Efficient coding in the whisker system: biomimetic pre-processing for robots?

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Introduction The Efficient coding hypothesis [1, 2] proposes that biological sensory processing has evolved to maximize the information transmitted to the brain from the environment, and should therefore be tuned to the statistics of the world. Metabolic and wiring considerations impose additional sparsity on these representations, such that the activity of individual neurons are as decorrelated as possible [3]. Efficient coding has provided a framework for understanding early sensory processing in both vision and audition, for example in explaining the receptive field properties of simple and complex cells in primary visual cortex (V1) and the tuning properties of auditory nerve fibres [4].

Whisker sensing has been the subject of growing interest both in neuroscience [5] and robotics [6]. Rodent whiskers are an excellent model mammalian sensorimotor system: they are highly amenable to study with a range of genetic and optical tools, and the sensory and motor neural pathways are delineated to a greater degree than in other systems [7]. For robotics, whiskers are low powered, cheap to assemble and certain perceptual decisions, such as contact localisation along the length of the whisker, can be made with very simple computations [8]. Tactile discrimination in more complex conditions, however, remains a challenge for robotics. A given whisker-surface contact can have a number of unknown parameters (whisker speed, contact angle, surface texture *et cetera*), making surface identification difficult [9]. Whisker movement in exploring rodents and robots is highly variable, and trial to trial changes in whisker-object contact geometry complicates surface classification [10].

Can such an efficient coding approach be applied to understanding the rodent whisker system? In addition, does a biomimetic efficient coding scheme provide insights for improving tactile discrimination in robots? Here we present preliminary results from a meta-analysis of 'natural' whisker deflection data (analogous to natural images in computer vision) collected from seven published experiments with robotic whisker systems [11–14, 9, 10, 8]. We show that certain features from efficient and sparse coding of whisker deflections appear to be aligned with the tuning curves of rodent primary afferent and thalamic relay neurons, suggesting that this system is performing efficient coding.

Results Whisker follicle primary afferent (PA) neurons have been broadly classified as 'contact', 'pressure' or 'detach' cells [15], as shown in Figure 1A, or as slowly and rapidly adapting units [16]. An common method of efficient encoding is principal components analysis (PCA). The first 3 eigenvectors from PCA of artificial whisker deflections from [14] is shown in Figure 1B. The gross shape of these PCs resemble the PA response properties in Figure 1A. This early result indicates that PA neurons may be performing an efficient transformation of natural whisker deflection signals. PCA is often used as an encoding step in its own right, but is also used as a 'whitening' pre-processing step. Flattening or whitening a signal is the operation of removing redundant correlations, ensuring that input signal features (such as spatial frequency in an image) have the same variance, and outputs are sparse.Sparse coding algorithms tune basis function populations to represent input distributions evenly, is related to Independent Component Analysis, and has been used to explain end-stopping and non-classical receptive field surround suppression in V1 neurons [17]. Rat ventral posterior medial thalamic nucleus (VPm) neurons have been described as a population of diverse, precise kinetic feature detectors [18], the most common of these (from a larger distribution) are shown in Figure 1C. We tested a non-linear sparse coding approach [17] on artificial whisker data from [11] to determine whether VPm-like kinetic features would emerge. Some resultant basis functions are shown in Figure 1D (from a larger distribution). The shapes of these basis functions resemble VPm neuron responses (Figure 1C), suggesting that this structure may be performing sparse coding. Work is ongoing to rigorously compare the distribution of features generated through efficient and sparse coding to population neural tuning properties. For robotics we propose that the two coding schemes presented here could be applied in succession and considered a biomimetic filter cascade for pre-processing signals on artificial whisker systems. Such an approach may endow robots with the capabilities of biological whisker systems, such as high representational capacity, sensory robustness to motor noise, and computational efficiency. **Acknowledgements** Funded by a University of Sheffield/EPSRC Doctoral Prize Fellowship

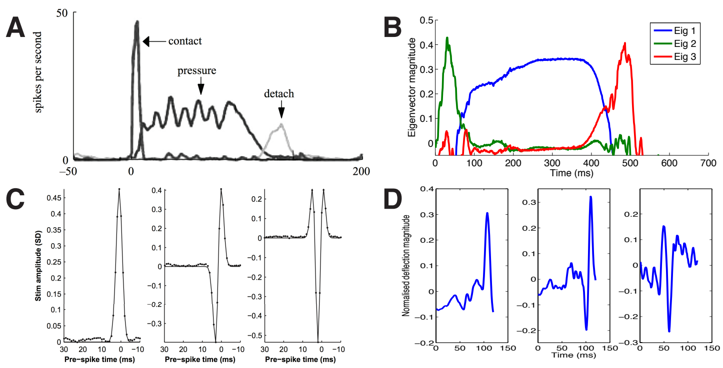

Fig. 1. Neural responses to whisker deflection resemble whisker deflection statistics. **A** Primary afferent responses from [15], adapted from [19]. **B** First 3 eigenvectors from PCA on artificial data resemble neural responses in **A**. **C** VPm thalamus responses from [18]. **D** Subset of sparsely generated basis functions (of a complete set of 64) that mimic the neural response properties shown in **C**. These results suggest rodent tactile sensory processing follows efficient coding principles, an approach which may improve robot sensing.

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