# A database of vibratory signals from free haptic exploration of natural material textures and perceptual judgments (ViPer): analysis of spectral statistics *

Matteo Toscani[1,2] and Anna Metzger[1,2]

[1] Justus-Liebig University, Giessen, Germany
[2] Bournemouth University, UK
ametzger@bournemouth.ac.uk

**Abstract.** We recorded vibratory patterns elicited by free haptic exploration of a large set of natural textures with a steel tool tip. Vision and audio signals during the exploration were excluded. After the exploration of each sample, participants provided judgments about its perceptual attributes and material category. We found that vibratory signals can be approximated by a single parameter in the temporal frequency domain, in a similar way as we can describe the spatial frequency spectrum of natural images. This parameter varies systematically between material categories and correlates with human perceptual judgements. It provides an estimate of the spectral composition of the power spectra which is highly correlated with the differential activity of the RA and PC afferents. In addition to their relevance for basic research, our results may represent a significant step ahead for tactile rendering in virtual reality.

**Keywords:** Statistics of Natural Textures · Materials · Perception · Touch

## 1    Introduction

When we touch natural surfaces, we are extremely good at distinguishing different materials (e.g. silk from satin) despite the complexity of the patterns of stimulation elicited by tactile exploration [1].

Touching a surface causes patterns of vibrations on our skin which are sensed by the mechanoreceptors embedded in the skin. Softness and temperature information is also available. The vibratory signals play an important role for perceiving natural textures [2–4]. Perceptual representations based only on vibratory signals acquired indirectly with a tool are remarkably similar to representations obtained with bare hand exploration [4]. These vibratory signals are highly dependent on exploration movements (e.g. speed) and on the local properties of

textures. Understanding how such complex signals yield to robust perception of material properties is not only interesting for perception science, but also for applications, e.g. for haptically rendering material properties by the application of vibratory signals on the skin.

In order to understand the relationship between the vibratory signals elicited by free exploration of natural textures and how we perceive these textures while we touch them, we built a database of vibratory patterns recorded while human participants freely explored a large set of natural textures with a steel tool tip. After the exploration of each signal, participants provided judgments about their perceptual attributes (e.g. roughness or friction) and rated how much the explored material feels like each of the seven material categories used in the experiment (wood, plastic, fabric, paper, metal, stone and animal).

Here we describe the properties of the vibratory signals we recorded in relation to the perceptual judgements provided by human participants. The spectral power $P$ relates to the temporal frequency $f$ according to a power law ($P = \frac{1}{f^s}$). We found that vibratory signals can be approximated by a single parameter $s$ in the temporal frequency domain. The same relationship characterizes the spatial frequency spectrum of natural visual textures (e.g. [5]). Crucially, this parameter $s$ varies systematically between material categories such that it can be used to classify physical category labels (e.g. metal vs. plastic). Classification performance improves when classifying perceptually assigned labels, suggesting a relationship between perception of material categories and the spectral statistic described by $s$. In fact, $s$ correlates with human judgements of some of the perceptual attributes participants rated.

In our previous research, we showed that haptic perceptual representations emerge by efficient encoding of vibratory signals [4]. These representations resemble the responses of the RA and PC afferents, tuned to lower temporal frequencies (peak around 50Hz) and higher (250 Hz), respectively [6]. Here we show that $s$ correlates with the ratio of the PC to the RA responses; i.e. the higher the contribution of high temporal frequencies as compared to lower frequencies, the higher $s$. Thus, $s$ provides a concise measure of the temporal frequency composition of the vibratory signals elicited by the exploration of natural images, provides information about material categories and perceptual attributes, and can be computed by comparing the responses of mechanoreceptors.

## 2    Methods

### 2.1    Participants

Eleven students volunteered to participate in the experiment; all were naïve to the purpose of the experiment and were reimbursed for their participation. They were right-handed and did not report any sensory or motor impairment at the right hand. The study was approved by the local ethics committee LEK FB06 at Giessen University and was in line with the declaration of Helsinki from 2008. Written informed consent was obtained from each participant.

## 2.2 Stimuli

Our natural textures consisted of 81 different material samples which were glued on wooden pieces (14 × 14 cm, Fig. 1).These materials samples are the same used by [7]. They belong to seven material categories: plastic, paper, fabric, fur and leather, stone, metal and wood, and were chosen to represent the large variety of material appearances we encounter in everyday life.



**Fig. 1.** Photographs of all material samples. Rows indicate different material categories: plastic, paper, fabric, fur and leather, stone, metal and wood, from top to bottom.

## 2.3 Procedure and Apparatus

Participants set at a table looking at a computer monitor elevated by a support. Material samples were positioned by the experimenter in front of them through a hole in the support so that they could easily be touched but no visual information was available. The sound from the exploration of materials was covered by earplugs and white noise presented via headphones.

Participants freely explored the 81 surfaces with a 3D printed pen containing a steel tip at its end and a mounted accelerometer (ADXL345). This way we could record the vibrations elicited by the interaction between the steel tip and material samples. Each participant explored each material once.

The onset of the white noise signalled that they could begin the exploration. They were instructed to slide the pen over the material's surface. After the exploration of each material, participants rated how much the explored material

felt like each of the seven material categories (paper, fabric, animal, stone, plastic, wood, metal) on a scale from "very different" to "very similar". Then, they rated how much the material could be described by each of seven perceptual attributes, as described by opposing adjective pairs. We used a subset of the descriptors used by [7]: rough vs. smooth, hard vs. soft, orderly vs. chaotic, warm vs. cold, elastic vs. not elastic, high friction vs. slippery, textured/patterned vs. homogeneous/uniform. The experimental software was written with Psychopy [8].

### 2.4    Vibratory Signals

For each material, 10 seconds of recording were acquired at 3200Hz temporal resolution. We started the recording after 2 seconds of exploration and stopped 2 seconds before the exploration was terminated (i.e. participants explored 14 seconds each sample), to prevent that signals are affected by contact onset and offset. We filtered out frequencies below 10Hz as they may be ascribed to exploratory hand movements [9–12]. We cleaned the signals by removing frequencies above 800Hz, which are not relevant for perception of texture properties of materials [13–15, 3, 1] and may be caused by measuring noise.

### 2.5    Analysis

We approximated the relationship between temporal frequency $f$ and the amplitude power $P$ with the following function $P = \frac{1}{f^s}$ In a log-log space, this equals to the following linear relationship $P = -sf$. We determined $s$ by fitting a line in log-log space. From now on we refer to $s$ as the *slope* (of the line). We assessed how well this linear relationship can approximate the power spectrum by computing $R^2$, i.e. the proportion of variance explained by the linear fit. *Slope* was computed for each material and each participant separately, i.e. for each exploration trial. Since signals only included power at frequencies between 10Hz and 800Hz, the linear fits were performed within this interval.

We used *slope* to classify the material categories by means of a linear classifier. For classification, we averaged *slope* across participants yielding one average *slope* per material. To prevent over-fitting, we iteratively left out one material and trained the classifier on the remaining slopes, then computed performance on the left-out material. We used bootstrap analysis to test whether classification performance was higher than chance: we repeated the classification analysis 5000 times shuffling the category labels every time. Thus we computed the distribution of classification accuracy under the null hypothesis of chance-level classification. The 95% confidence interval was computed by reading out the $2.5^{th}$ and the $97.5^{th}$ percentiles of the distribution. The empirical chance level corresponded to the mean of that distribution. We repeated the classification analysis based on perceptual labels. To determine perceptual category labels, first we assigned to each material the highest rated material category by each participant, then we chose the most frequent category, i.e. the one chosen by the majority of participants.

To relate *slope* to the responses of the mechanoreceptors, we estimated the responses of the RA and PC afferents using the TouchSim toolbox [16].

## 3 Results

Figure 2 shows one example of vibratory signal per material category. For all categories the linear model seems to provide a good approximation of the spectral profile.
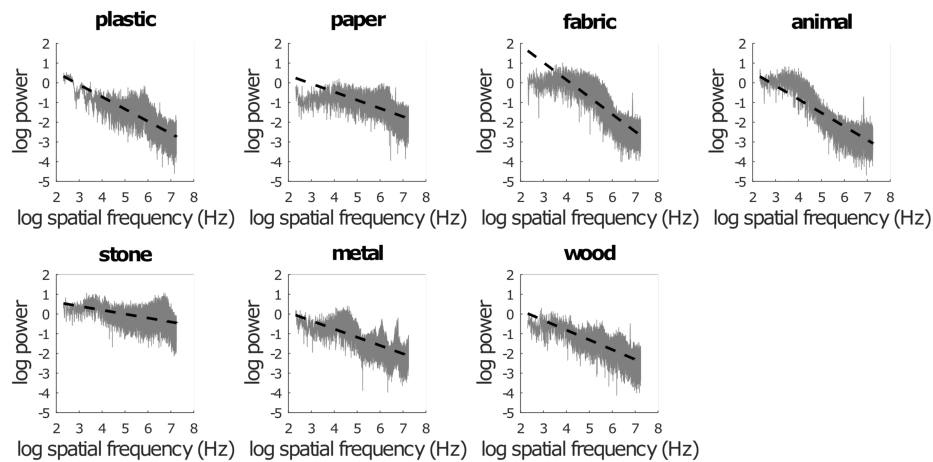


**Fig. 2.** Spectral profiles of example materials for each of the seven categories. Natural logarithm of the amplitude spectrum on the y-axis, as a function of the natural logarithm of temporal frequency (x-axis). Each diagram represents the spectral profile of one example material, explored by one participant in one experimental trial. The seven diagrams represent one example per category.

On average, the linear fits could explain 43% of the variance of the spectral profiles, indicating that almost half of the variability in such high dimensional signals (32000 dimensions) can be approximated by two parameters (slope and intercept). We used a linear classification analysis to determine whether *slop* variations across different vibratory patterns provide information about material properties. Based on *slope* we could classify material categories better than chance (classification performance = 33.3%; empirical chance level =14.8 %, with [6.17 23.46] 95% Confidence interval). Performance increased when we repeated the classification analysis based on perceptually assigned categorical labels (classification performance = 38.27%; empirical chance level =16.67%, with [6.17 27.16] 95% Confidence interval). This means that human misclassifications could be explained by differences in *slope*, suggesting that perception is at least in part based on *slope*. To explore this possibility, we investigated the relationship between *slope* and human ratings of perceptual attributes (Fig. 3).
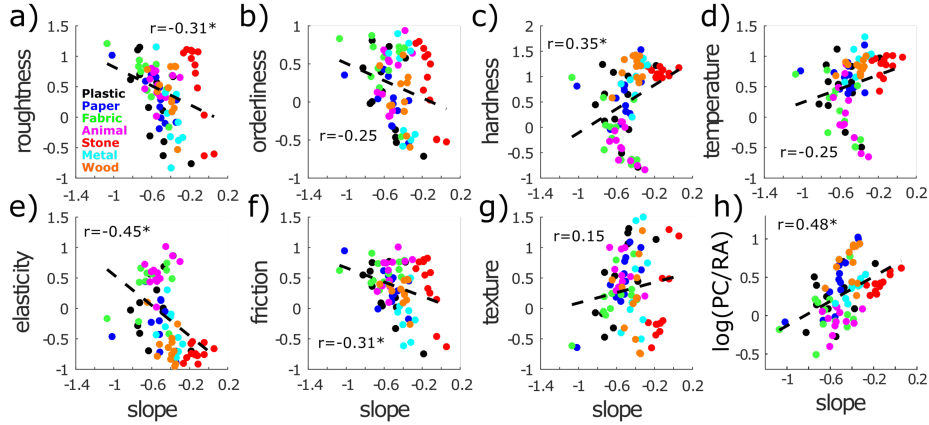
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**Fig. 3. a)-g)** Relationship between human ratings of perceptual attributes and *slope*. Z-transformed perceptual ratings averaged across participants, on the y-axis. *Slope* on the x-axis. **h)** Relationship between activity of mechanoreceptors and *slope*. The differential activity of the PC and RA receptors is represented by the natural logarithm of the ratio between the activity of the PC and the RA afferents, on the y-axis. *Slope* on the x-axis. Different material categories are indicated by the different colours in the legend in the top left panel. Dashed lines indicate regression lines.

Correlation analyses show that shallower *slope* is significantly associated with low roughness, elasticity, fiction and with high hardness judgments (r=-0.31, r=0.35, r=-0.45, r=-0.31; all *p*-values $< \alpha$, with ($\alpha$=0.00714), according to Bonferroni correction for seven post-hoc comparisons).

RA and PC afferents seem crucial for perception of natural textures [3, 4]. RA respond to relative low temporal frequencies, whereas PC to higher temporal frequencies. Therefore, the differential activity of these two afferents provides information about the composition of the power spectrum of the tactile input. We quantified this information as the natural logarithm of the ratio (PC/RA) between the activity of the RA and the PC afferents. For each vibratory signal we computed the RA and PC responses using the TouchSim toolbox [16], and related this quantity to *slope* (Fig. 4).

The ratio PC/RA correlates with *slope* (r=0.48, p $<$ 0.00001), indicating these two measures employ a similar way to summarize the power spectrum of vibratory signals elicited by exploration of natural materials.

## 4    Discussion

We recorded the vibratory signals elicited by free exploration of a large number of natural materials. Each exploration is associated by perceptual judgments of categories and perceptual attributes. Other databases of vibratory signals have been published. Vibratory signals were measured with the same system we used at controlled speed and free exploration [9, 10, 12]. To our knowledge,

our database is the only one to present perceptual judgments, effectively ruling out the influence of visual and audio information. Furthermore, we focused on everyday life materials (like wool, or fabric) rather than following industrial conventions for sampling and naming our material samples. Our database with vibratory signals and perceptual judgements (ViPer) is publicly available on GitHub (https://github.com/matteo-toscani-24-01-1985/ViPer).

By analysing the vibratory signals in the frequency domain, we showed that they can be approximated by a single parameter representing the *slope* of the linear relationship between spectral power and temporal frequency in log-log space. This parameter can be used to classify material categories. Classification performance improves when classifying perceptual labels, suggesting that *slope* can account for human misclassifications. The bond between *slope* and perception is strengthened by the correlations with human judgements of perceptual attributes like roughness, hardness, elasticity and friction.

The same linear relationship characterizes the spatial frequency spectrum of natural visual textures (e.g. [5]). This may indicate scale invariance of the visual world. Spatially rescaling an image by a factor of $\alpha$ implies rescaling the corresponding frequency domain axes by a factor of $\frac{1}{\alpha}$. A power spectrum that falls as a power law will retain its shape under this transformation, i.e. would show scale invariance. We speculate that the *slope* we used to describe vibratory signals exhibit time invariance, i.e. would change minimally for explorations at different speed. Hence, perceptual systems could estimate *slope* based on the differential activity of the RA and PC afferents (as suggested by the correlation depicted in Fig. 3h) and use it to perceiving material properties despite different velocities of exploratory movements, i.e. to achieve what is usually referred to as speed invariance [17]. However, we did not measure the speed of exploratory movements, therefore we cannot test how much it affects *slope*. We plan to systematically investigate our speculation in future research.

We previously showed that haptic perceptual representations emerge by efficient encoding of vibratory signals [4]. Such compressed representation can be described within a space whose dimensions resemble the activity of RA and PC afferents. In this space, the compressed representations of different materials tend to lay on a line (see [4], Fig. 3A), along which it is possible to distinguish between different material categories, i.e. materials can be distinguished based on the differential activity of the RA and PC afferents. As *slope* is able to capture the differential activity of the RA and PC afferents, we speculate that *slope* may be a prominent feature, if not the main one, of the compressed representation we previously discovered.

Our analyses showed that a simple statistical property of the Fourier spectrum is able to capture nearly half of the variability within the vibratory signals elicited by a large number of natural textures. This property systematically differs between material categories and correlates with perceptual judgments. Our results may represent a significant step ahead for tactile rendering in virtual reality, just like in vision pink noise is used for synthesizing naturalistic textures (e.g. [18]).

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