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Encoding/decoding of first and second order tactile afferents in a neurorobotic application

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A B S T R A C T

We present a neurorobotic framework to investigate tactile information processing at the early stages of the somatosensory pathway. We focus on spatiotemporal coding of first and second order responses to Braille stimulation, which offers a suitable protocol to investigate the neural bases of fine touch discrimination. First, we model Slow Adaptive type I fingertip mechanoreceptor responses to Braille characters sensed both statically and dynamically. We employ a network of spiking neurones to transduce analogue skin deformations into primary spike trains. Then, we model second order neurones in the cuneate nucleus (CN) of the brainstem to study how mechanoreceptor responses are possibly processed prior to their transmission to downstream central areas. In the model, the connectivity layout of mechanoreceptor-to-cuneate projections produces a sparse CN code. To characterise the reliability of neurotransmission we employ an information theoretical measure accounting for the metrical properties of spiking signals. Our results show that perfect discrimination of primary and secondary responses to a set of 26 Braille characters is achieved within 100 and 500 ms of stimulus onset, in static and dynamic conditions, respectively. Furthermore, clusters of responses to different stimuli are better separable after the CN processing. This finding holds for both statically and dynamically delivered stimuli. In the presented system, when sliding the artificial fingertip over a Braille line, a speed of 40 – 50 mm/s is optimal in terms of rapid and reliable character discrimination. This result is coherent with psychophysical observations reporting average reading speeds of 30 – 40 ± 5 mm/s adopted by expert Braille readers.

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1. Introduction

Fine touch discrimination is mediated by rapid and reliable responses to stimuli sensed by fingertip mechanoreceptors (Johansson and Birznieks, 2004). Even simple object manipulation requires the ability to convey optimal accounts of tactile percepts to the central nervous system in order to adopt closed-loop control policies. More specifically, peripheral encoding/decoding mechanisms must produce faithful spatiotemporal representations of sensed stimuli and all subsequent stages of the ascending somatosensory pathway must transmit these codes to downstream structures as efficiently as possible.

Microneurography studies in humans demonstrated the precision and rapidity of primary afferent neurones (e.g. fingertip mechanoreceptors) in encoding fine tactile stimuli into perfectly discriminable spike train patterns (Johansson and Birznieks, 2004). Mechanoreceptors innervate the epidermis and discharge according to mechanical indentations of the fingertip skin. The spike latencies of mechanoreceptor responses convey information about contact parameters fast enough to account for the use of tactile signals in natural manipulation (Johansson and Birznieks, 2004; Johansson and Flanagan, 2009). Primary afferent signals are processed by second order neurones in the cuneate nucleus (CN) of the brainstem, which constitutes the main synaptic relay along the somatosensory pathway from the fingertip to the central nervous system. The functional link between first and second order neurones (i.e. mechanoreceptors and cuneate cells) has not been thoroughly investigated, and experimental and computational findings on how information is processed along this pathway are still lacking.

We propose a neurorobotic framework to study neural coding at the level of first and second order tactile afferents. The presented approach arises from a larger study on haptic perception, in which a robotic setup was used to investigate fine touch discrimination during Braille reading tasks (Fig. 1A and B). Here, we simulate skin indentation protocols in which Braille-like tactile stimuli are delivered statically and dynamically to an artificial touch sensor (Fig. 1C). We model deformation analogue values through a simulator mimicking

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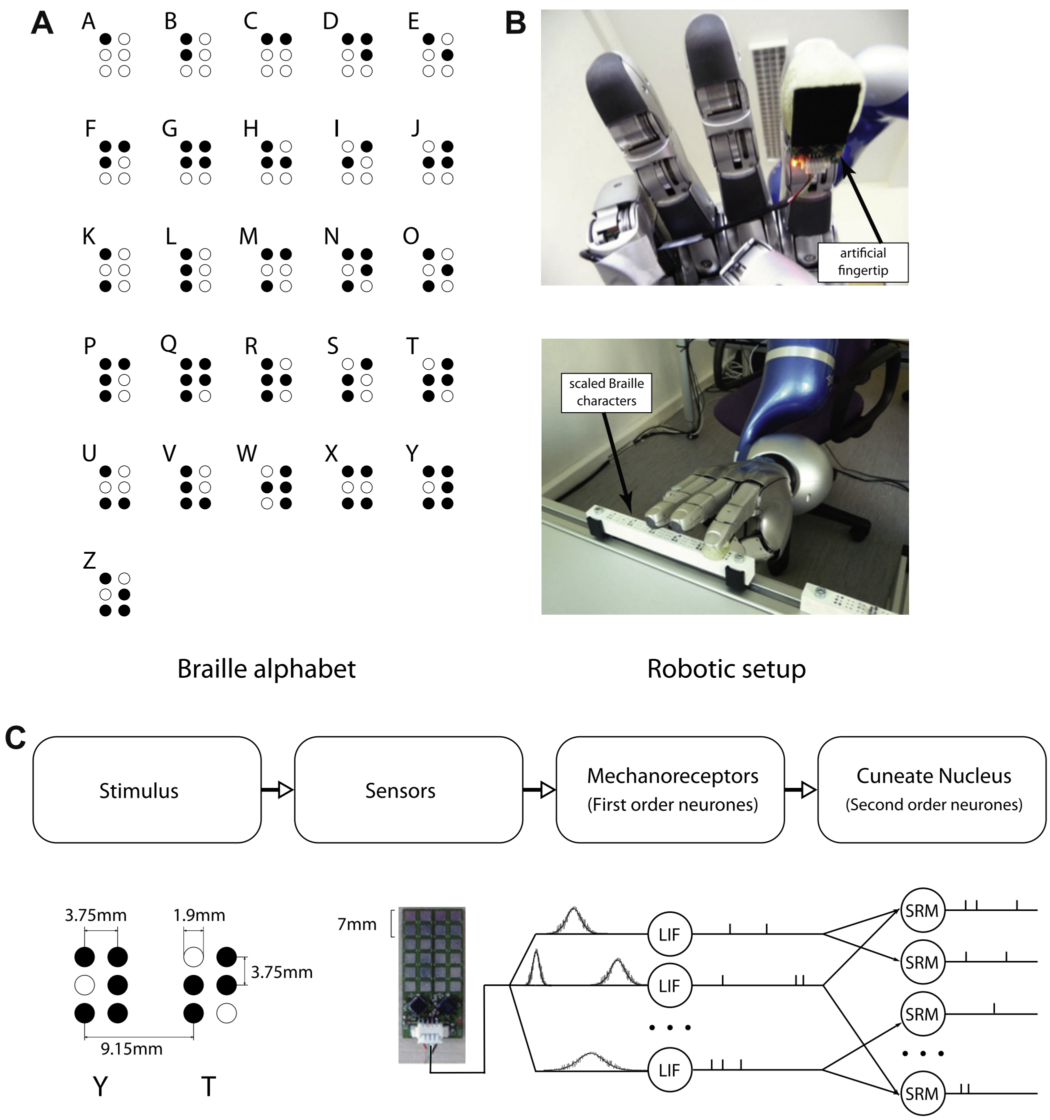

Fig. 1. *Overview of the robotic setup and entire encoding/decoding pathway*. (A) Braille alphabet. (B) The artificial fingertip mounted on a robotic hand/arm setup (© Institute of Robotics and Mechatronics, German Aerospace Center). (C) From left to right: we employ Braille-characters as tactile stimuli to indent a capacitive artificial touch sensor. The analogue responses provided by the touch sensor drive a network of Leaky-Integrate-and-Fire (LIF) neurones (Chacron et al., 2003) converting analogue signals into spiking activity and mimicking fingertip mechanoreceptors. The population of LIF neurones projects onto a network of Spike-Response-Model (SRM) units (Gerstner and Kistler, 2002) implementing second order cuneate nucleus (CN) cells of the brainstem.

skin indentation following orthogonal forces exertion. These analogue signals form the inputs to a network of leaky-integrate-and-fire neurones (LIF). The latter performs an analogue-to-spike conversion aiming at reproducing the activity of Slow Adapting type I (SA-I) mechanoreceptors in terms of both spiking discharge and receptive fields (see Johansson and Flanagan, 2009, for a recent review). The population of LIF neurones (i.e. simulated primary afferents) projects onto a network of second order units modelling CN neurones. We employ the Spike Response Model (SRM) (Gerstner and Kistler, 2002) to capture the stochastic nature of single cuneate responses (unpublished data by H. Jörntell). Drawing inspiration from our recent theoretical analysis of human microneurography recordings (Brasselet et al., 2011), we use a metrical information measure to estimate the amount of information transmitted by first and second order neurones about tactile stimulation. The same information measure quantifies stimulus separability at both stages of the considered pathway. The presented system succeeds in reconstructing both statically and dynamically delivered Braille-like stimuli rapidly and reliably. Also, the CN sparse re-encoding of primary afferent signals facilitates downstream discrimination of tactile stimuli and minimises destructive interference between similar percepts sensed by the artificial fingertip.

2. Material and methods

Fig. 1 shows the robotic setup used for the Braille scanning task and illustrates an overview of the considered encoding/decoding pathway. We adopt different experimental protocols in order to characterise neural coding at each processing stage (i.e. upstream and downstream from the cuneate nucleus network) and investigate fine touch discrimination. For the static stimulation protocols, we employ a set of 26 different probes reproducing a scaled version (1:1.67) of all Braille characters and we simulate orthogonal indentation on the fingertip skin. Following an experimental protocol used for microneurography recordings in humans (Johansson and Birznieks, 2004), we take a protraction phase of force application of 125 ms, a plateau phase of 250 ms, and a retraction phase of 125 ms. For the dynamic stimulation protocols, we rub the same probe set of Braille-characters over the simulated fingertip at different constant velocities, from 5 to 90 mm/s.

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