of the steering system feedback bandwidth. For the two road surfaces considered in the current study the results suggest that steering wheel stimuli should contain vibrational energy to frequencies in excess of 40 or 60 Hz in order to permit accurate detection in situations where detection relies solely on the tactile sense modality. When reinforced by the presence of adequate visual and/or acoustic stimuli, detection might be found to require a lower bandwidth, but relatively high bandwidth appears to be necessary in cases when the tactile feedback alone is relied upon for surface identification. This point may be of importance to steering designers since some current “by-wire” systems [10] do not reach these frequencies by means of their actuators.

A final aspect of the road surface detection problem that appears to emerge from the current findings is the complexity of the human detection mechanism. The measured human responses to changing stimuli level and bandwidth suggest that the long term memory model, or cognitive interpretation mechanism [27], differed for different road surfaces. The observation that a single vibration level was not optimal under all road surface types suggests the need to categorise and classify incoming data before an optimal choice of steering feedback can be made. A electromechanical system, which can be termed a *Perception Enhancement System* [21], appears necessary in order to optimise steering feedback under varying driving conditions.

**6 Conclusions**

A study was performed to investigate the human ability to detect road surface type based on the associated automotive steering wheel vibration feedback. Tangential direction acceleration time histories measured during road testing of a single mid-sized European automobile were used as the basis for the study. Scaled and frequency filtered copies of the base stimuli were presented to test subjects in a laboratory setting during two experiments which each involved 25 participants. *Theory of signal detection (TSD)* was adopted as the analytical framework for the analysis and the results were summarised by means of the detectability index *d'* and as *receiver operating curve (ROC)* points.

The results of the experiment to investigate the effect of scaling of the acceleration stimuli suggested monotonic relationships between stimulus level and detection for both road surfaces used in the study. Detection of the tarmac surface improved with reductions in level while the opposite was true of the cobblestone surface. The *ROC* points for both surfaces were characterised by gradual increases in detection as a function of acceleration level, obtaining hit rates of nearly 100% at optimum. The results of the experiment to investigate the effect of acceleration stimuli frequency bandwidth suggested a monotonically increasing relationship between detectability and bandwidth. Detection of both road surfaces improved with increases in bandwidth. Average hit rates exceeded 80% for stimuli covering the frequency range from 0 to 80 Hz. Human detection of road surface type appears to depend on the long term memory model, or cognitive interpretation mechanism, associated with each surface. The complexity of the measured response suggests the need to categorise and classify incoming data before an optimal choice of feedback stimuli can be made in automotive steering systems.

**Acknowledgements**

The authors wish to express their gratitude to the Hyundai Motor Company for sponsoring the research project and also to our colleagues at MIRA who provided the vibration data used in the study.

**References**


**1 Gillespie, T.D.** *Fundamentals of vehicle dynamics*, 1992 (S.A.E. International, Warrendale Pennsylvania).

**2 Morioka, M.** Effect of contact location on vibration perception thresholds in the glabrous skin of the human hand. Proceedings of *The 34$^{Th}$ UK Group Meeting on Human Responses to Vibration*, Ford Motor Company, Dunton, Essex, England, 22$^{nd}$-24$^{th}$ September, 1999.

**3 Lee, S.I.** Human sensitivity responses to vibtotactile stimulation on the hand: measurement of absolute thresholds. *Journal of the Ergonmics Society of South Korea*, 1998, **17** (2), 1-10.

**4 Meh, D.** and **Dešlic, M.** Influence of age, temperature, sex, height and diazepam on vibration perception. *Journal of the Neurological Sciences*, 1995, **134**, 136-142.

**5 Giacomin, J., Shayaa, M.S., Dormegnie, E.** and **Richard, L.** Frequency weighting for the evaluation of steering wheel rotational vibration. *International Journal of Industrial Ergonomics*, 2004, **33**, 527-541.

**6 Pottinger, M.G., Marshall, K.D, Lawther, J.M.** and **Thrasher, D.B.** A review of tire/pavement interaction induced noise and vibration. In *The Tire Pavement Interface* (Eds M.G. Pottinger and T.J. Yager), 1986, ASTP STP 929 (American Society for Testing and Materials, Philadelphia), 183-287.

**7 Pak, C.H., Lee, U.S, Hong, S.C., Song, S.K., Kim, J.H** and **Kim, K.S**. A study on the tangential vibration of the steering wheel of passenger car. *SAE Technical Paper Series*, 1991, Paper 912565, 961-968.

**8 Fujikawa, K.** Analysis of steering column vibration. Motion & Control, 1998, 4, 37-41.

**9 Giacomin, J.** and **Abrahams, O.** Human fatigue due to automobile steering wheel vibration. *Proceedings of the SIA conference on Car and Train Comfort*, Le Mans, France, 15$^{th}$-16$^{th}$ November, 2000.

**10 Jurgen, R.K.** *Electronic Steering and Suspensions Systems*, 1999 (S.A.E. International, Warrendale Pennsylvania).

**11 British Standards Institution** *BS6842 : Measurement and evaluation of human exposure to vibration transmitted to the hand*. 1987 (British Standards Institution, London).

**12 International Organization for Standardization** ISO5349-1 : *Mechanical Vibration - Measurement and assessment of human exposure to hand-transmitted vibration - Part 1: General guidelines*. 2001 (International Organization for Standardization, Geneva).

**13 Schoeggl, P. and Ramschak, E.** *Neural networks for development, calibration and quality tests*. SAE Paper 01-0702, 2001.

**14 Quek, F. and Petro, M.** Human-Machine Perceptual Cooperation. *Proceedings of the International Conference on Computer-Human Interaction INTERCHI'93: Human Factors in Computing Systems*, Amsterdam, The Netherlands, 24$^{th}$-29$^{th}$ April, 1993, 123-130.

**15 Rombaut, M.** Prolab2: a driving assistance system. *Mathematical and Computational Modelling*, 1995, **22** (4-7), 103-118.

**16 Stanton, N. A. and Pinto, M.** Behavioral compensation by drivers of a simulator when using a vision enhancement system. *Ergonomics*, 2000, **43** (9), 1359-1370.

**17 Toffin, D., Reymond, G., Kemeny, A.** and **Droulez, J.** Influence of steering wheel torque feedback in dynamic driving simulator. *Proceedings of the DSC North America Driving Simulation Conference*, Dearborn, Michigan, U.S.A., 8$^{th}$-10$^{th}$ October, 2003.

**18 Shannon, C.E.** *A mathematical theory of communication*, 1949 (University of Illinois Press, Illinois).

**19 Corning, P.A.** Control information: the missing element in Norbert Wiener's cybernetic paradigm. *Kybernetes*, 2001, **30** (9-10), 1272-1288.

**20 Bea, J.A. and Marijuan, P.C.** The information patterns of laughter. *Entropy*, 2003, **5**, 205-213.

**20 Nakayama, O., Futami, T., Nakamura, T. and Boer, E.R.** *Development of a steering entropy method for evaluating driver workload*. SAE Paper 01-0892, 1999.

**21 Giacomin, J.** and **Woo, Y.J.** 2004, Beyond comfort: information content and perception enhancement. *Engineering Integrity*, 2004, **16** (July), 8-16.

**22 Tanner, W.P**. and **Swets, J.A.A.** A decision-making theory of visual detection. *Psychological Review*, 1954, **61**, 401-409.

**22 Gesheider, A.G**. *Psychophysics: The Fundamentals*, 1997 (Lawrence Erlbaum Associates Publishers, London).

**23 Coombs, S.** Signal detection theory, lateral-line excitation pattern and prey capture behaviour of mottled sculpin. *Animal Behaviour*, 1999, **58**, 421-430.

**24 Giacomin, J., Steinwolf, A.** and **Staszewski, W.J.** An algorithm for mildly nonstationary mission synthesis [MNMS]. *Engineering Integrity*, 2000, **7** (January), 44-56.

**25 Williams, C. S.** *Designing Digital Filters,* 1986 (Prentice Hall, Englewood Cliffs N.J.).

**26 British Standards Institution** BS7085 : *Safety aspects of experiments in which people are exposed to mechanical vibration and shock*. 1989 (British Standards Institution, London).

**27 Lakoff, G.** *Women, fire and dangerous things, what categories reveal about the mind*, 1987 (The University of Chicago Press, Chicago)

| | | Response | |
|---|---|---|---|
| | | Yes | No |
| Stimulus | Signal + Noise | ***Hit*** | ***Miss*** |
| | Noise | ***False alarm*** | ***Correct rejection*** |

Table 1 Stimulus-response outcome matrix for the human observer.

| | Tarmac stimuli | Cobblestone stimuli | Concrete stimuli | Bump stimuli |
|---|---|---|---|---|
| Scaled Factor 0.6 | 0.029 | 0.163 | 0.056 | 0.149 |
| Scale Factor 0.8 | 0.038 | 0.217 | 0.075 | 0.199 |
| **Scale Factor 1.0** | **0.048** | **0.271** | **0.092** | **0.249** |
| Scale Factor 4.0 | 0.193 | 1.09 | 0.368 | 0.996 |
| Scale Factor 7.0 | 0.337 | 1.89 | 0.644 | 1.74 |
| Frequency Bandwidth 0-20 Hz | 0.029 | 0.112 | 0.056 | 0.112 |
| Frequency Bandwidth 0-40 Hz | 0.038 | 0.204 | 0.083 | 0.201 |
| Frequency Bandwidth 0-60 Hz | 0.044 | 0.266 | 0.089 | 0.245 |
| Frequency Bandwidth 0-80 Hz | 0.046 | 0.268 | 0.091 | 0.247 |
| Frequency Bandwidth 0-100 Hz | 0.047 | 0.269 | 0.091 | 0.248 |

Table 2 Root mean square acceleration values of the tarmac, cobblestone, concrete and bump test stimuli in units of $m/s^2$.

| Geometric Parameter | Value |
|---|---|
| Steering column angle (H18) | 23° |
| Steering wheel hub centre height above floor (H17) | 710 mm |
| Seat H point height from floor (H30) | 275 mm |
| Horizontal distance adjustable from H point to steering wheel hub centre (d=L11-L51) | 390–550 mm |
| Steering wheel tube diameter | 12.5 mm |
| Steering wheel diameter | 325 mm |

Table 3 Geometric dimension of the steering wheel rotational vibration test rig.

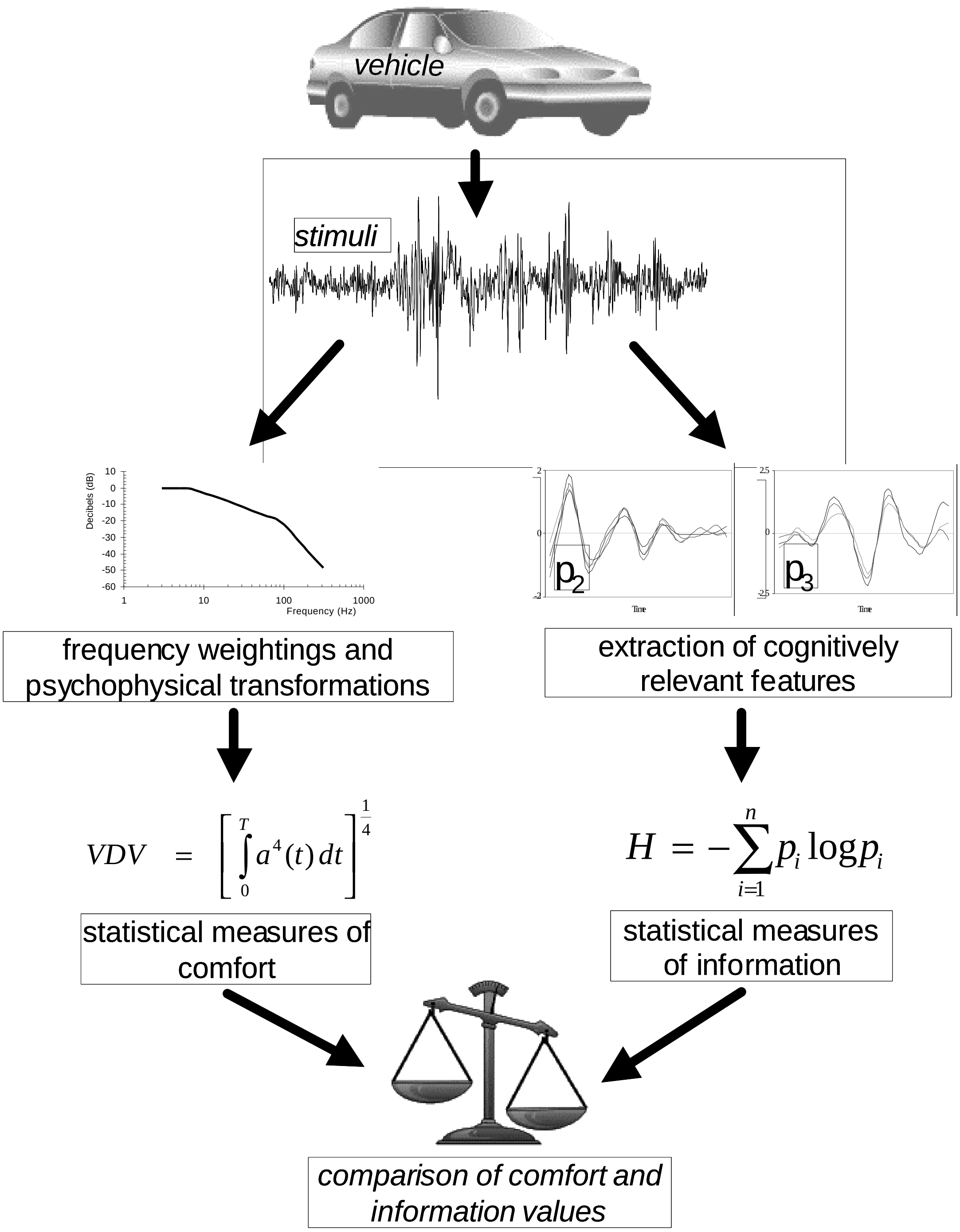


Figure 1 Evaluation of the comfort and information properties of vehicle vibrational stimuli.

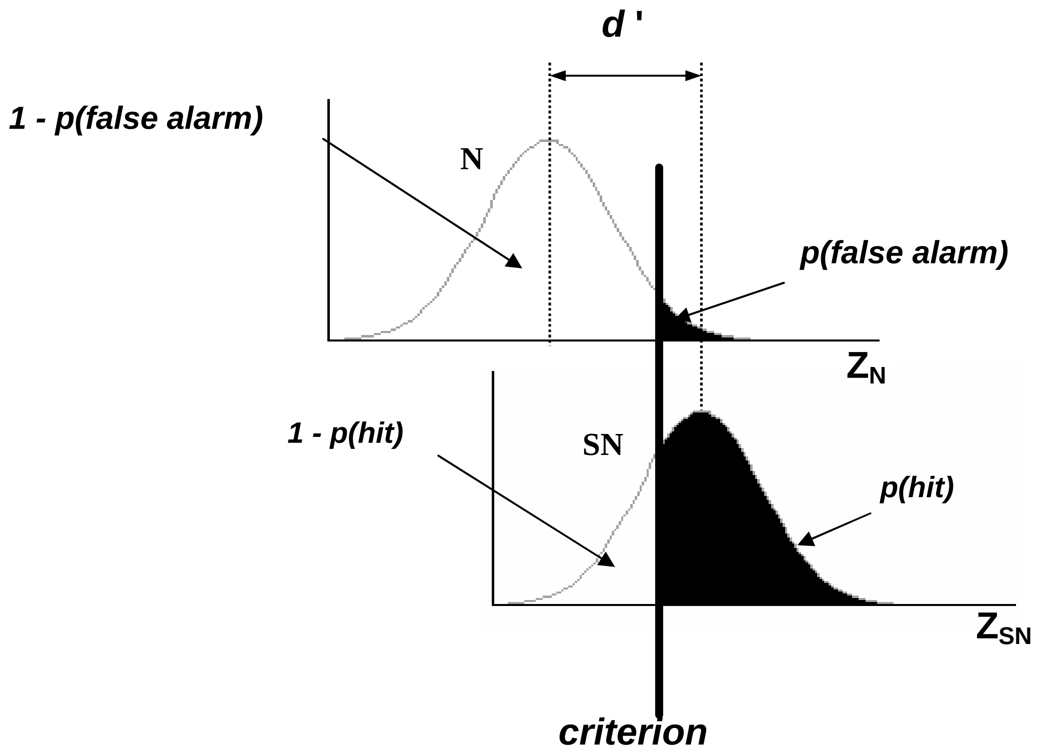


Figure 2 Quantities considered in Theory of Signal Detection (TSD) analysis.

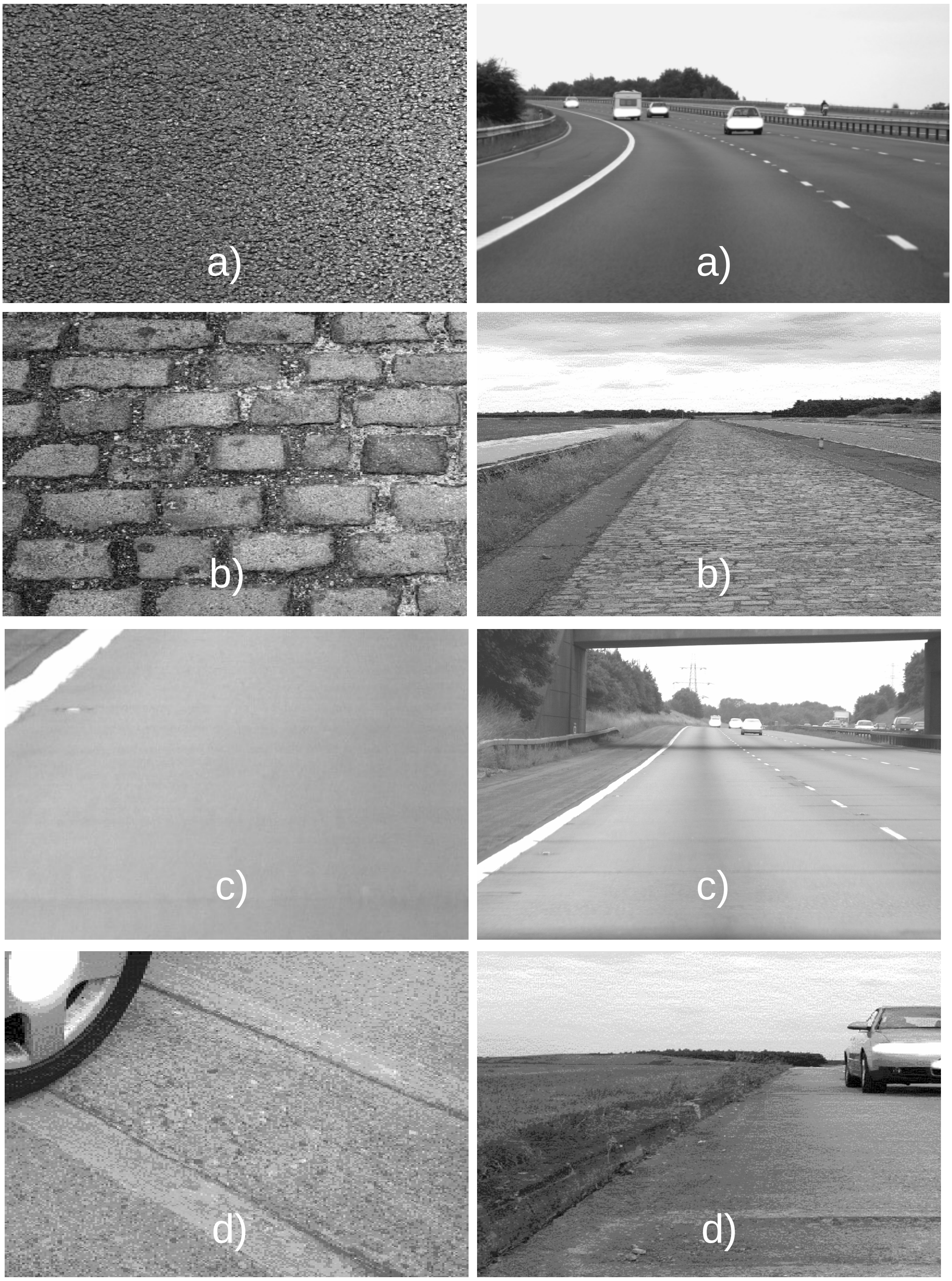


Figure 3 Road surfaces which produced the steering wheel acceleration time histories used in the laboratory experiments.

a) Tarmac road surface (vehicle speed: 96 km/h).

b) Cobblestone road surface (vehicle speed: 30 km/h).

c) Concrete road surface (vehicle speed: 96 km/h)

d) Bump road surface (vehicle speed: 50 km/h)

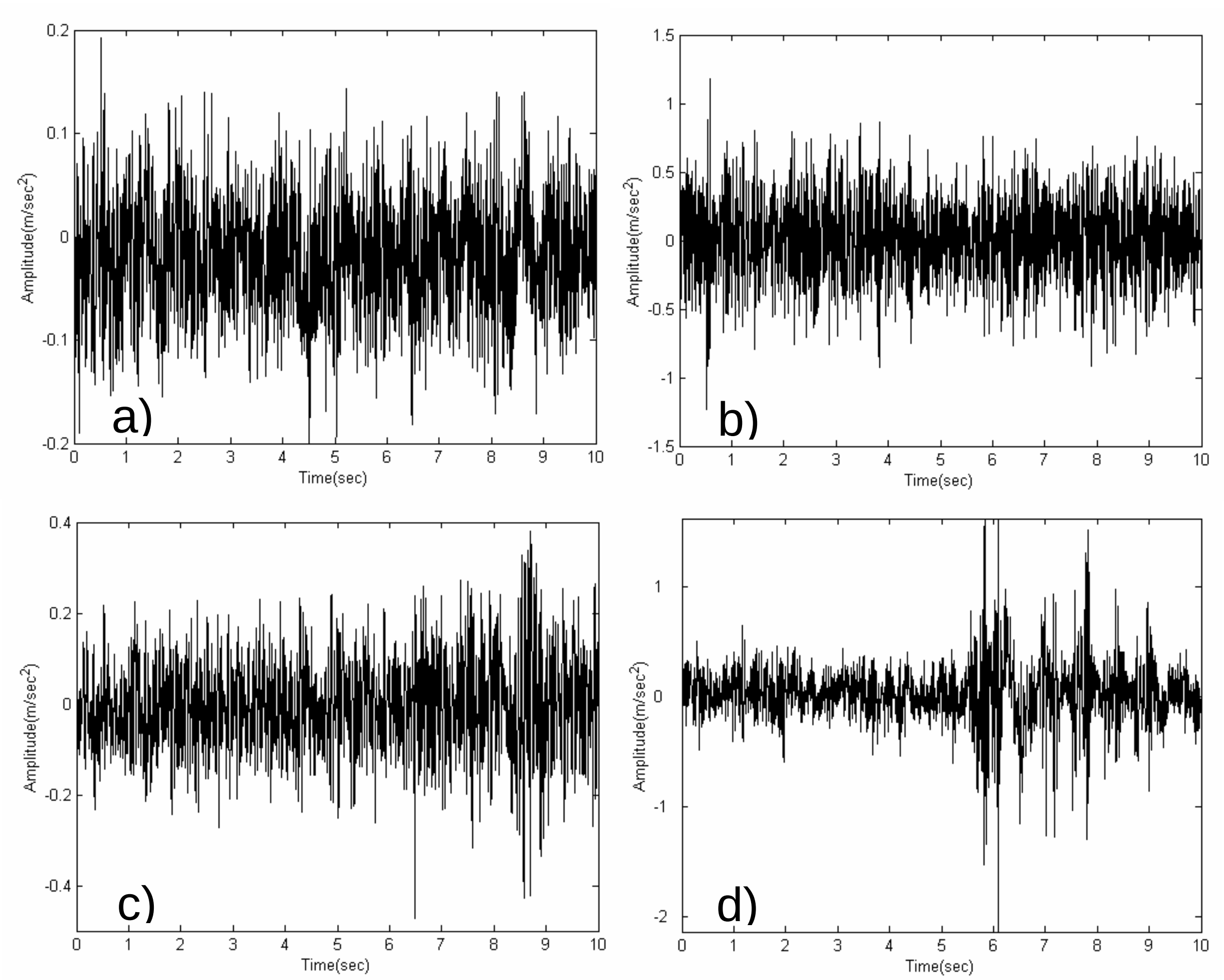


Figure 4 Steering wheel tangential direction acceleration time histories used in the laboratory experiments.
a) Tarmac road surface (vehicle speed: 96 km/h).
b) Cobblestone road surface (vehicle speed: 30 km/h).
c) Concrete road surface (vehicle speed: 96 km/h)
d) Bump road surface (vehicle speed: 50 km/h)

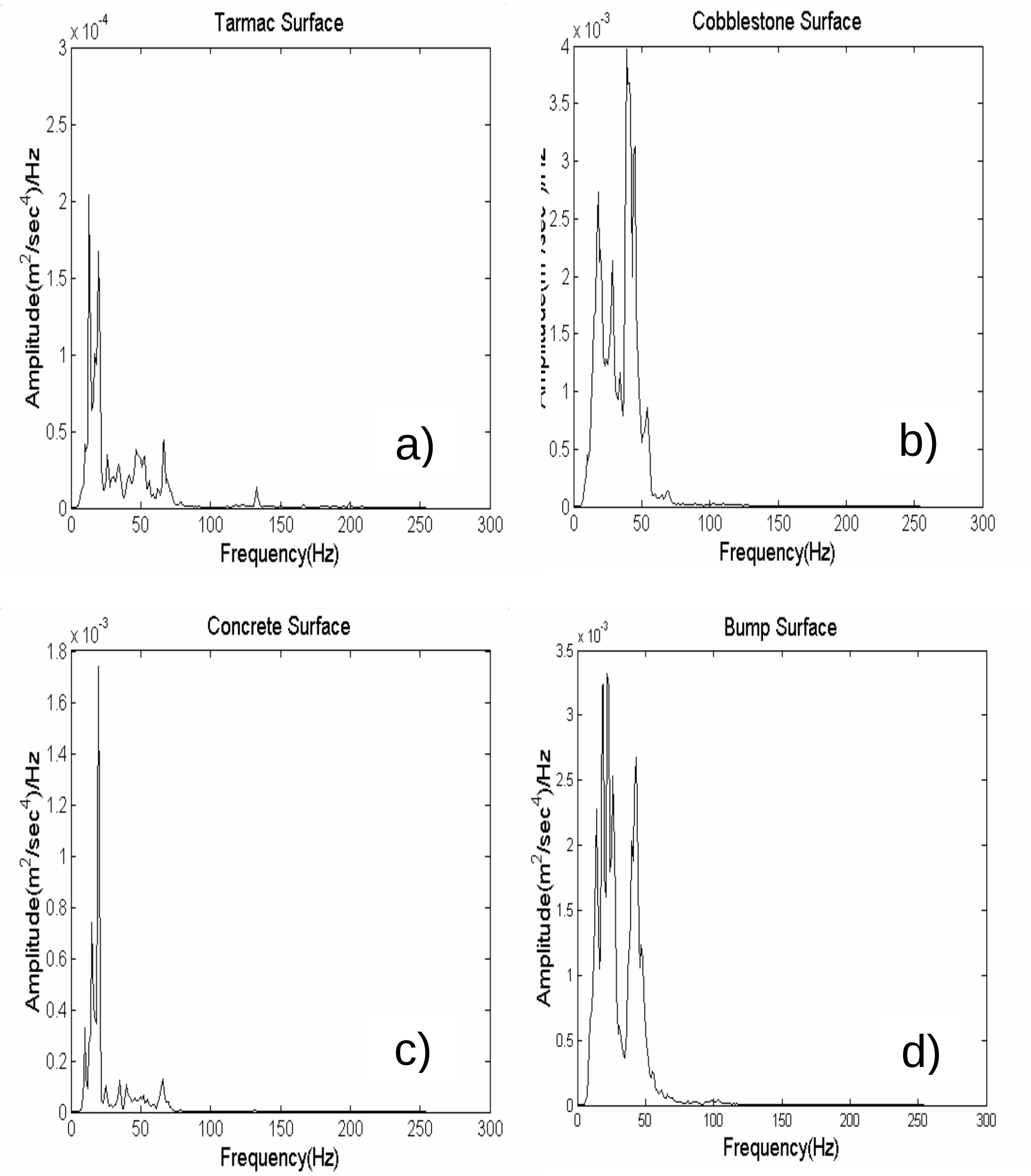


Figure 5 Acceleration power spectral densities of the steering wheel tangential direction acceleration time histories.

a) Tarmac road surface (vehicle speed: 96 km/h).

b) Cobblestone road surface (vehicle speed: 30 km/h).

c) Concrete road surface (vehicle speed: 96 km/h)

d) Bump road surface (vehicle speed: 50 km/h)

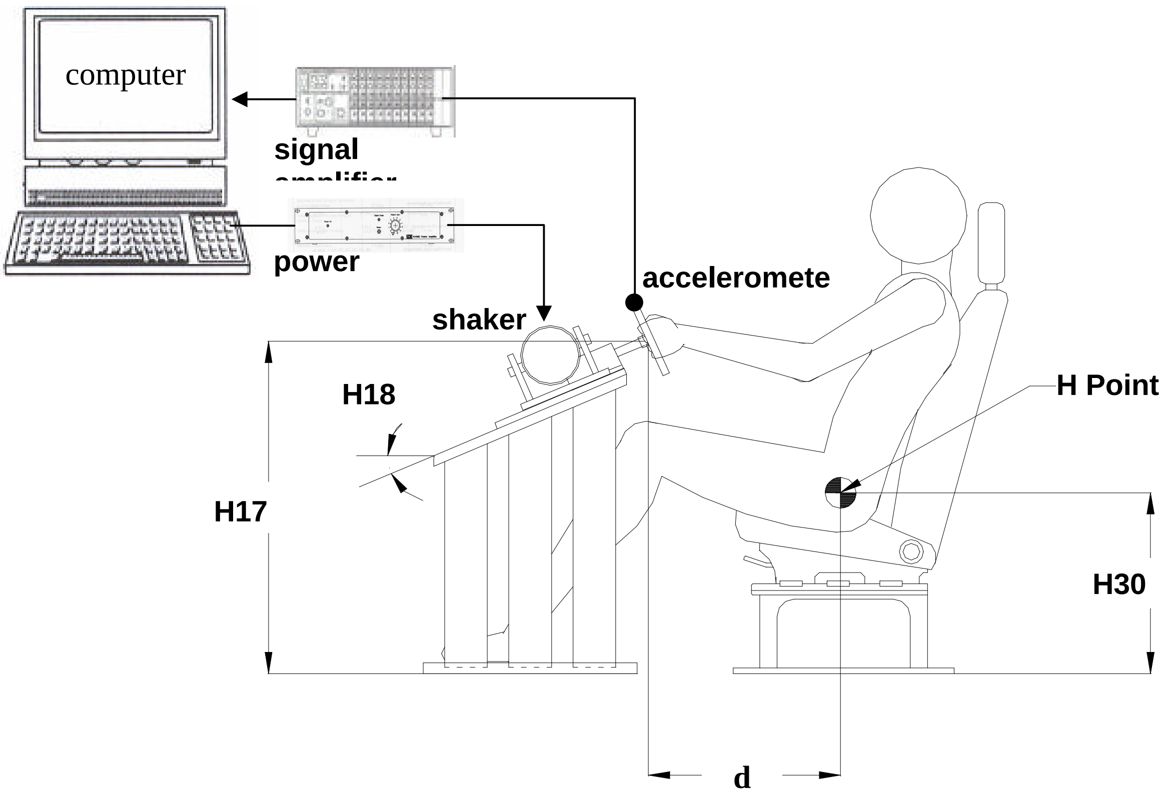


Figure 6 Steering wheel rotational vibration test facility.

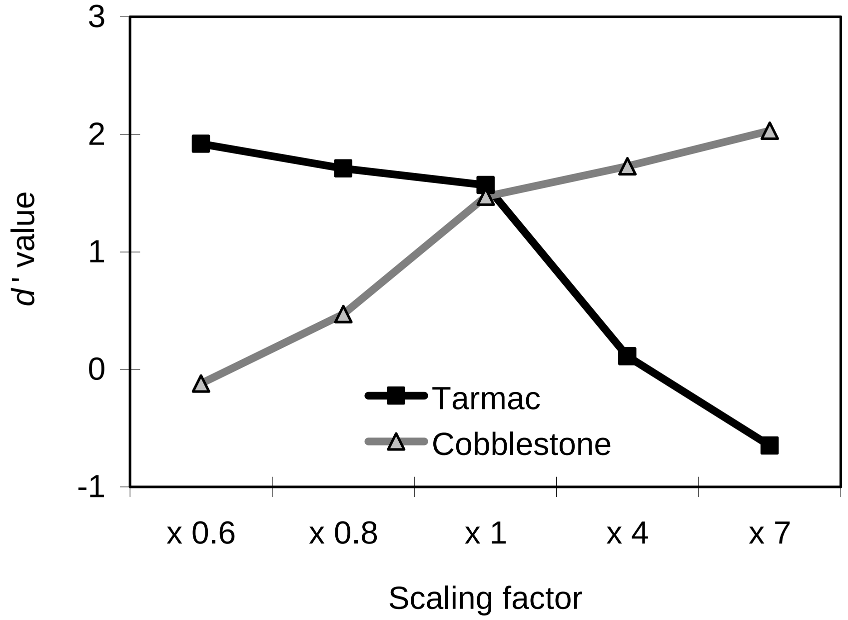


Figure 7 Sensitivity *d'* determined from the data of the experiment to investigate the effect of stimuli acceleration level.

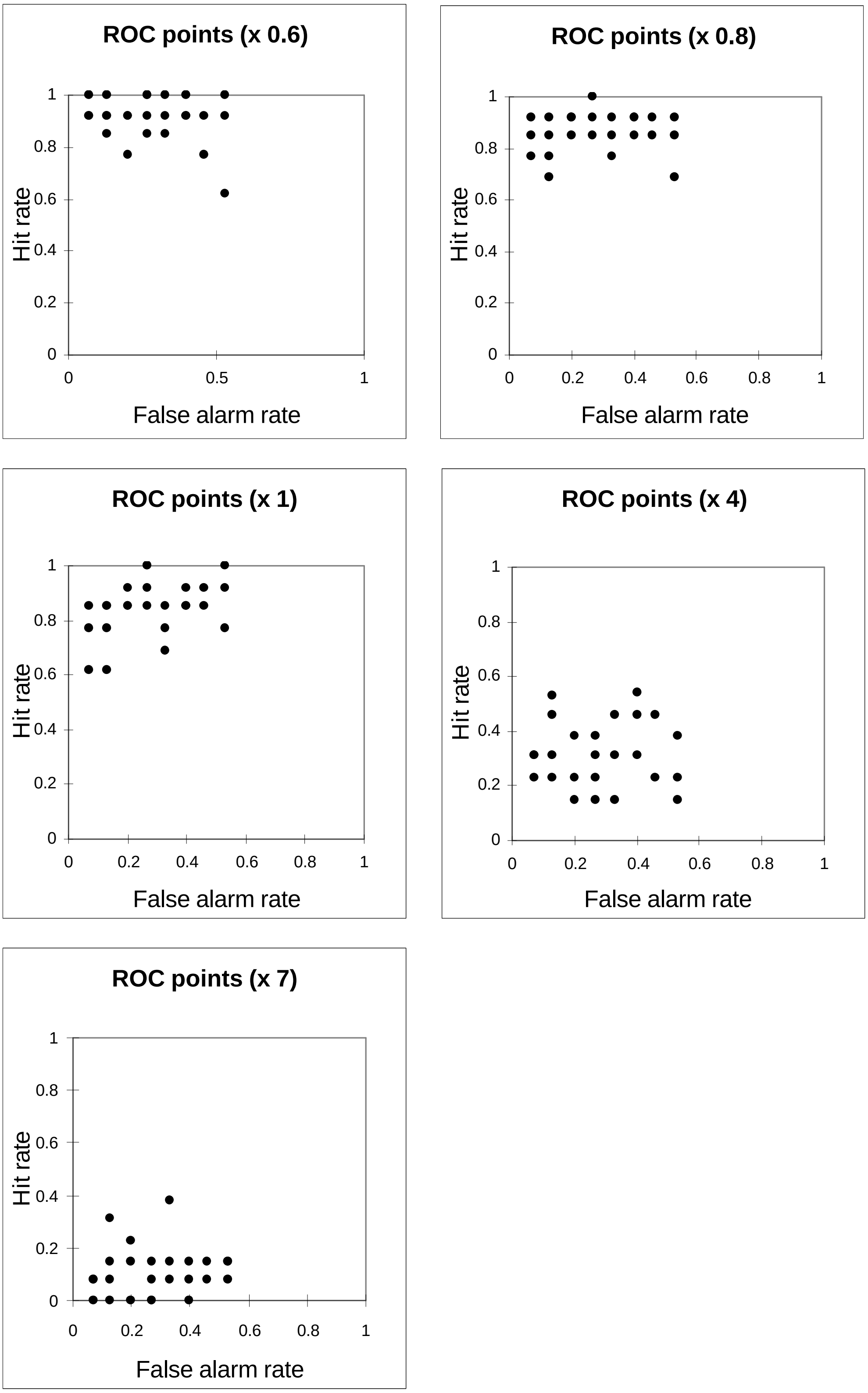


Figure 8 ROC points for the tarmac surface stimuli determined from the data of the experiment to investigate the effect of stimuli acceleration level.

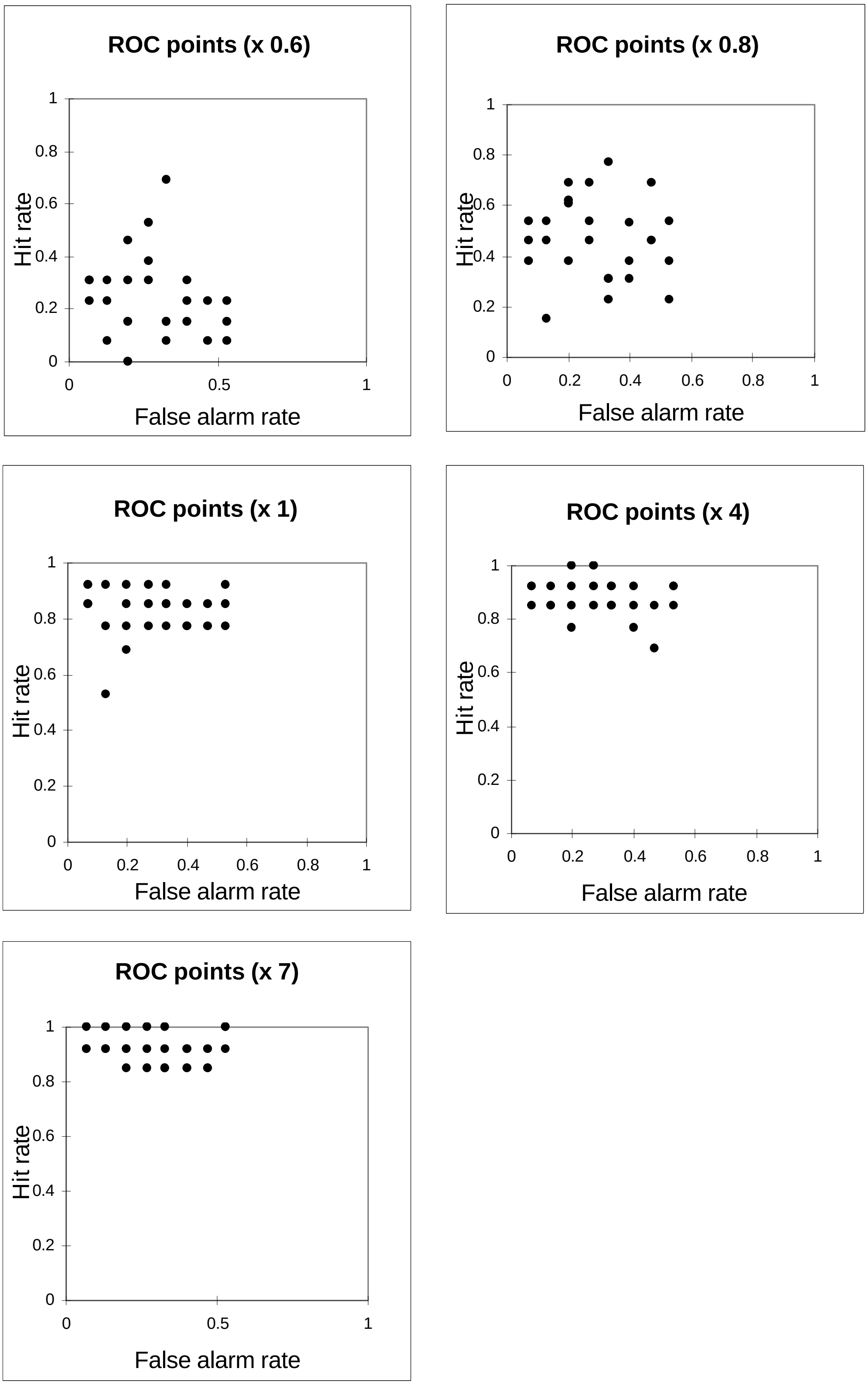


Figure 9 ROC points for the cobblestone surface stimuli determined from the data of the experiment to investigate the effect of stimuli acceleration level.

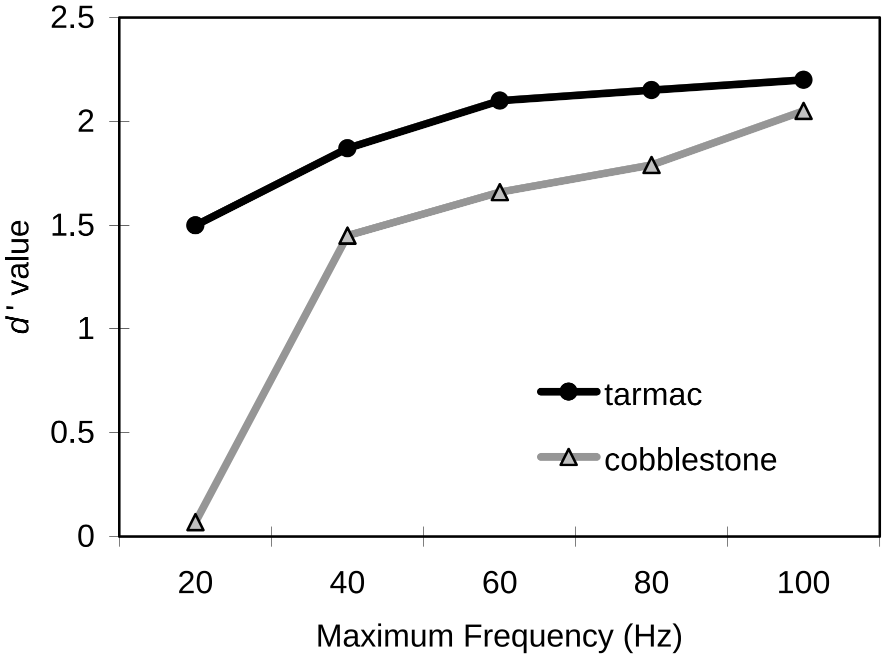


Figure 10 Sensitivity *d'* determined from the data of the experiment to investigate the effect of stimuli frequency bandwidth.

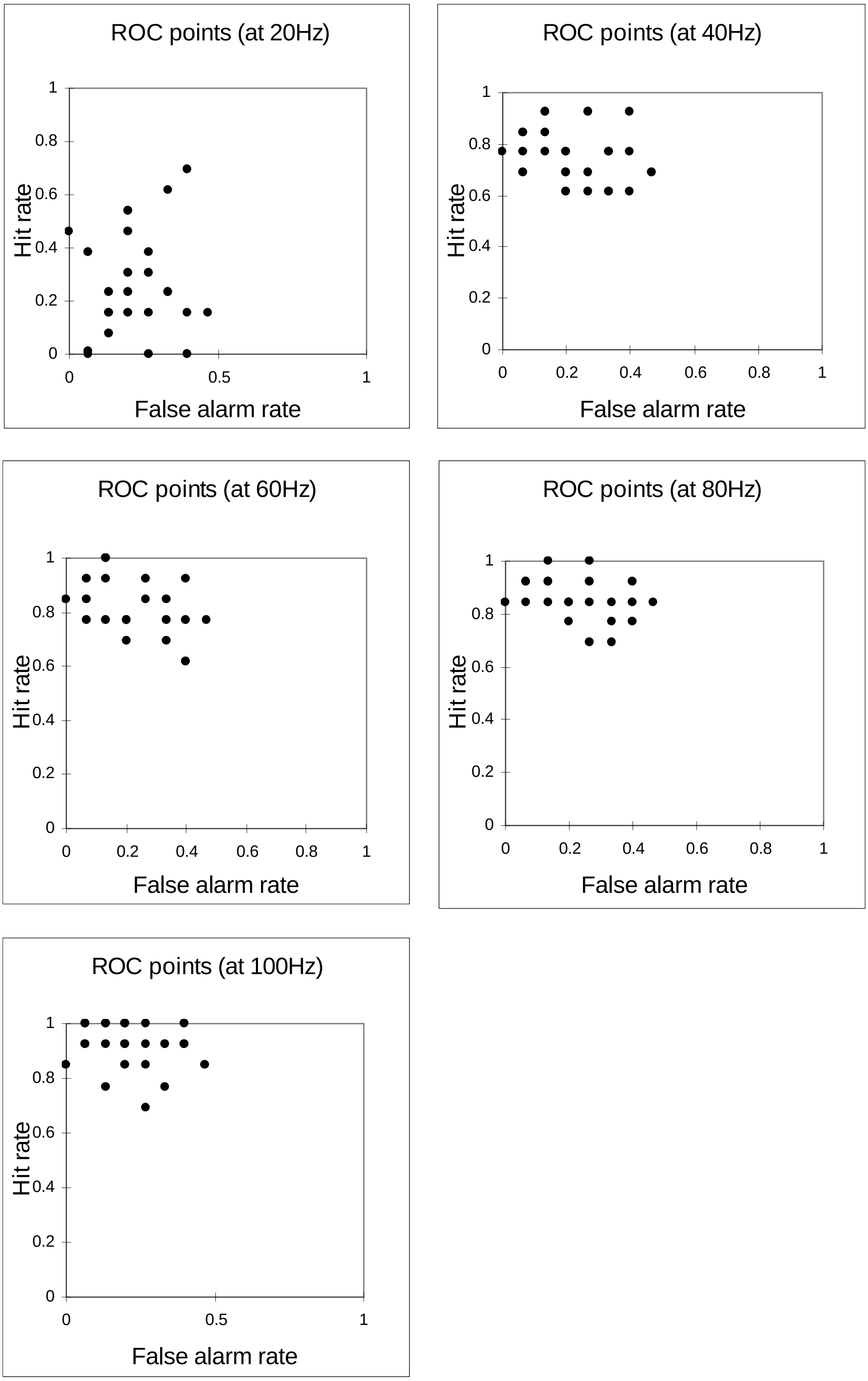


Figure 11 ROC points for the cobblestone surface stimuli determined from the data of the experiment to investigate the effect of stimuli frequency bandwidth.