A comparison of neuronal and behavioral detection and discrimination performances in rat whisker system

Mehdi Adibi and Ehsan Arabzadeh

School of Psychology, University of New South Wales, Sydney NSW 2052, Australia

Corresponding author

Ehsan Arabzadeh
tel: +61 2 93853523
fax: +61 2 9385 3641
ehсан@unsw.edu.au

9 figures, 23 pages
Abstract: 239 words

Keywords: vibration, barrel cortex, extracellular recording, perception, dipper function

Running head: The pedestal effect in rat whisker system
**ABSTRACT**

We used the rat whisker touch as a model system to investigate the correlation between the response function of cortical neurons and the behavior of rats in a sensory detection versus discrimination task. The rat whisker-barrel system is structurally well characterized and represents one of the main channels through which rodents collect information about the environment. In Experiment 1, we recorded neuronal activity (n=235) in the whisker area of the rat somatosensory cortex in anesthetized rats while applying vibro-tactile stimuli of varying amplitudes to the whiskers. Neurons showed a characteristic sigmoidal input/output function with an accelerating non-linearity at low stimulus amplitudes and a compressive nonlinearity at high stimulus amplitudes. We further quantified the performance of individual neurons for stimulus detection and for discrimination across different stimulus pairs with identical amplitude differences. For near threshold stimuli, the neuronal discrimination performance surpassed the detection performance despite the fact that detection and discrimination represented identical amplitude differences. This is consistent with the accelerating non-linearity observed at low stimulus intensities. In the second stage of the Experiment, four rats were trained to select the higher amplitude stimulus between two vibrations applied to their whiskers. Similar to neuronal results, the rats’ performance was better for the discrimination task compared to the detection task. The behavioral performance followed the same trend as that of the population of individual neurons. Both behavioral and neuronal data are consistent with the “pedestal effect” previously reported in human psychophysics.

**INTRODUCTION**

To quantify how brain activity underlies sensory experience, researchers have asked two key questions: How are sensory stimuli represented in neuronal activity? How does neuronal activity contribute to behavior? A body of research has focused on the correlation between neuronal activity and perception (Parker and Newsome 1998) regarding stimulus detection (Cook and Maunsell 2002; de Lafuente and Romo 2005; Hawken and Parker 1990; Johansson and Vallbo 1979; Mountcastle et al. 1972; Palmer et al. 2007) and stimulus discrimination (Britten et al. 1992; Celebrini and Newsome 1994; Cohen and Newsome 2009; Hernández et al. 2000; LaMotte and Mountcastle 1975; Luna et al. 2005; Mountcastle et al. 1990). Here, we provide a fresh approach by comparing the detection and
discrimination performances at two separate levels; (i) at the level of cortical neurons recorded in anaesthetized rats and (ii) at the behavioral performance of rats engaged in an active detection/discrimination task.

As nocturnal animals, instead of using vision, rats rely on their whiskers to collect information from their surrounding environment (Brecht 2007; Brecht et al. 1997; Carvell and Simons 1990; Knutsen and Ahissar 2009; Vincent 1912; von Heimendahl et al. 2007). Due to its functional efficiency, and well-described anatomical characteristics (Chmielowska et al. 1989; Durham and Woolsey 1977; Herron and Schweitzer 2000; Petersen 2007; Woolsey 1996), the rodent whisker touch provides a suitable model system for studies in systems neuroscience (Diamond et al. 2008). The whisker region of the primary somatosensory cortex of rodents contains a group of anatomically-distinguishable clusters of neurons called “barrels” (Woolsey and van der Loos 1970). In rats, each barrel is approximately 0.3–0.5 mm in maximal diameter (Hodge Jr et al. 1997) and contains an average of 2500 neurons (Jones and Diamond 1995; Woolsey and van der Loos 1970) that respond primarily to their corresponding whisker (Welker 1971).

To provide a comparison of detection and discrimination performances, at the neuronal and behavioral levels, the present experiments used sinusoidal stimuli. This is an ideal stimulus for two reasons: first, because it simulates and is highly informative about naturally occurring stimuli (Arabzadeh et al. 2003; Arabzadeh et al. 2005); second, because its simple parameters – amplitude ($A$), frequency ($f$) – can be precisely controlled in experimental settings. Previous research has demonstrated that single neurons and cortical ensembles reliably encode the product $Af$ of a vibration (Arabzadeh et al. 2004; Arabzadeh et al. 2003).

Here, in Experiment 1 we recorded neuronal activity from barrel cortex of anesthetized rats and characterized the response of individual neurons to a range of vibration amplitudes. The neuronal response function made quantifiable predictions for the detection versus discrimination performance which was tested in Experiment 2 where rats engaged in a detection/discrimination task. Finally, we demonstrate that the behavioral performance followed the same trend as that of the population of individual neurons.

METHODS

Experiment 1: Electrophysiology
Subjects, surgery and recording

Sixteen adult male Wistar rats, weighing 390-540 g were used for acute recording. All components of the experiment were conducted in accordance with the APA guidelines for the treatment of animals and approved by the Animal Care and Ethics Committee at the University of New South Wales. Anesthesia was induced by intraperitoneal administration of Urethane (30% wpv, 5 ml/kg body weight) to the right side. During the recording sessions, the level of anesthesia was monitored by the hind paw and the corneal reflexes, and maintained at a stable level by administering 10% of the original dose, if necessary. The rat’s head was fixed in a stereotaxic apparatus, an incision was made from bregma to lambda and the fascia was removed. Craniotomy was performed directly over the barrel cortex on the right hemisphere on an area of 3mm×4mm, centered at 2.6 mm posterior to bregma and 5mm lateral. The dura mater was left intact.

Neuronal activity was acquired using tungsten electrodes with an impedance of 2-4 MΩ at 1 kHz. During each penetration the electrode was lowered by means of a micromanipulator until a single neuron or a neuronal cluster was identified. The principal whisker was determined by manual flicks imposed to individual whiskers. Data acquisition and online amplification were performed using Cheetah data acquisition hardware and software (Neuralynx, Inc., Tuscan, AZ, USA). During the recording sessions, data was acquired at a sampling rate of 30.3 kHz and filtered online by applying a bandpass filter between 600 and 6000 Hz. From the filtered data, spikes were detected using an amplitude threshold which was set manually. A liberal threshold was used for online spike detection to avoid missing neuronal activity. A more rigorous spike sorting was performed offline using template matching implemented in MATLAB (Mathworks, Inc., Natick, MA). Recordings were limited to barrel cortex (layer IV). This was achieved by monitoring the penetration depth of the recording tungsten electrode and was further confirmed by the fast neuronal response onset latencies (< 8 msec) to the stimulus with highest amplitude. Across 16 rats we recorded a total of 93 single neurons and 142 multi-unit neuronal clusters.

Whisker stimulation
A series of nine sinusoidal whisker vibrations (frequency of 80Hz; amplitudes of 3 to 28 μm with equal increment steps) were delivered to the principal contra-lateral whisker while recording the neuronal activity. Stimuli were generated in MATLAB, and were presented through the analogue output of a data acquisition card (National Instruments, Inc., Austin, TX) at a sampling rate of 44.1 kHz. The output of the NI-Card was amplified (25.4 dB gain) before arriving at a piezoelectric ceramic (Morgan Matroc, Bedford, OH). Using a custom-built infrared optic sensor, the vibro-tactile stimulators were calibrated and their vibration trajectory were measured at 10 kHz sampling frequency and verified to follow and precisely match the desired sinusoidal stimuli. For the vibration stimuli, the frequency of 80Hz was selected because it allowed a wide range of amplitudes (0 to 30 μm) to be reliably produced.

To ensure precise whisker stimulation, a lightweight thin piece of plastic micropipette was glued to the piezoelectric ceramic. The principal whisker was placed into the micropipette such that the distance of the micropipette tip to the base of the whisker was 5 mm with a precision of ±1 mm. In order to engage the whisker with the inside border of the micropipette opening, the stimulator was slightly tilted by ~10º with respect to the relaxed position of the whisker shaft. Each trial consisted of a 500 msec stimulation followed by an inter-stimulus interval of 500 msec. Each stimulus was presented 100 times in a pseudorandom order to provide a measure of trial by trial variability in the neuronal response.

**Neuronal analyses: ROC**

The sequences of spikes corresponding to trials of the same stimulus were separated and aligned with respect to the stimulus onset to generate raster plots (see Fig. 2a). The probability of spiking over time was evaluated by counting the average number of spikes within each bin of 10 msec. This provided the neuronal response profile over time (also known as the peri-stimulus time histogram or PSTH) for each stimulus (Fig. 2a). Neuronal response to different stimulus amplitudes was further characterized by counting the number of spikes generated in each trial over the window 0-50 msec post stimulus onset (Fig. 2b). The 0-50 msec window was chosen based on previous findings showing a rapid build up of spike count information in rat barrel cortex neurons for decoding simplified stimuli applied to the whiskers (Arabzadeh et al. 2004) or the forepaw (Foffani et al. 2004) as well as more complex stimuli applied to whiskers (Arabzadeh et al. 2006). The duration of the selected window is also compatible with the protraction phase of a single “whisk” (Kleinfeld et al. 1998).
In order to quantify the trial-by-trial variability in neuronal response (Fig. 2c), a receiver operating characteristics (ROC) analysis was performed in the framework of signal detection theory (Green and Swets 1966). The area under the ROC curve (Fig. 2d) provides an index of detection or discrimination performance supported by the observation of the neuronal response. Such a measurement takes into account the trial by trial variability in neuronal response, provides a criterion-free metric which is similarly applicable to the rat behavioral data, and thus allows further comparison of neuronal and behavioral performances. To obtain an index of stimulus detectability, for all trials of that stimulus, the histogram of spike counts within the post-stimulus time window of 50 msec was compared with the histogram of spike counts within a corresponding window of 50 msec before the stimulus onset. The overlap between the two histograms was quantified by applying all possible values of the decision criterion, ranging from the minimum to the maximum observed spike count (Fig. 2c). Each criterion yielded a hit and false-alarm rate. Plotting the hit rates versus the false alarm rates led to an ROC curve (Fig. 2d). The area under ROC was then calculated by approximating the missing parts of the ROC curve between two consecutive criteria by a trapezoid (Fig. 2d). In the same way, to obtain an index of discriminability between each pair of stimuli, the histograms of spike counts within the post-stimulus time window of 50 msec were compared across 100 trials of each stimulus amplitude. The ROC area falls within the range of 0 to 1. An ROC area of 0.5 indicates that the proportion of hits is equal to the proportion of false alarms reflecting a complete overlap between two histograms, and thus representing chance performance. An area of unity, on the other hand, indicates a hit rate of 1 and a false positive rate of 0 and no overlap between two histograms which is equivalent to perfect detection or discrimination.

In order to compare the detection and discrimination performances for each recording, the stimulus amplitude whose detection performance was closest to 60% was chosen as detection threshold (Th). If available, the stimuli that corresponded to the ½, 1½ and 2 times threshold amplitude were then selected for estimating the discrimination performances. This allowed two discrimination performances to be measured separately for ½Th versus 1½Th pair and for Th versus 2Th pair (Fig. 5 and 9).
Experiment 2: behavior

Subjects, behavioral apparatus and procedure

Four adult male Wistar rats, weighing 350-420 g, were used in the behavioral experiment. Rats were maintained on a 12:12 hour light-dark cycle (with lights on at 7am) in a climate-controlled colony room. Rats were water deprived and were rewarded with a 5% sucrose solution during the experiment. After each daily experiment session, the rats had ad libitum access to water for one hour and were fed 15-18 g of rat chow.

The experiment was performed in a Plexiglas chamber with the following dimensions: 30 cm (length), 20 cm (width), and 50 cm (height). The rat was placed on a platform composed of metal bars spaced at 1 cm as flooring which was raised 20 cm from the ground. An aperture (40 mm×40 mm) was located in the front wall of the chamber. Nose-pokes into the aperture were detected by an infra-red optical sensor. Two mesh plates (35 mm×30 mm) were positioned 2 mm from the edges of the aperture slanted towards each other at a 55° angle (Fig. 1). These two mesh plates were attached to piezoelectric ceramic bars that delivered vertical sine-wave vibration stimuli to the whiskers. The position of the nose-poke sensor was adjusted in a way that the rats were required to maintain a consistent head posture to receive the stimulus. This minimized the trial by trial variability of head position with respect to the meshes and of head movements during the stimulus presentation. The reward was delivered through two drinking spouts located at either side of the aperture in the front wall (Fig. 1).

The behavior of the rat (nose-poke or the response at either reward spout) was continuously registered into a data acquisition card (National Instruments, Inc., Austin, TX) using a custom-built circuit that measured contact at the spouts or nose-poke through optical sensors. A MATLAB script controlled the presentation of the stimuli, registered the behavior of the rats along with the corresponding time stamp of each behavioral action, and controlled the delivery of rewards through two separate water pumps. The behavior of the rats was monitored during the experiment using an infrared camera positioned in front of the aperture.

-- Fig. 1 about here --

The stimulus set consisted of sine-wave vibrations with a frequency of 80 Hz and a maximum duration of 3 sec. The stimuli were generated in MATLAB and sent to a low-latency sound card (Creative Sound Blaster X-Fi series, Creative Labs, Inc.) at a 44.1 kHz sampling rate.
and sent to the piezoelectric stimulators through an amplifier (25.4 dB gain). In order to quantify each rat’s sensitivity, stimuli were presented at multiple amplitudes ranging from 0 to 30 μm based on the method of constant stimuli. Fig. 1 illustrates the basic experimental design and sequence of events in the task. The rat initiated a trial by a nose-poke (snout entry in between the two meshes) through the aperture. Nose-poke resulted in the presentation of the stimulus which was the vibration of the meshes with different amplitudes. The stimulus started with a variable delay after the nose-poke initiation, provided that the rat maintained the nose-poke throughout this delay. The onset delay was selected from a uniform distribution from 100 msec to 1 sec. Observation of behavior indicated that in a great majority of the trials the rats kept their head fixed until they started to retract to choose one of the drinking spouts. Furthermore, monitoring of whisking motion showed that on the majority of trials the rats did not whisk against the meshes during stimulus presentation. The rat then responded by choosing one of the two reward spouts during a window from 50 msec after the stimulus onset lasting for 5 sec. The first lick at either drinking spout was considered as the behavioral choice and its time instance was recorded as the response time. A correct response was to turn toward the spout located on the side of the mesh with the higher amplitude vibration. Correct trials were rewarded with 0.08 ml of sucrose solution. For incorrect responses no reward was given and an extra time-out penalty of 4 sec was imposed. The proportion of the stimulus presentation at each side was adaptively chosen based on the inverse proportion of the history of responses the rat made towards either side. This adaptive strategy prevented the rat from forming a response bias by ensuring that roughly equal numbers of choices were made towards either spout. Retrospective analysis of the stimulus side revealed that the bias correction strategy did not have a significant effect on the proportion of stimulus assignments at each side (i.e. for none of the rats, the sequence of Left/Right assignments was significantly different (p<0.05) from a binomial distribution with a probability of 50%).

The first behavioral experiment employed a detection task based on the method of constant stimuli. A sinusoidal vibration was delivered only on one of the meshes. The amplitude of the stimulus was adjusted for each rat (Fig. 6). After the familiarization to the set up and the initial shaping of the behavior, the detection task was conducted over 5 days. Rats performed an average of 50-65 blocks of trials where each block contained a pseudorandom order of stimuli of varying amplitudes. The detection performance was characterized by fitting a cumulative Gaussian function to the empirical data (Fig. 6). Once the psychometric curves
were obtained for each rat, the detection threshold corresponding to the 60% correct performance was calculated from the fitted curve and was used for the second phase of the behavioral experiment.

In the second phase, the rats performed a discrimination task. The detection threshold ($T_h$) obtained from phase 1 was used to generate multiple base amplitudes to be added to both sides. This procedure constructed new stimuli with the base amplitudes of zero, $\frac{1}{2}T_h$ and $T_h$. The stimulus pairs, therefore, consisted of $0-T_h$ (i.e. detection), $\frac{1}{2}T_h$ versus $1\frac{1}{2}T_h$, and $T_h$ versus $2T_h$. All pair wise discriminations thus represent an amplitude difference equal to the absolute detection threshold obtained in phase 1. A high-amplitude stimulus that was easily detectable was presented in $\frac{1}{4}$ of trials in order to increase the overall performance and keep the rats motivated in the task. The 3 pairs of stimuli in addition to the easily detectable stimulus were presented in a pseudorandom order in blocks of 4 trials. This procedure ensured that all stimulus pairs were presented for similar number of trials which varied from 150 to 330 per stimulus for different rats.

RESULTS

The aim of these experiments was two-fold: first, to characterize how barrel cortex neurons respond to a selected set of vibration stimuli; and second, to investigate the performance of rats in a detection and discrimination task involving the same stimulus set. Experiment 1 measured the responses of rat barrel cortex neurons to sinusoidal vibrations of varying amplitude. Fig. 2 illustrates a step by step quantification of the response of a typical barrel cortex neuron. Fig. 2a shows the response of the neuron to an 80 Hz/22 $\mu$m vibration with the corresponding peri-stimulus time histogram (PSTH) aligned to the instant of stimulus onset. The neuronal response increased after stimulus onset, with a peak at 16 msec post stimulus onset. Fig. 2b shows the response of the same neuron to the entire set of vibration stimuli (black data points) measured as the average number of spikes during the 0-50 msec window post stimulus onset (black rectangle in Fig. 2a), as well as its spontaneous activity (gray data point) defined as the average number of spikes in a 50msec window preceding stimulus onset (-10 to -60 msec, as indicated by the gray rectangle in Fig. 2a). As vibration amplitude
increased, average spike count increased in the form of a sigmoid function ($r^2$ of the fit was greater than 0.99).

Although the spike counts summated across 100 trials clearly represent the stimulus amplitude, sensory judgments usually are made from small numbers of trials or single contacts with external stimuli (von Heimendahl et al. 2007) rather than averages across many trials. In fact, the recorded neuron exhibited a high degree of trial-to-trial variation which questions the extent to which the stimulus could be identified on the basis of a single trial observation. Fig. 2c illustrates this variability in spike counts observed in the post- and pre-stimulus windows across 100 trials. We further quantified the trial-to-trial response variability using an ROC analysis (Fig. 2d). The area under the ROC curve for the detection performance of this neuron was 0.83 indicating a significant increase in the hit rate compared to the false alarm rate across the full range of response criteria.

Fig. 3a shows the area under ROC to quantify the neuronal detection performance for the full range of stimulus amplitudes as well as pair wise discrimination performances across all pairs of stimuli. For the illustrated neuron, the absolute detection performance (i.e. when base amplitude equals zero) increased with stimulus amplitude. This neuron could not detect vibrations below 6μm amplitude, but its detection performance for all other amplitudes was significantly better than chance. While 6μm was not detectable against no stimulation (base amplitude of 0), the same increment was highly detectable when added to a base amplitude of 9μm (the discrimination between 9 and 15 as indicated by the arrow in Fig. 3a). Further increases in the base amplitude resulted in a decline in the discrimination performance, pointing to the compressive non-linearity in the response of the neuron at high stimulus amplitudes. This compressive nonlinearity is equivalent to Weber’s law. Fig. 3b show the generality of the principal results obtained in a single neuron to the full set of recorded neurons. Across all neurons, at low base amplitudes, the discrimination performance improved with increasing the base amplitude.
The neuronal analysis up to here focused on firing rates in a 50 msec window post stimulus onset. This window was chosen based on the adaptation profiles observed in the neuronal PSTHs recorded here (see Fig. 2a for a typical response) and was consistent with previous observations of the spike count information in rat somatosensory cortex during decoding of vibrotactile stimuli (Arabzadeh et al, 2004; 2006). In order to further quantify the effect of the integration time window on the detection/discrimination performances, we repeated the preceding analysis on multiple integration time windows. The selection of the window lengths was based on the behavioral results obtained in Experiment 2 (see Fig. 8 below). From the analyses of behavioral reaction times the sensory integration time was estimated to be between 50 and 400 msec. Fig. 4 illustrates the ROC values for integration time windows across this range (specifically 50, 100, 200 and 400 msec) presented separately for single neurons (Fig. 4a) and multi-unit clusters (Fig. 4b). The neuronal detectability and discriminability indices followed the same trend across multiple integration windows. Although at high base amplitudes longer integration times significantly improved discrimination performances (open circles in Fig. 4a and b), the integration time window had no effect at lower base amplitudes (filled circles).

Fig. 5 further quantifies the effect of base amplitude at the level of individual recordings, by comparing the detection performance of individual neurons (squares) and neuronal clusters (circles) with their corresponding discrimination performance at identical amplitude increments. Overall, 89% of recordings show an improved discrimination performance compared to the detection performance. And this was true both for $\frac{1}{2} Th$ versus $1\frac{1}{2} Th$ discrimination (marked in black) and for $Th$ versus $2Th$ discrimination (marked in gray). This figure demonstrates that at low base amplitudes the single neuron and neuronal clusters nearly always improve their performance when tested at discrimination compared to an absolute detection. A Wilcoxon signed rank test on the difference in performance between detection and discrimination showed that across recordings discrimination was significantly better than detection ($p \text{ value} < 0.001$).
Since in behavioral experiments involving whisker discrimination paradigms, the animal’s judgment of stimulus has been shown to closely correlate with the spike count per trial in barrel cortex (von Heimendahl et al. 2007), we expected that rats engaged in a vibration discrimination task would show a similar improved performance when presented with a low amplitude discrimination task, compared to an absolute detection one. Experiment 2 tested this hypothesis in four rats.

In the first stage of the experiment, rats were trained to perform a simple detection task (Fig. 1). Rats were trained to nose-poke into the stimulus aperture in order to receive a vibration stimulus on one of the two stimulus plates. Having identified the vibrating plate, the rat made a behavioral choice by turning towards the corresponding drinking spout in order to receive a sucrose reward. Fig. 6 shows the psychometric detection performance of each of the four rats as a function of stimulus peak velocity. Despite the variability in sensitivity across subjects, all showed the characteristic sigmoid profile. Similar to the neurometric functions the empirical data was well fit by the cumulative Gaussian (the r$^2$ of the fits were > 0.96). The sigmoid curve allowed us to estimate a detection threshold separately for each rat. The detection threshold was defined as the stimulus amplitude corresponding to 60% correct performance (dashed lines in Fig. 6). The estimated thresholds were 10.7, 13.9, 16.2, and 20.9 $\mu$m and these values were used for the second stage of Experiment 2.

Using a similar paradigm, the second stage of Experiment 2 compared the detection and discrimination performances for each individual rat. At this stage of the Experiment, upon nose-poking into the aperture the rat either received a single vibration equal to the rat’s threshold amplitude obtained from Experiment 1 on one side (i.e. detection task) or two vibrations with different amplitudes on either side of the snout (i.e. discrimination task). Fig. 7a shows the discrimination and detection performances across all rats. The median discrimination performance at both low (i.e. half threshold) and intermediate (i.e. threshold) base amplitudes was higher than the median detection performance. Fig. 7b shows the discrimination performances relative to the detection performance for each individual rat. A Wilcoxon signed rank test on the difference in performance between detection and discrimination showed that across rats discrimination was significantly better than detection ($p$ value < 0.01).
Fig. 8a illustrates the distribution of the reaction times (in terms of the median, the interquartile range, and the 99.3% coverage range of distribution) for rat number 2. The reaction time in each trial was defined as the time interval between the stimulus onset and the departure of the nose-poke aperture as measured by the nose-poke sensor. Reaction times were significantly shorter for the easy detection trials compared to the near threshold detection and the two discrimination trials (p value < 0.01, Wilcoxon rank sum test). This difference was significant for all four rats. Furthermore, across the three experimental trials (threshold detection and the two discrimination tasks), reaction times varied systematically with task difficulty (both in terms of the median and the interquartile range). This trend is better visualized in Fig. 8b which demonstrates the median reaction times averaged across rats: reaction times decreased as the base amplitude increased.

Finally, Fig. 9a compares behavioral detection performances with the performance of single neurons and multi-unit clusters obtained in Experiment 1. Average thresholds were significantly lower for multi-unit clusters than single barrel neurons (p value < 0.001). Multi-unit clusters also outperformed rats by showing detection thresholds that were significantly lower than the behavioral thresholds (p value < 0.01). However single neurons’ detection sensitivity was not significantly different from the behavioral sensitivities obtained in 4 rats (p value = 0.49). While single neurons had a mean threshold of 14.1 μm (interquartile range of 8.7 to 18.8 μm), the average behavioral detection threshold was 15.4 μm. The most sensitive single neuron showed a detection threshold of 3.7 μm which was lower than the detection threshold of the most sensitive rat (10.7 μm).

We further compared the detection and discrimination performances based on average values obtained from single neurons and neuronal clusters recorded in Experiment 1 with the performance values obtained from the four rats in Experiment 2. The analysis was limited to those recordings which met the following criteria: (i) a near threshold (55% to 65%) performance at one of the employed stimuli and (ii) stimuli at ½th, 1½th, and 2th were also present in the stimulus set. Thirty five single units and 58 multi-unit clusters met the inclusion criteria. Fig. 9b illustrates the behavioral and neuronal detection/discrimination performances averaged separately across single neurons (light gray bars) as well as multi-unit
clusters (intermediate gray bars). Both for single neurons, and for multi-unit clusters, the average performances followed a trend that was remarkably similar to that of the behavioral performances (dark gray bars).

-- Fig. 9 about here –

399 DISCUSSION

We trained rats in a vibro-tactile task and compared their detection performance with their discrimination performance at various stimulus intensities, which we define as the product of amplitude ($A$) and frequency ($f$) in line with primate studies. Rats nose-poked into an aperture where they received a vibration only on one side (i.e. detection task) or two vibrations with different amplitudes on each side of the snout (i.e. discrimination task). To receive a reward, rats had to turn towards the side with the vibration (in the detection task) or the side with the higher amplitude vibration (in the discrimination task). We also recorded neuronal activity from the barrel cortex of anesthetized rats while passively applying the same set of stimuli as used in the behavioral task. This allowed the comparison of the behavioral performances of rats engaged in the active detection/discrimination task with the neuronal findings recorded in anesthetized animals.

All neurons showed a characteristic sigmoid input/output function with an accelerating non-linearity at low stimulus amplitudes (near detection threshold) and a compressive nonlinearity at high stimulus amplitudes. This is compatible with findings across sensory modalities where sensory processing is normally characterized by a transfer function with a sigmoid shape converting the physical stimulus into neural response (Laughlin 1989). In presence of a constant noise level, a minimum perceptual difference is required for a perceiver to discriminate reliably between two stimulus intensities. Given the accelerating non-linearity, as stimulus intensity increases, progressively smaller increments generate the minimum response difference that is needed to overcome the noise. Quantification of neuronal discrimination performance was consistent with this prediction – for near threshold stimuli, the neuronal discrimination performance was significantly higher than the absolute detection
performance. Similar to the neuronal results, the behavioral performance was better for the
discrimination task compared to the detection task. Furthermore, the effect of base amplitude
on behavioral sensitivity was remarkably similar to its effect on neuronal discriminability
(Fig. 9b).

Previous psychophysical experiments across different modalities in human subjects indicated
that adding a base intensity or “pedestal” to two stimuli can improve discriminability of those
stimuli, a phenomenon known as the pedestal effect (Nachmias and Sansbury 1974; Solomon
2009). This is because at low stimulus levels progressively smaller stimulus increments are
required to produce the smallest stimulus difference detectable by the subject – the Just-
Noticeable-Difference (JND). This gives the subject’s sensitivity a characteristic profile
where the JND dips for low pedestals – and hence is called the “dipper” function (Graham
1989; Nachmias and Kocher 1970). A recent experiment, applied tactile sinusoidal vibrations
to fingertips of human participants that performed a detection/discrimination task and
measured their JND thresholds for vibrations of different amplitudes. Participants showed a
clear dipper function with the lowest JND thresholds observed for pedestal values around
threshold (Arabzadeh et al. 2008). This is consistent with our rat psychophysics findings
reported in Experiment 2 (Fig. 7).

Electrical micro-stimulation has been used as a powerful technique to establish a causal link
between behavior and the activity of neuronal populations (Penfield and Rasmussen 1950).
These studies have established the close link between neuronal activity and behavior in the
somatosensory cortex (Romo et al. 2000; Romo et al. 1998) as well as multiple higher order
visual areas (Afraz et al. 2006; Britten and Van Wezel 1998; Salzman et al. 1992). These
experiments demonstrated that the activation of a population of cortical neurons with similar
tuning properties (e.g. face-selective neurons in the inferior temporal cortex or motion
selective neurons in the middle temporal area) by electrical microstimulation can generate a
simple perceptual bias towards the response property of the selected population. In a two
interval vibration discrimination task, Romo and colleagues (1998) trained the monkeys to
compare a vibration with a train of current pulses injected into the primary somatosensory
cortex. Animals reliably judged the frequency of the mechanical signal with respect to that of
the electrical stimulation, even when both frequencies changed across trials. These findings
imply that electrical stimulation could sum with the neuronal activity evoked by external
sensory stimuli. This means that microstimulation could potentially act as a pedestal to
enhance perceptual sensitivity by increasing the baseline activity of the neuronal population.
In a recent experiment using trans-cranial magnetic stimulation (TMS) in human visual cortex, we found that the activation of visual cortical neurons by TMS can improve detection performance (Abrahamian et al, under review). Future experiments may test this in animals implanted with microelectrodes where more controlled activity can be introduced in a selective population of neurons.

The present results confirmed previous observations on sensory coding in barrel cortex. Neuronal firing rate increases with whisker velocity (Arabzadeh et al. 2003; Gibson and Welker 1983; Pinto et al. 2000). It is important to note that unlike a ramp-and-hold stimulus where amplitude and velocity can be varied independently of each other (i.e. velocity can be held constant and greater amplitude achieved by applying the ramp for a longer period), in a sinusoidal vibration greater amplitude directly leads to greater velocity. In the current experiment stimulus frequency was kept constant and only the amplitude varied across trials. Therefore, both at the level of single neurons and behavior, velocity can be considered the critical stimulus feature. Velocity coding also underlies the representation of ecologically important sensory stimuli such as surface textures (Arabzadeh et al. 2005; Lottem and Azouz 2008). Rats move their whiskers back and forth in a controlled manner (Mitchinson et al. 2007) to collect information from their surrounding environment. As the whiskers contact different surfaces, rapid changes are observed in their movement trajectory – these high-velocity deflections are represented throughout the whisker sensory pathway with remarkable precision (Arabzadeh et al. 2005; Lottem and Azouz 2009; Petersen et al. 2008).

Our recordings revealed that at least in the anesthetized condition, the average detection performance of single neurons is comparable to the range of performances obtained in 4 rats (Fig. 9a). We know from anatomical studies that each barrel column contains approximately 8500 neurons (De Kock et al. 2007). Given the high level of information carried by single cortical neurons in our recordings, and given the fact that the activity of a single cortical neuron can potentially affect the behavior (Houweling and Brecht 2007), one may question the contribution of the high number of cortical neurons to tactile perception. Our results showed a high degree of variability across neurons in their absolute detection threshold, their response saturation, and their response range. In general, individual neurons had a response range narrower than the range of amplitudes across which the rats were able to discriminate. It is therefore possible that barrel cortex employs a high number of neurons to broaden the range of stimuli that the rats could behaviorally process.
To verify this possibility, we calculated the discrimination/detection performance of the pooled population of neurons recorded across multiple sessions in Experiment 1. The analysis demonstrated an error-less discrimination performance across all stimulus pairs (data not shown). This suggests that a population of the order of 100 neurons would be adequate for a perfect detection/discrimination across the range of stimuli employed in the current study and thus support a higher level of sensitivity than what was achieved by the rats. Previous research has shown that the variability in neuronal response can be correlated across neurons recorded at the same time (Darian-Smith et al. 1973; Petersen et al. 2001; Snippe 1996). Such “noise correlation” might prevent the pooled response of neurons that are simultaneously recorded to reach the high levels of performance observed here. However, here, noise correlation could not be quantified as the neuronal activity was pooled across different sessions.

It is also important to note that although Experiments 1 and 2 employed similar stimuli, they entail fundamentally different experimental conditions. In Experiment 1, the rat was anesthetized and head-fixed and the vibration stimuli were always presented at a specific distance from the base of the whiskers while no whisking action was present. In contrast, in Experiment 2, rats were free to whisk against the vibrating plates while keeping their head under the optical sensor in the middle of the nose-poke aperture. Although monitoring whiskers showed little whisking action during stimulus presentation, and despite the fact that the behavioral set up minimized the trial by trial variability in the head position, there was still some residual variability present in the distance from snout to the vibrating plates and the angle of contact. These differences could potentially cause higher response variability in neurons and impair performance in the behaving rats. Despite the different experimental conditions under which behavioral and neuronal data were collected, detection and discriminations followed similar trends (Figure 9b): the coexistence of the pedestal effect thus reflects the ubiquity of sigmoid response functions and rate coding at the level of single neurons, neuronal populations, and behaviour.

Due to the difference in the conditions of Experiments 1 and 2, one cannot draw a causal link between the rats' choice behavior and the precise neuronal firing rates measured here. To link neural activity and perception, a further step in our approach is to record from barrel cortex neurons during the psychophysical detection and discrimination tasks. This can eliminate inter-subject variability, the differences in the stimulus presentation, and the level of arousal
between the two experimental conditions employed here and thus allow a direct investigation
of the contribution of single cortical neurons and neuronal ensembles to behavior.

ACKNOWLEDGEMENTS

We are grateful to J Scott McDonald and Fred Westbrook for valuable discussions. John
Bolzan provided outstanding technical support for the behavioral control set up. This research
was supported by the Australian Research Council (Discovery Project DP0987133).

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Figure 1 Schematic representation of the detection task

(1) The rat initiated a trial by nose-poking into the stimulus aperture while touching the two mesh plates with its whiskers. After a random delay period (2) during which nose-poke was continually maintained, the rat received a vibration stimulus on one of the two plates (3). Having identified the vibrating plate, the rat made a behavioral choice (4) by turning towards the corresponding drinking spouts (circles). Correct choices were rewarded by sucrose water (5).

Figure 2 Response characteristics of a typical barrel cortex neuron and the quantification of the neuronal detection and discrimination performance.

(a) Raster plot and PSTH from a single neuron in barrel column D4. Responses were summated across 100 trials to form the PSTH aligned below the raster plot with zero indicating stimulus onset. Stimulus was 80 Hz, 21 μm peak-to-peak amplitude. PSTH bin size was 10 msec. (b) Spikes are counted over a 50 msec time window as indicated in part a. The gray dot indicates spontaneous activity while black dots indicate average spike count for each stimulus. Three stimuli are selected at 0, 9, and 18 μm amplitudes. Because of the sigmoid shape of the function, the difference in firing rate across these stimulus pairs increased with increasing stimulus intensity (gray lines). The inset captures the accelerating nonlinearity - the first bar shows the difference in spike counts between no stimulation and the 9 μm stimulus; the second bar shows the difference in spike counts between 9 and 18 μm stimuli. All error bars indicate the standard error of the mean across 100 trials. (c) Histogram of spike counts measured in a 50 msec window either before the stimulus onset (gray bars) or after the stimulus onset (black bars). (d) ROC curve corresponding to the histogram illustrated in part c. Every dot indicates hit and false alarm rates for one response criterion. The empirical dots are connected by straight lines in order to estimate the area under curve with a trapezoid method.

Figure 3 Neuronal detection/discrimination performance defined as the area under ROC

(a) The ROC values for all pair wise stimulus comparisons supported by the example neuron illustrated in Fig. 2. Each line connects the stimulus pairs with similar amplitude difference. Δs indicates the peak-to-peak amplitude difference in each pair. Neuronal responses are defined as spike counts over the 50 msec time window post stimulus onset. ROC values averaged across 93 single-units (b) and 142 multi-units (c) recorded in Experiment 1. Error bars are the standard error of the mean ROC value across recordings.

Figure 4 Neuronal integration time window To investigate the effect of neuronal integration time, we repeated the same analysis as in Fig. 3, with multiple windows of lengths 50, 100, 200, and 400 msec. Average ROC values for all pair wise stimulus comparisons across 93 single neurons (a), and 142 multi-unit clusters (b) recorded in Experiment 1. Error bars are the standard errors of the mean ROC value across integration time. Filled circles indicate pair wise comparisons that showed no significant effect of integration window (ANOVA, p>0.05), while open circles indicate pair wise comparisons that showed a significant effect of integration time window (ANOVA, p<0.05). The inset shows the average ROC values for each integration window for all pair wise comparisons at 9 μm peak-to-peak amplitude.
difference. Error bars in the inset correspond to the standard error of the mean ROC values for the 100 msec integration time window. For clarity, error bars are shown for only one integration time window.

**Figure 5 Neuronal detection versus discrimination performance**
Every symbol represents data collected from a single neuron or a neuronal cluster. Squares indicate single neurons while circles represent multi units. For each recording, the stimulus intensity whose detection performance was closest to 60% was chosen as detection threshold (Th). The stimuli corresponding to ½, 1½ and 2 times Th were then selected for estimating the discrimination performances. Black symbols represent ½Th – 1½Th discrimination, while gray symbols represent Th – 2Th discrimination. The inset histogram shows the distribution of each discrimination performance across all recordings. White bars in the histogram correspond to single units. The black and gray lines represent the mean value for each distribution. The dashed diagonal line marks equal performance between detection and discrimination.

**Figure 6 Psychometric functions for the detection task**
Gray circles represent the empirical data while the solid black lines show the Gaussian fit. Error bars represent 95% confidence intervals (binomial distribution, Wilson score). The dashed lines indicate the 60% detection threshold.

**Figure 7 Behavioral detection versus discrimination performance**
(a) Bars indicate median performance across rats. Error bars represent standard error of the mean performance across rats. (b) The filled circles represent ½Th – 1½Th discrimination performance, while the open circles represent Th – 2Th discrimination performance. Error bars indicate standard error of the mean based on a binomial distribution (Wilson score).

**Figure 8 Behavioral response times**
(a) Reaction times were defined as the time duration from stimulus onset to the departure of the nose-poke area for rat #2. The boxes indicate the interquartile range and the error bars indicate 99.3% of the total population. The notches represent the 95% confidence intervals. (b) The median reaction time averaged across rats (n=4). Error bars represent the standard error of mean across rats.

**Figure 9 Comparison of the behavioral and neuronal detection and discrimination performances**
(a) The absolute detection thresholds estimated from neuronal and behavioral data. In order to estimate the detection threshold a sigmoid was fit to the neuronal response function. 142 multi-unit clusters and 76 single neurons met the selection criterion (r-square goodness of fit > 0.8). The boxes indicate the interquartile range and the error bars indicate 99.3% of the total population. The notches represent the 95% confidence intervals. (b) The neuronal performance is the average performance across single- (n=35) and multi-unit clusters (n=58) that met the inclusion criteria (see Results). Error bars indicate standard error of mean across rats or neurons.
Figure 1
Figure 3

(a) Area under ROC

(b) Area under ROC

(c) Area under ROC

Base amplitude (μm)
Figure 4
Figure 5

Detection Performance (%) vs Discrimination Performance (%)
Figure 6
Figure 7
Figure 8
Detection threshold (μm)

Multi-units

Single-unit

Behavioral

Figure 9