UNIVERSITY OF BIRMINGHAM

CNCR

Modelling First-Order Tactile Neurons

Davide Deflorio

Mind, Brain, and Models 2022

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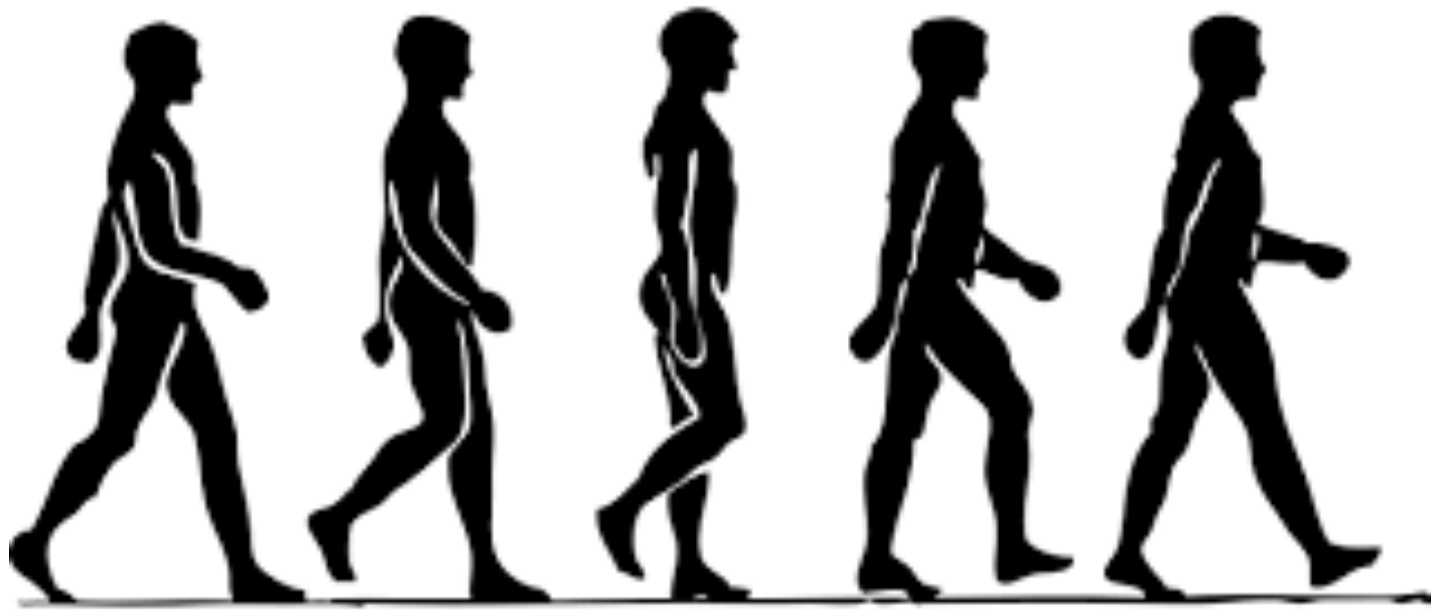
Outline

- Tactile System and Tactile Perception
- Microneurography
- Modelling First-order Tactile Neurons
- Applications
- Limitations

- **WORKSHOP:** Saal et al. (2017)

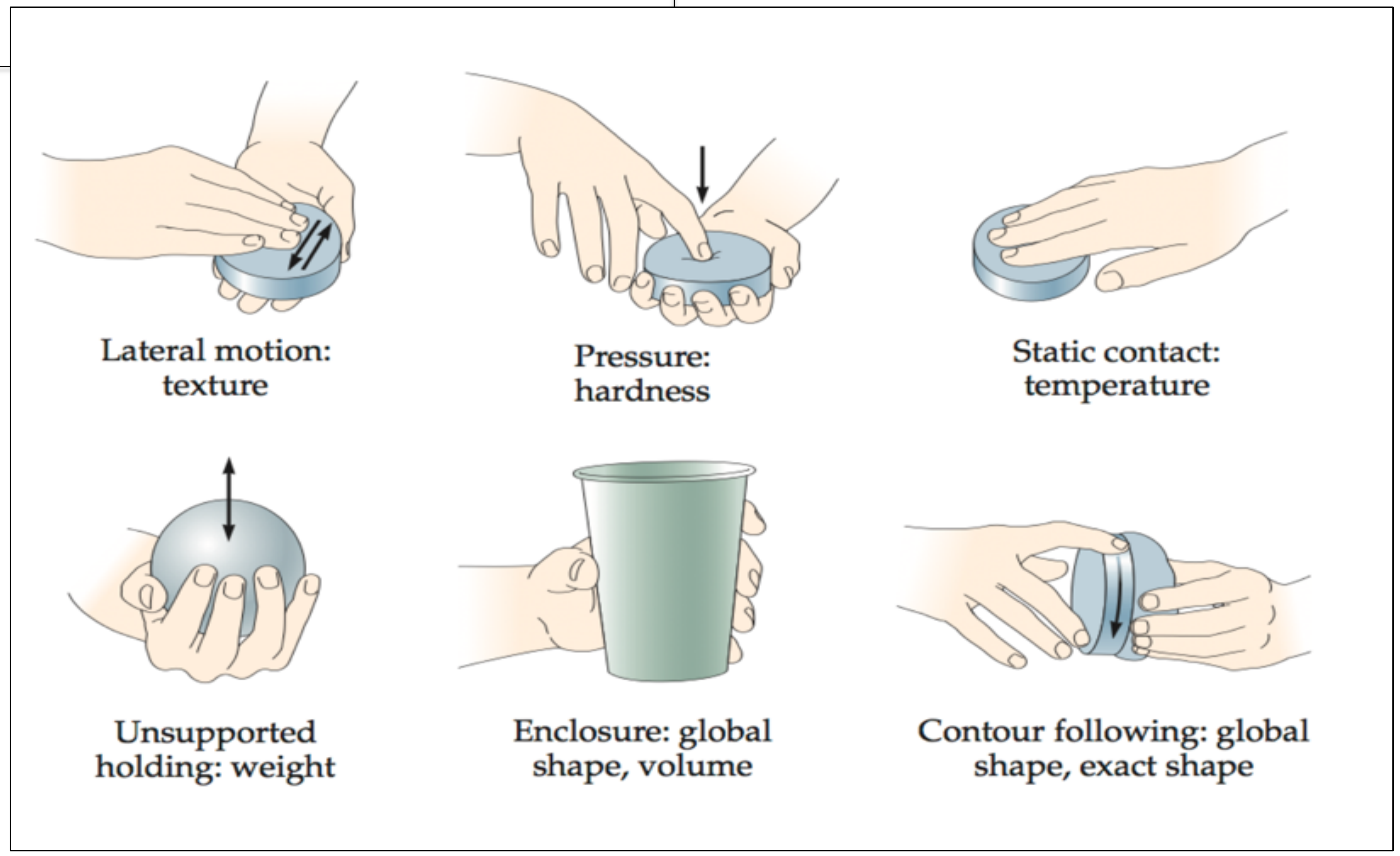
The Sense of Touch

The Sense of Touch



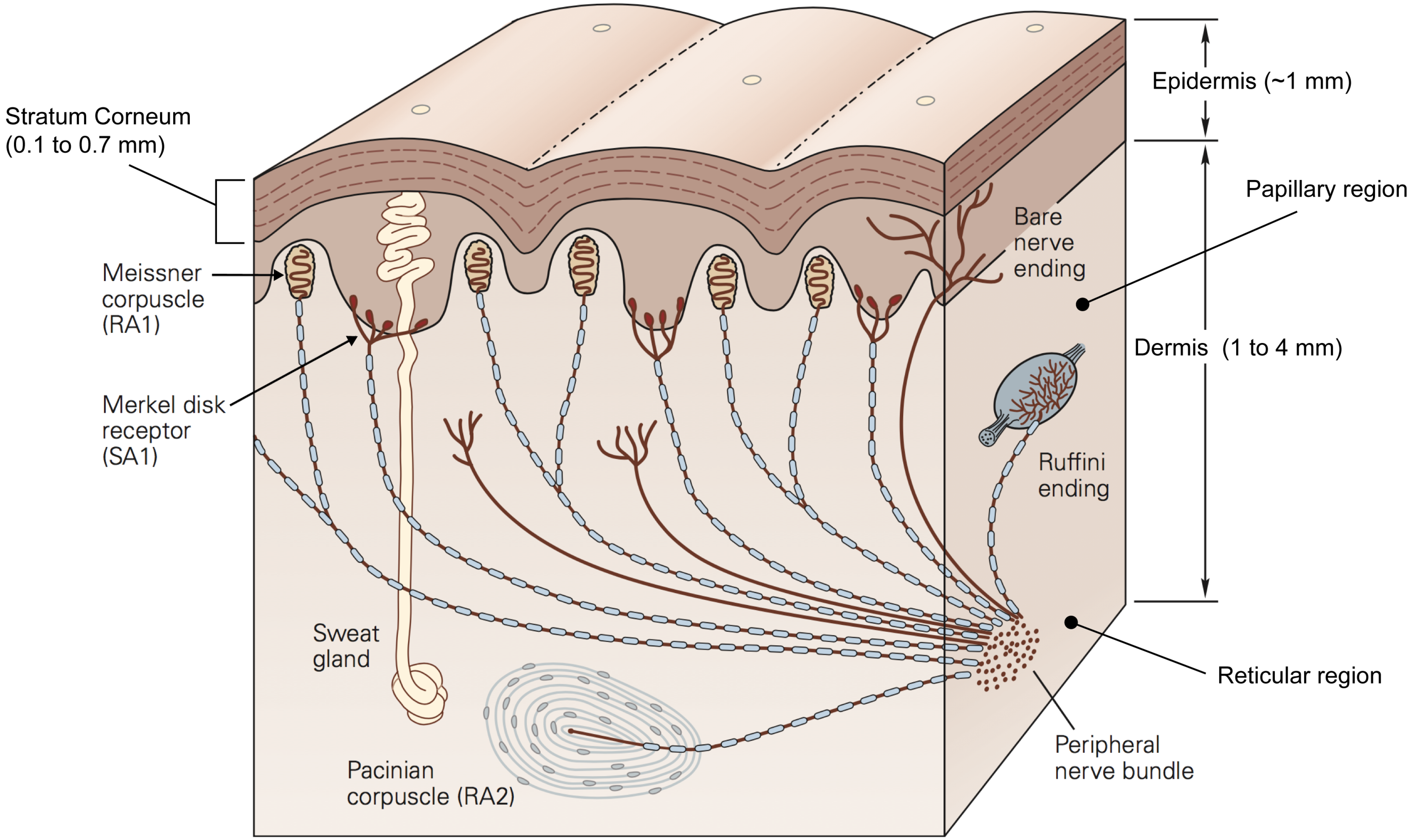
Proprioception/Kinesthetic
- Muscles
- Joints
- Tendons

Tactile (and Haptics)
- Cutaneous
- Objects' properties
- Affective and social



Lederman and Klatzky, 1987

Tactile System - Skin

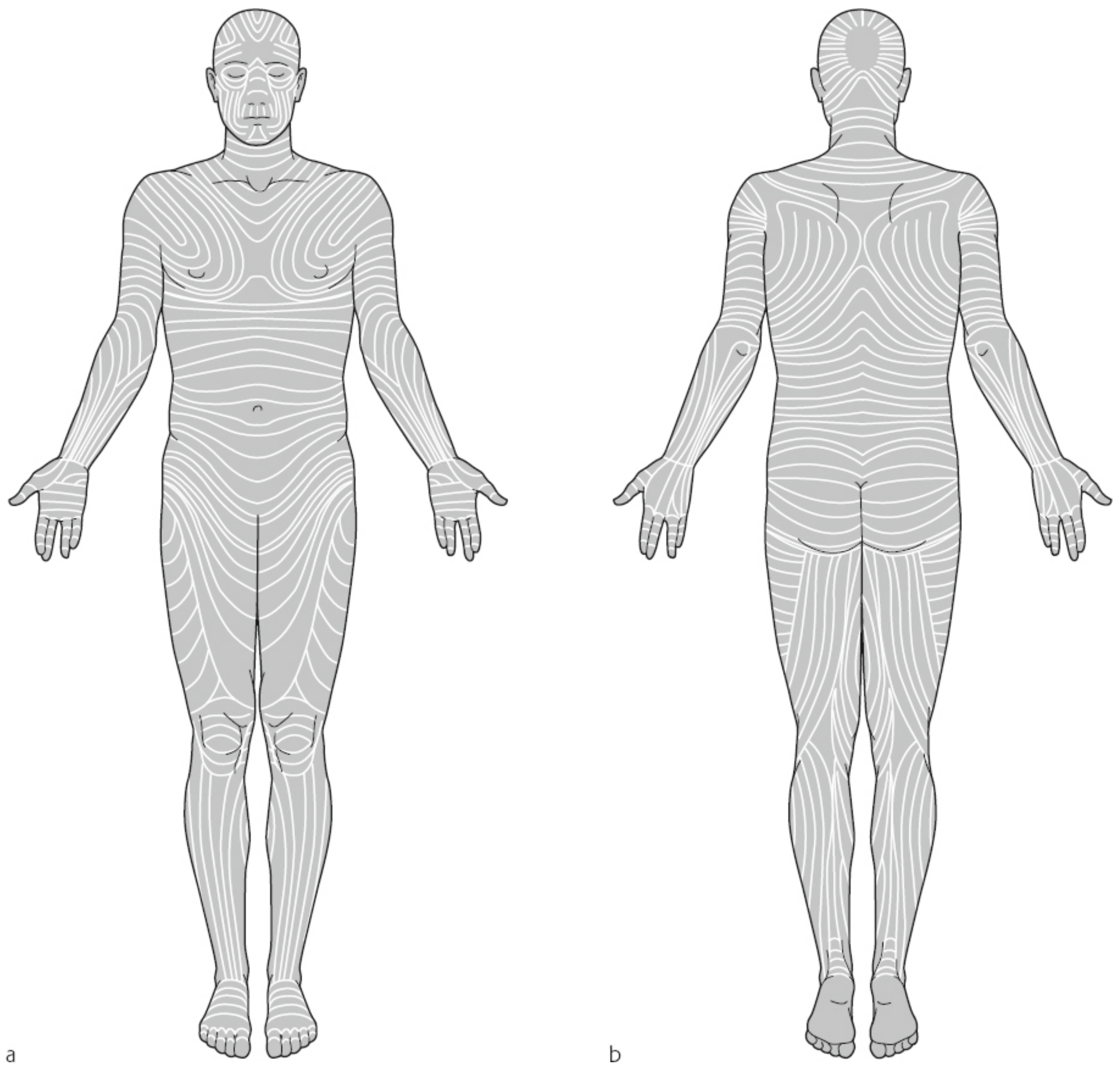


Kandel, Principles of Neural Science. 2013

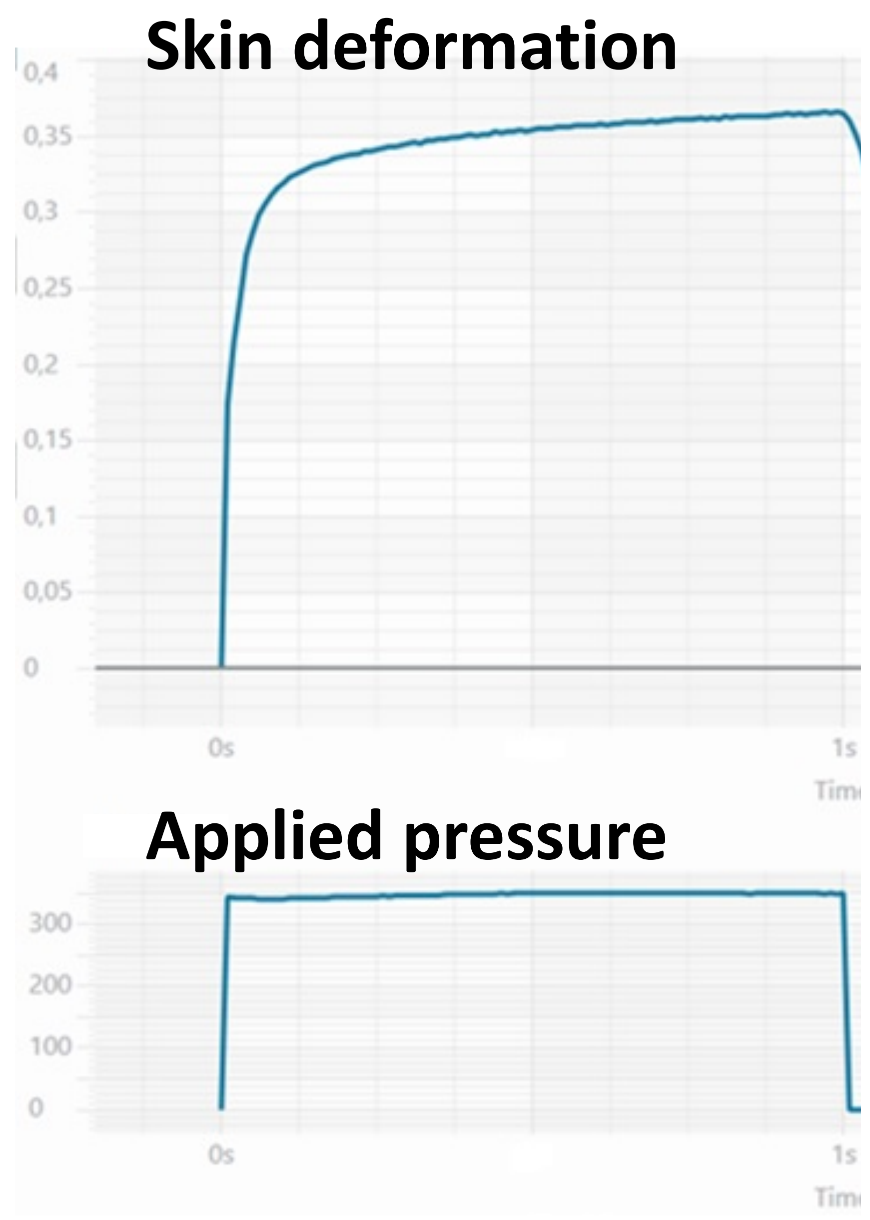
DERMIS:
- Nerve endings
- Sweat and sebaceous glands
- Papillary and reticular region

Tactile System - Skin

- <u>Anisotropy:</u> properties depend on direction
- e.g. higher tension across Langer's lines



- <u>Viscoelasticity</u>
  - *Creep:* dynamics of skin extension under a constant stretching force



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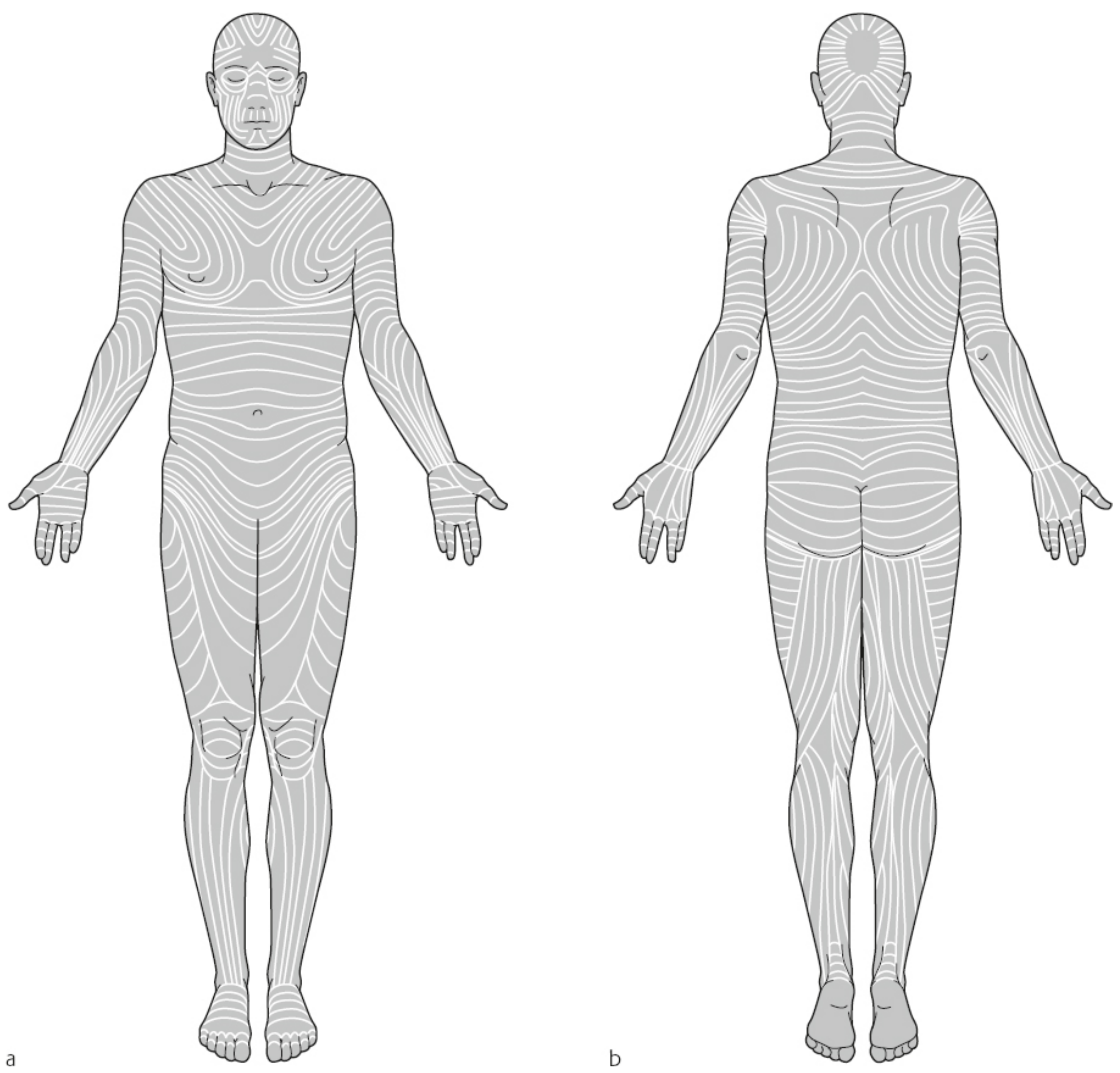

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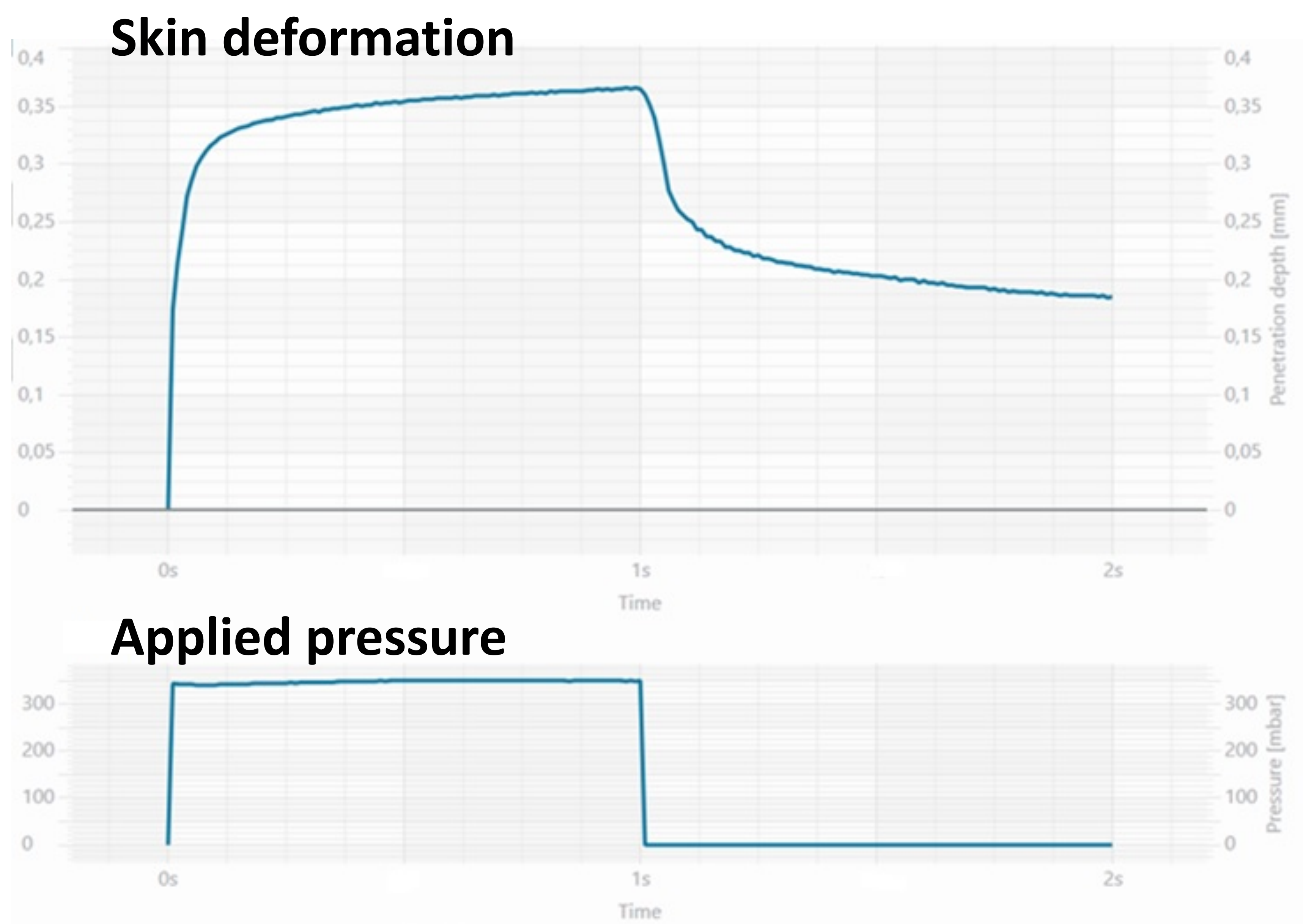
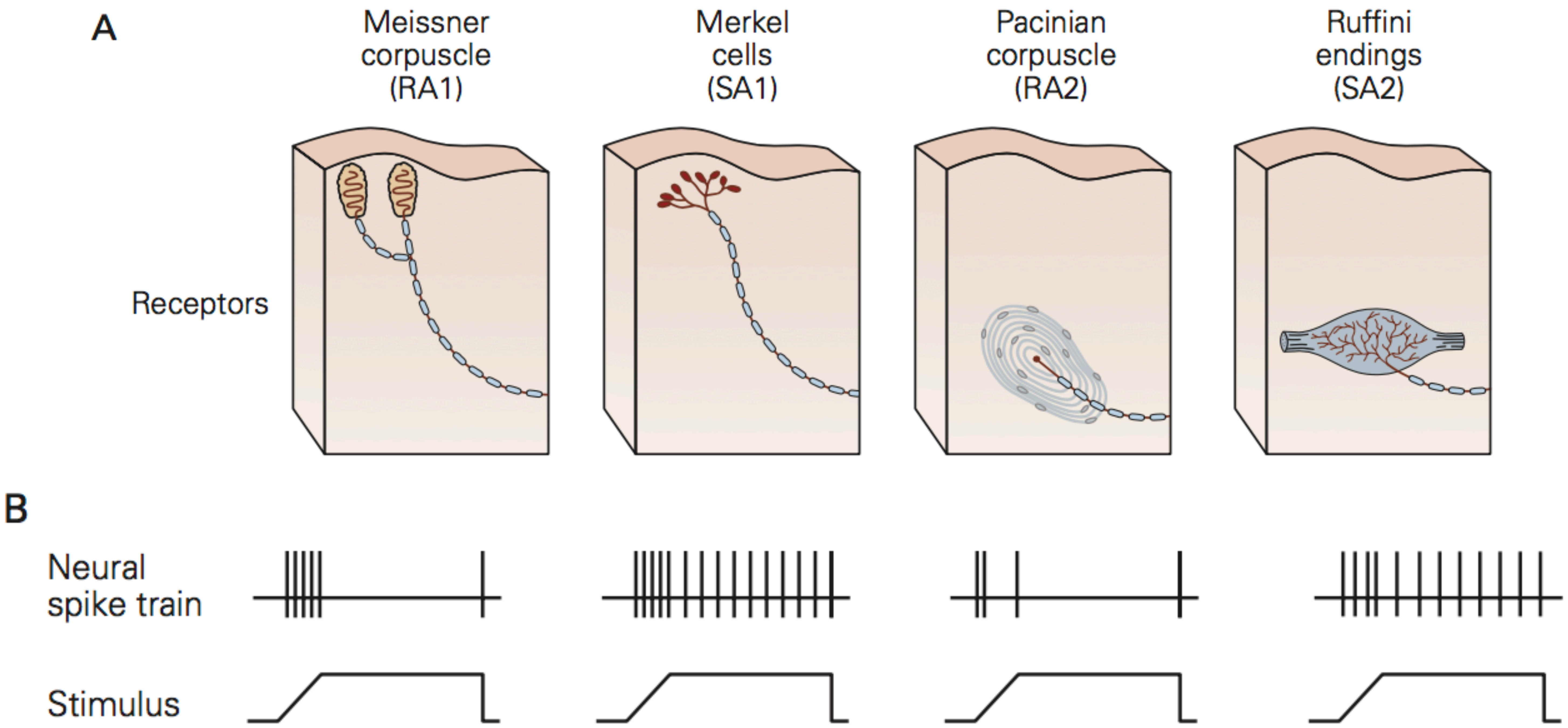


  - *Hysteresis:* energy loss between loading and unloading phase (time-dependent)

Tactile System - Mechanoreceptors

- Mechanoreceptors are sensitive stresses and strains and respond in different ways due to their morphology and location
- There are 17.000 fibres in the glabrous skin of the hand.



RA1
- Complex RFs
- Rapid adaptation
- Frequency response 1-300 Hz, best = 50 Hz

SA1
- Complex RFs
- Slow adaptation
- Frequency response 1-100 Hz, best = 5 Hz

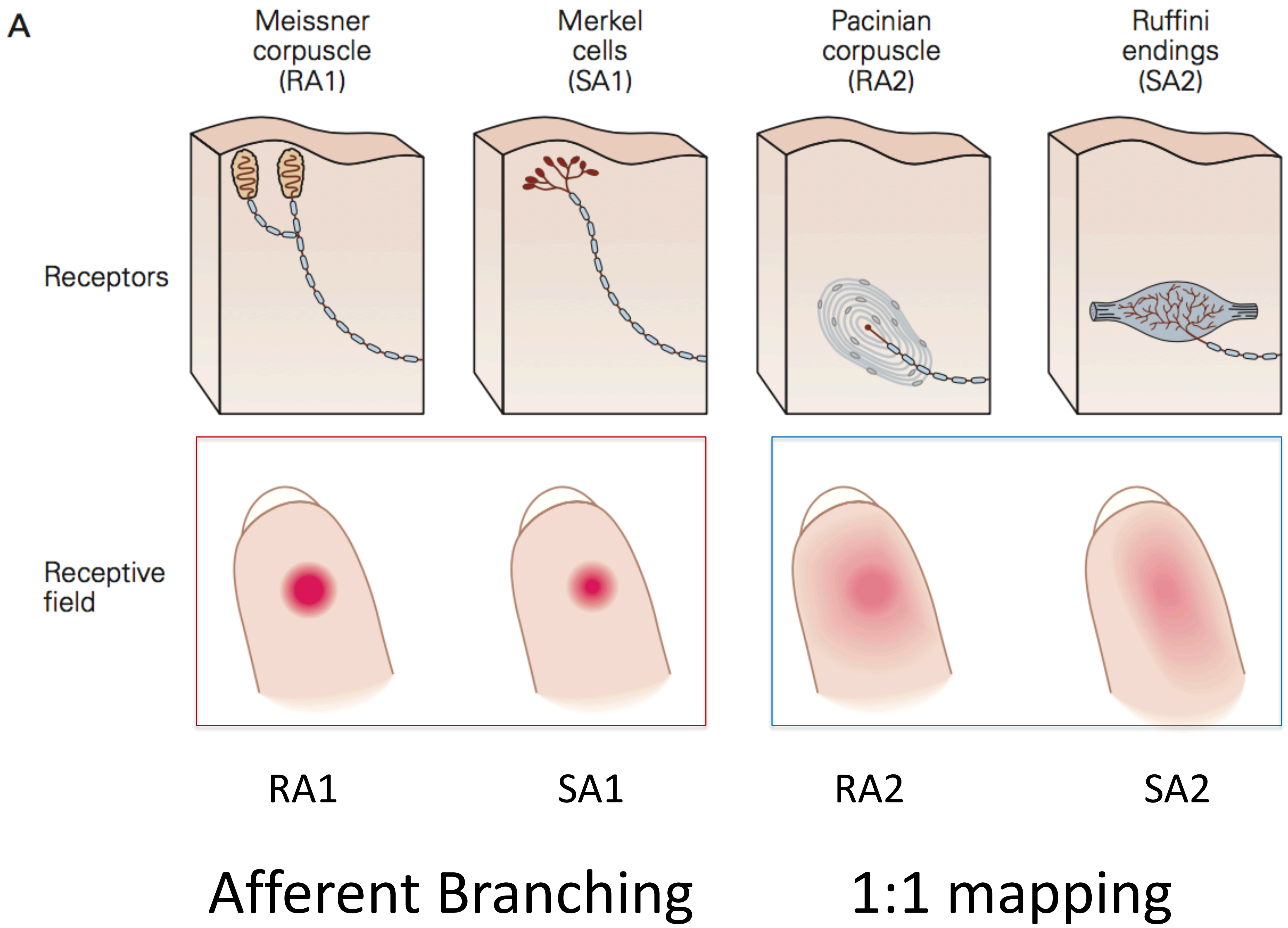
RA2 (PC)
- Simple RFs
- Rapid adaptation
- Frequency response 5-1000 Hz, best = 300 Hz

SA2
- Simple RFs
- Slow adaptation

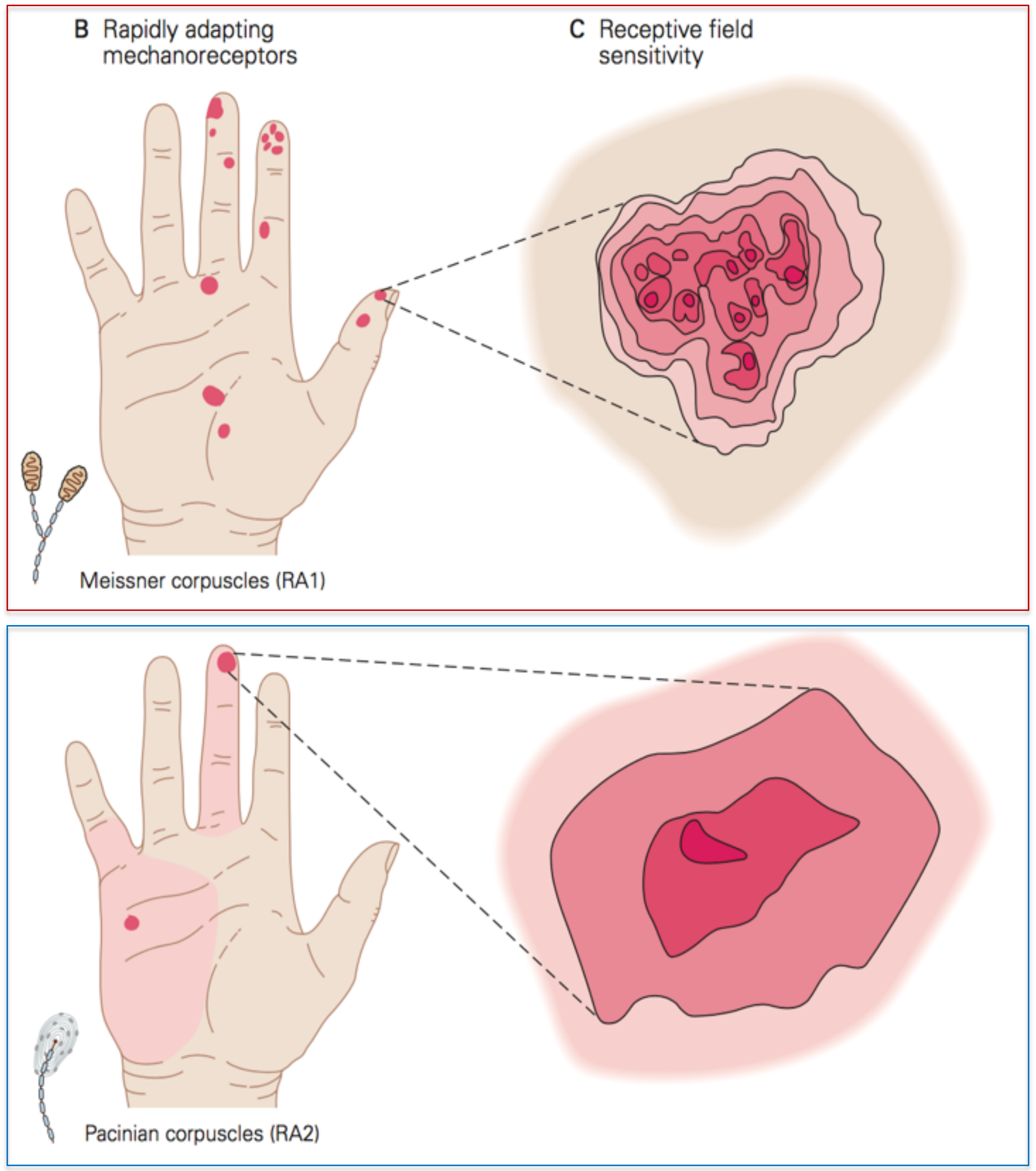
Kandel, Principles of Neural Science. 2013

Tactile System - Mechanoreceptors

- They are connected to type II A fibres which transmit the information to the brain.



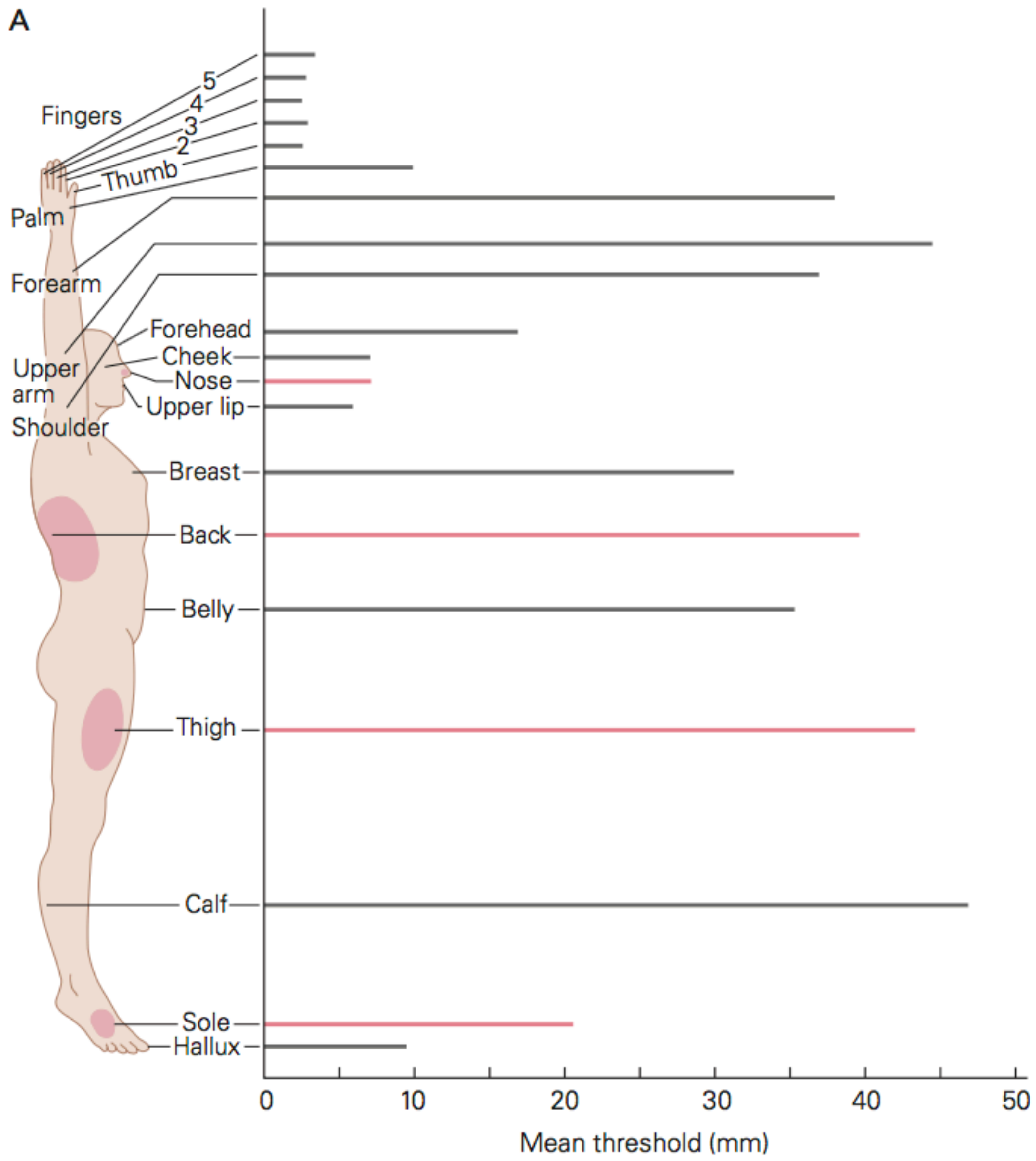
RECEPTIVE FIELD



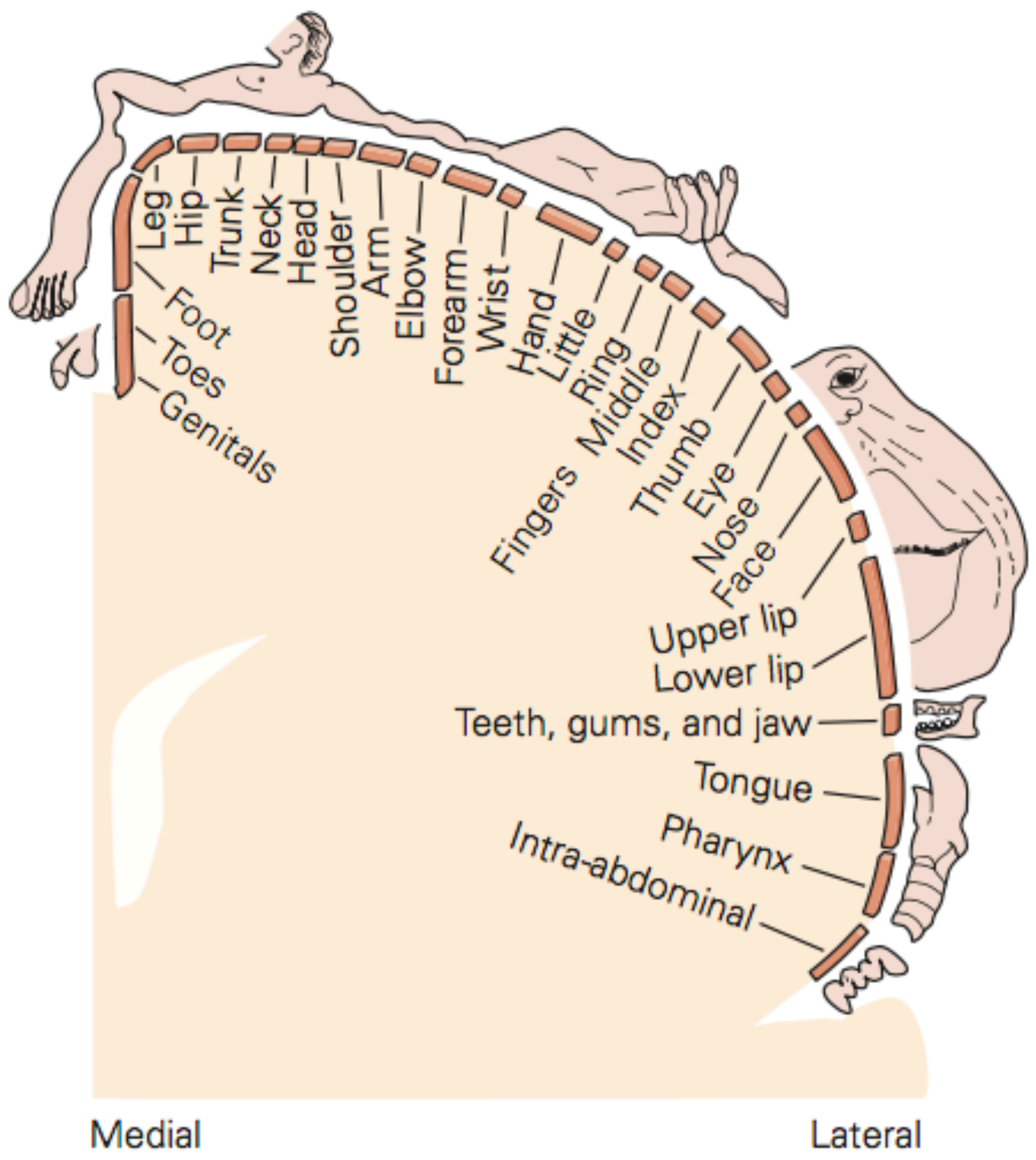
Kandel, Principles of Neural Science. 2013

Tactile System

- Density of receptors determine tactile spatial sensitivity of a body part.

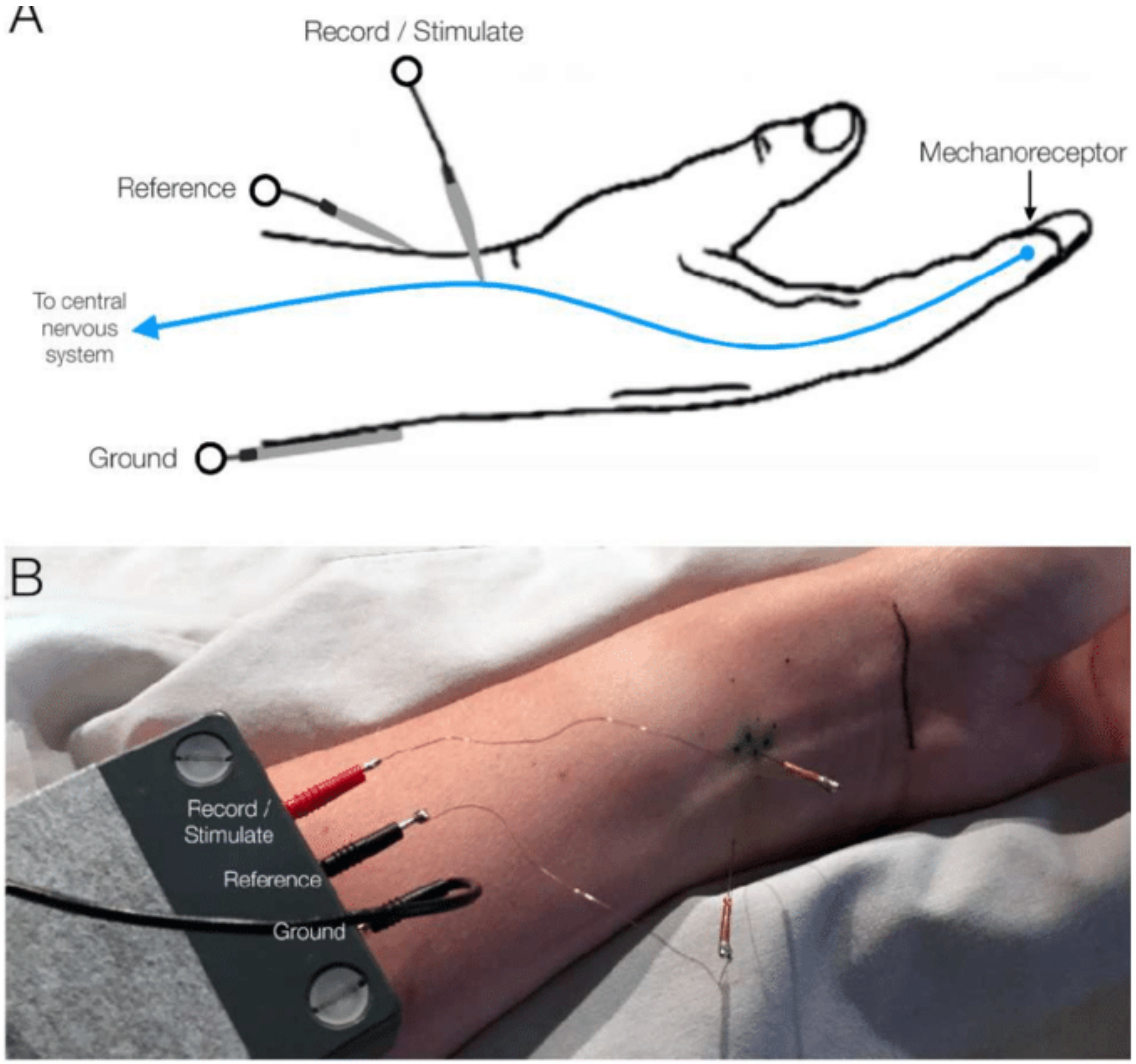


2-point discrimination

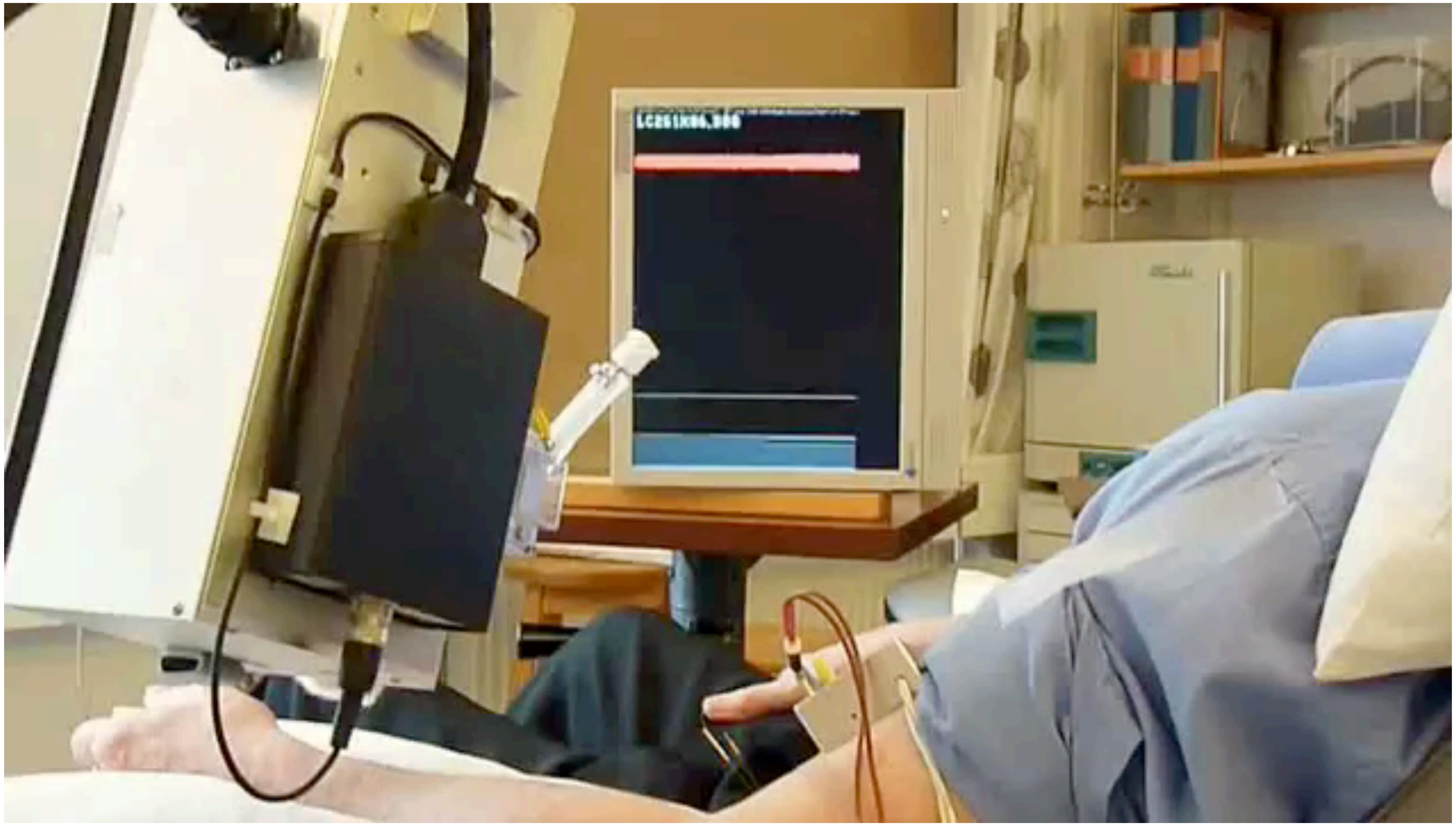


Kandel, Principles of Neural Science. 2013

Classical Approach - MICRONEUROGRAPHY



Classical Approach - MICRONEUROGRAPHY



- https://www.youtube.com/watch?v=QYt44mm94yQ&ab_channel=BBCEarth

Classical Approach - MICRONEUROGRAPHY

Limitations:

- Only one or few fibres can be recorded at the same time
- Invasive
- Slow and difficult
- Short session
- Passive stimulation

Sensory Mechanisms of Tactile Perception

DUPLEX THEORY (Katz, 1925): ***Spatial versus Temporal code***

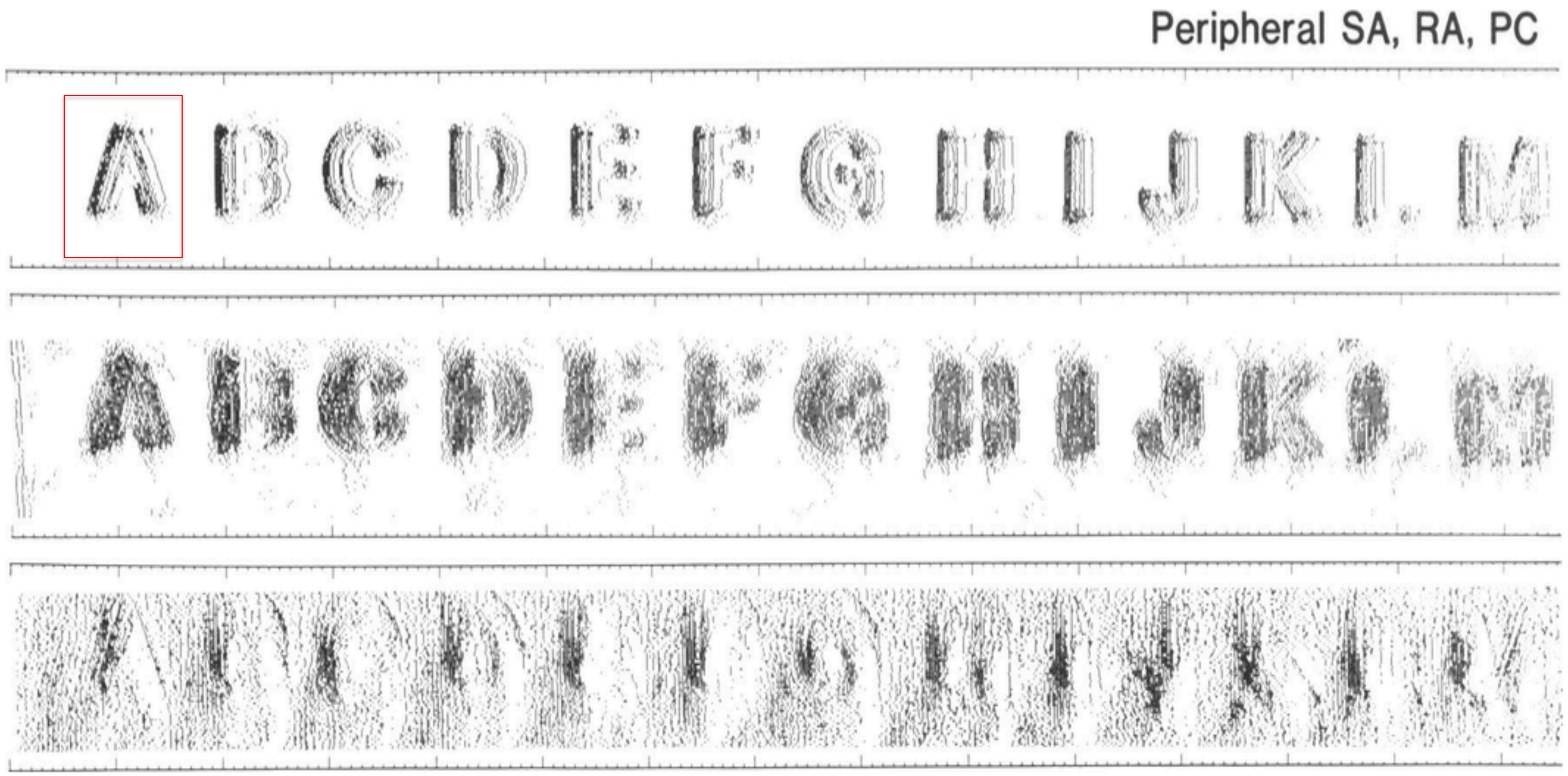
- **Coarse features (> 0.1 - 0.2 mm) are encoded in a spatial manner**
  - The firing rate (i.e. number of spikes) variations between afferents reflects the spatial layout of the stimulus
  - Static pressure, no sliding movement

- **Fine features (< 0.1 - 0.2 mm) are encoded in a temporal manner**
  - The spike timing of individual afferent reflects the properties of the stimulus
  - Dynamic movement, vibrations

Sensory Mechanisms of Tactile Perception

Spatial versus Temporal code

- **Spatial code (static pressure):** the firing rate variations between mechanoreceptors reflects the spatial layout of the stimulus



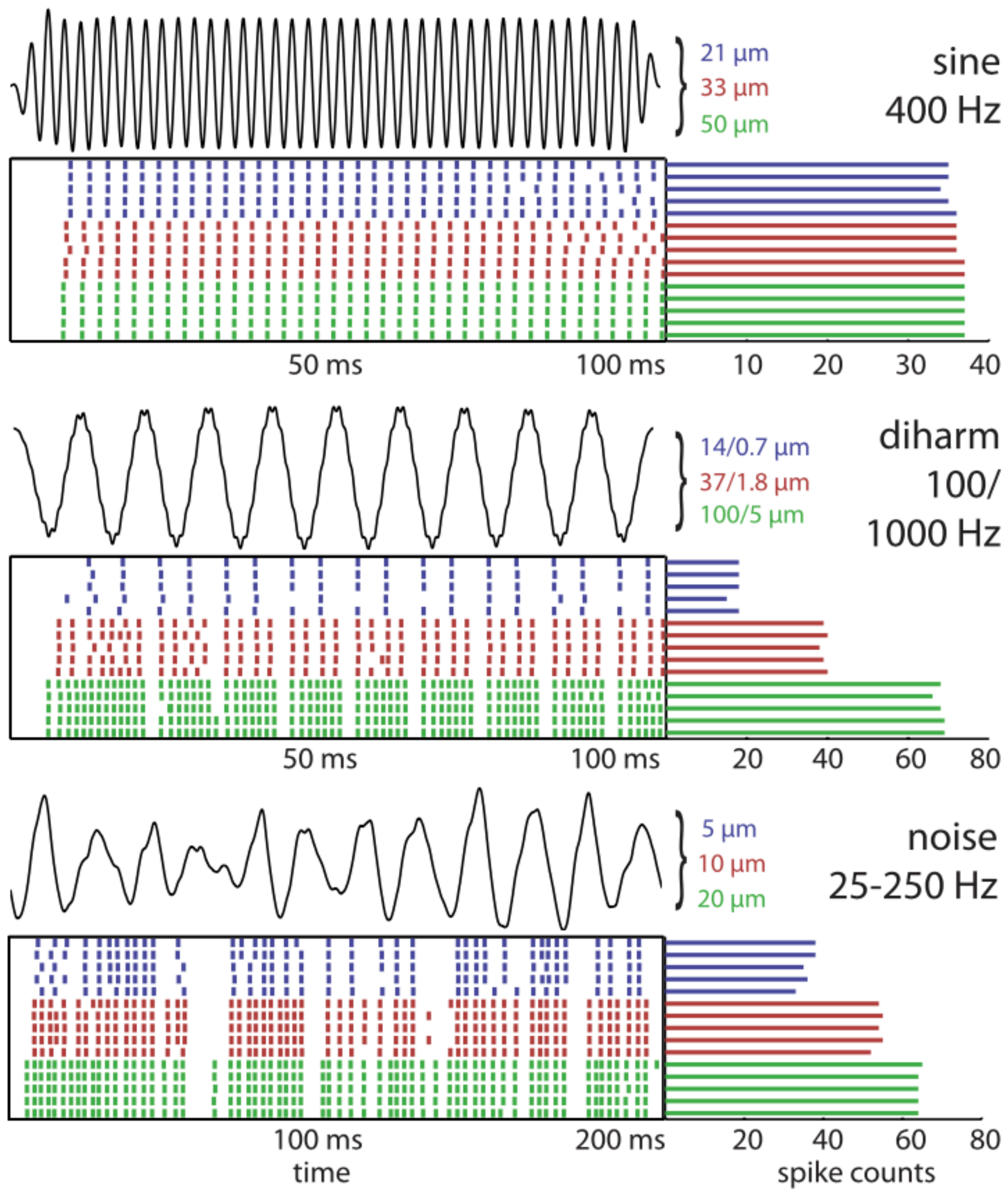
89 afferents (34 SA, 36 RA, and 19 PC)

Phillips et al., 1988

Sensory Mechanisms of Tactile Perception

Spatial versus Temporal code

- **Temporal code (dynamic, vibrations):** the individual spike timing of the mechanoreceptors reflects the properties of the stimulus



27 afferents (8 SA, 14 RA, and 5 PC)

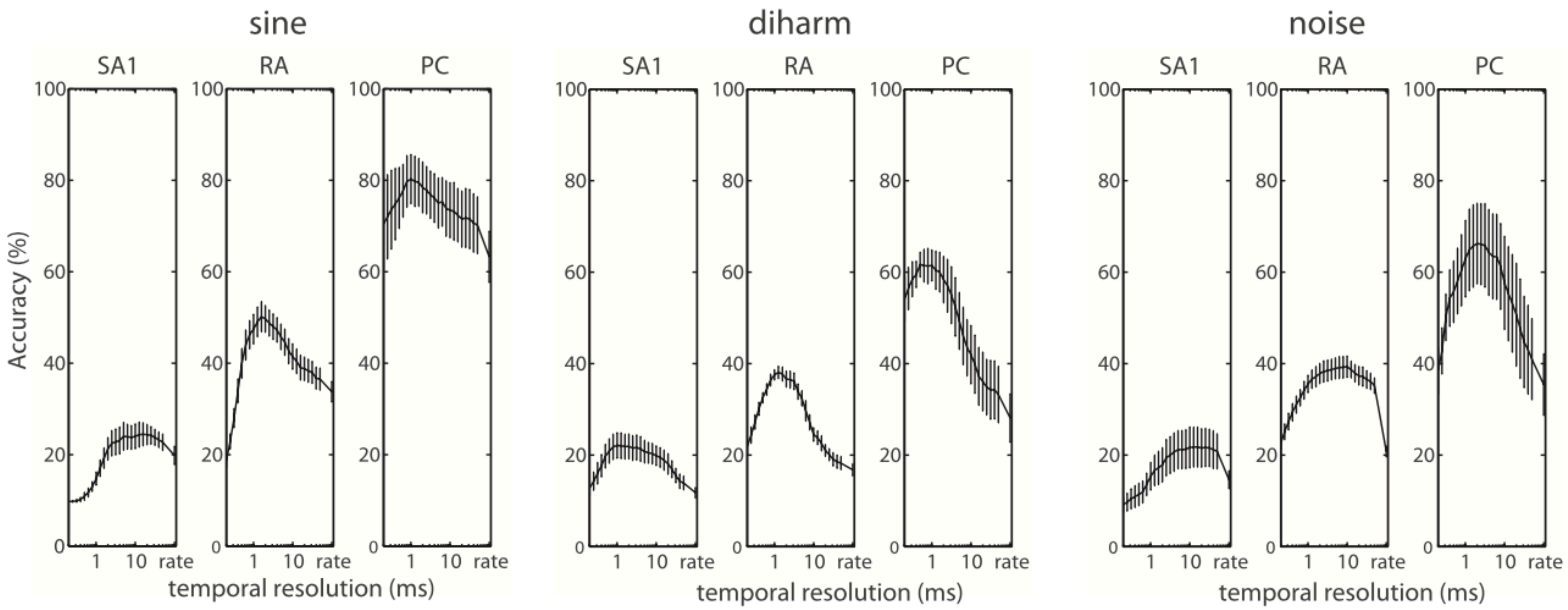
- While spike counts tend to change with stimulus amplitude, temporal patterning in the afferent response is more consistent across amplitudes

Mackevicius et al, 2012

Sensory Mechanisms of Tactile Perception

Spatial versus Temporal code

- **Temporal code (dynamic, vibrations):** the individual spike timing of the mechanoreceptors reflects the properties of the stimulus



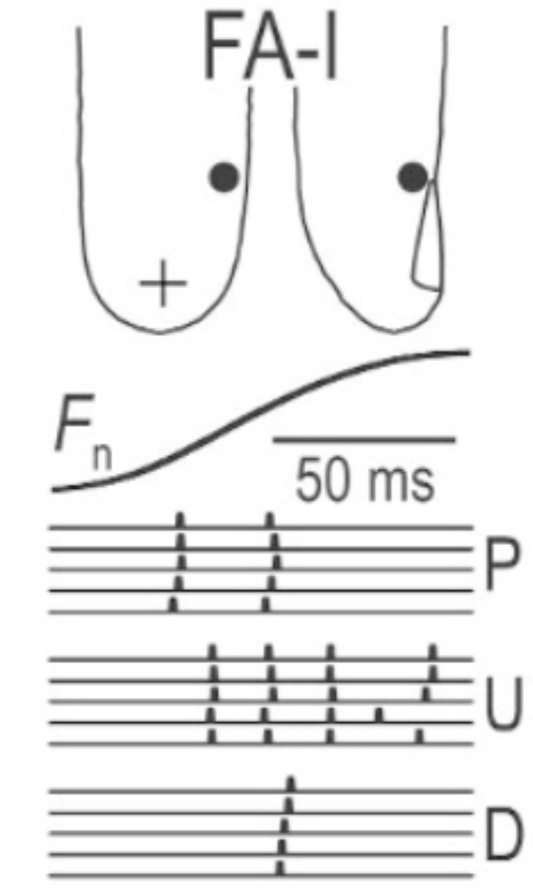
- Taking into account spike timing improves classification performance

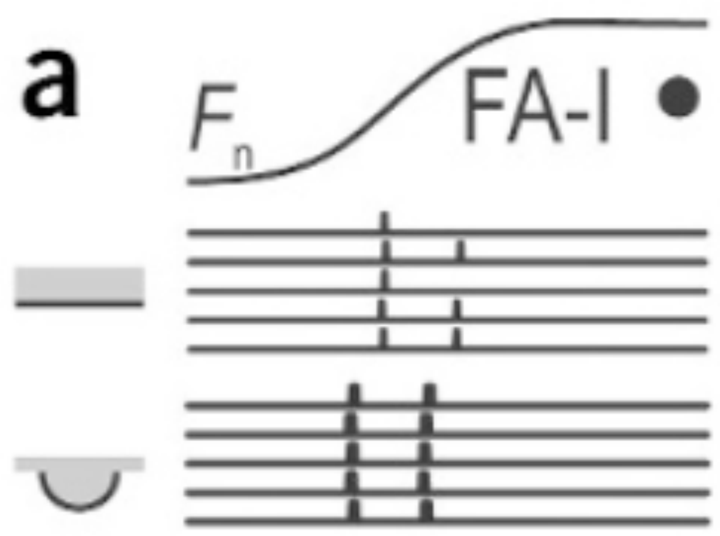
Mackevicius et al, 2012

Sensory Mechanisms of Tactile Perception

<u>Other mechanisms include:</u>

- **First spike latency:** time of first spike with respect to stimulus onset. Involved in detecting direction of fingertip force and the shape of the surface (Johansson and Birznieks, 2004)





- **Phase coding:** spike interval between different neurons

Challenges

- How skin properties affect the activation of afferents and so perception?
- How stimulus information is encoded at population level?
- What is the impact of peripheral changes on perception?
- How different receptor types contribute to the encoding of stimulus information?

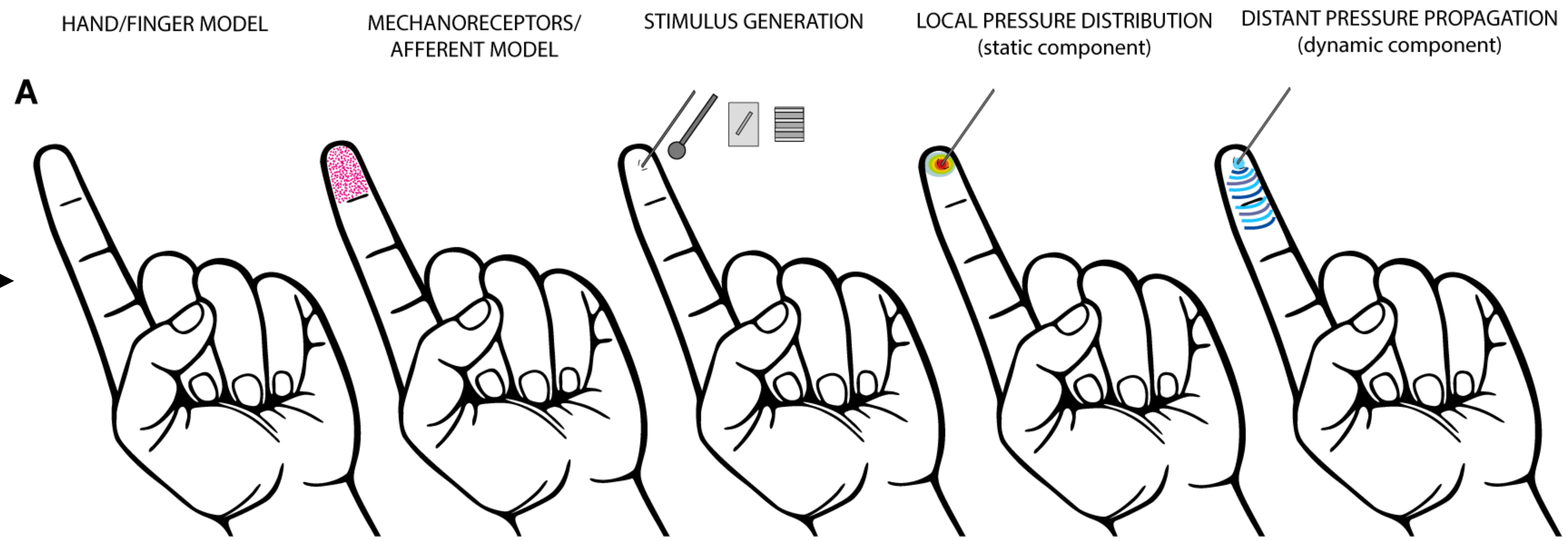
Modelling First-Order Tactile Neurons

Advantages:

- Entire population of afferents can be simulated at the same time
- No training in microneurography needed
- Relatively fast
- No need for long recording session and participants
- Testing new hypothesis / theory with ease

Modelling First-Order Tactile Neurons - Overview

HAND / SKIN MODEL



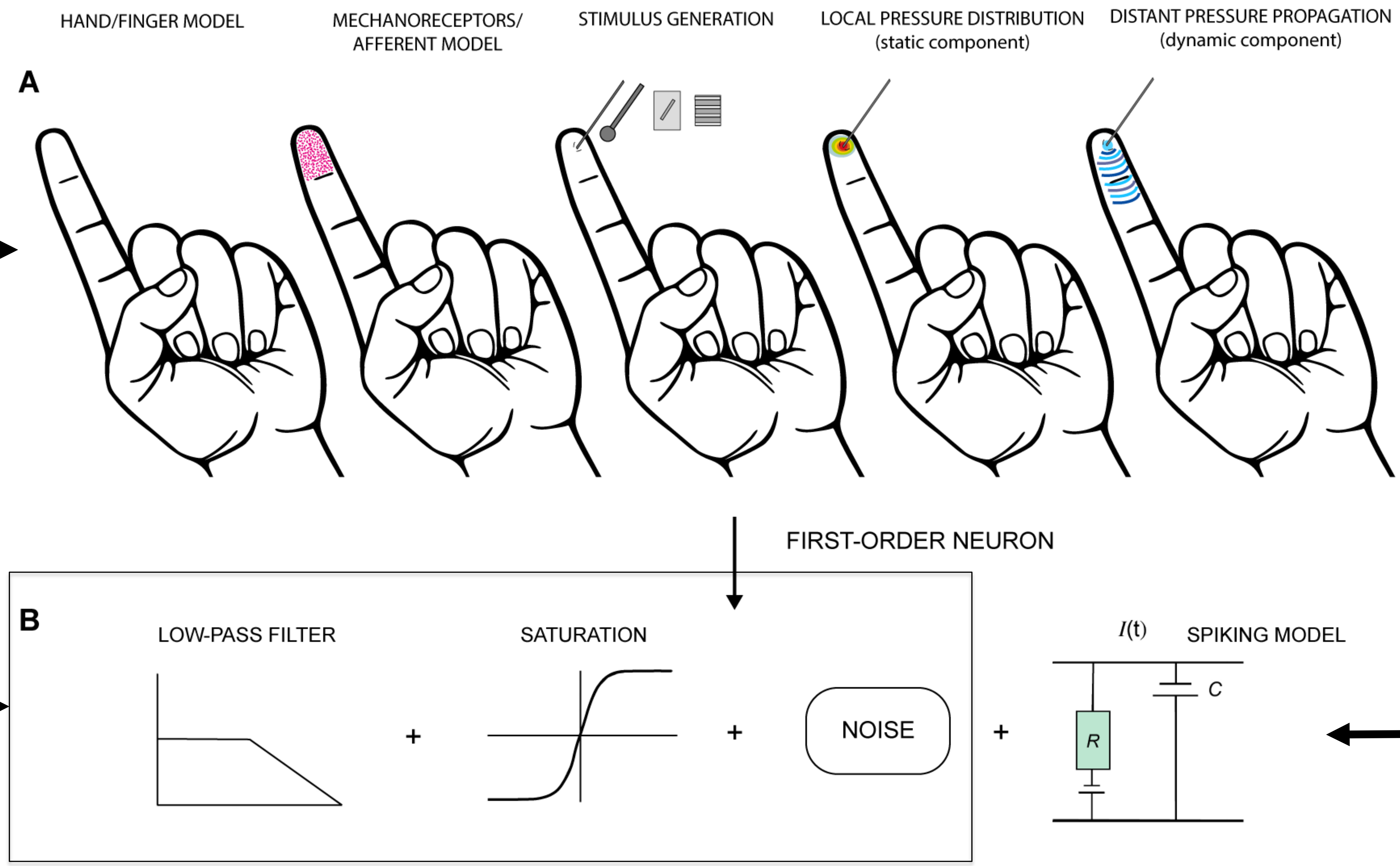
STIMULUS GENERATION
&
SKIN RESPONSE

Deflorio, Di Luca, Wing (2022, in press)

Modelling First-Order Tactile Neurons - Overview

HAND / SKIN MODEL

STIMULUS GENERATION & SKIN RESPONSE



SIGNAL PROCESSING

NEURAL MODEL

Deflorio, Di Luca, Wing (2022, in press)

Modelling First-Order Tactile Neurons - Overview

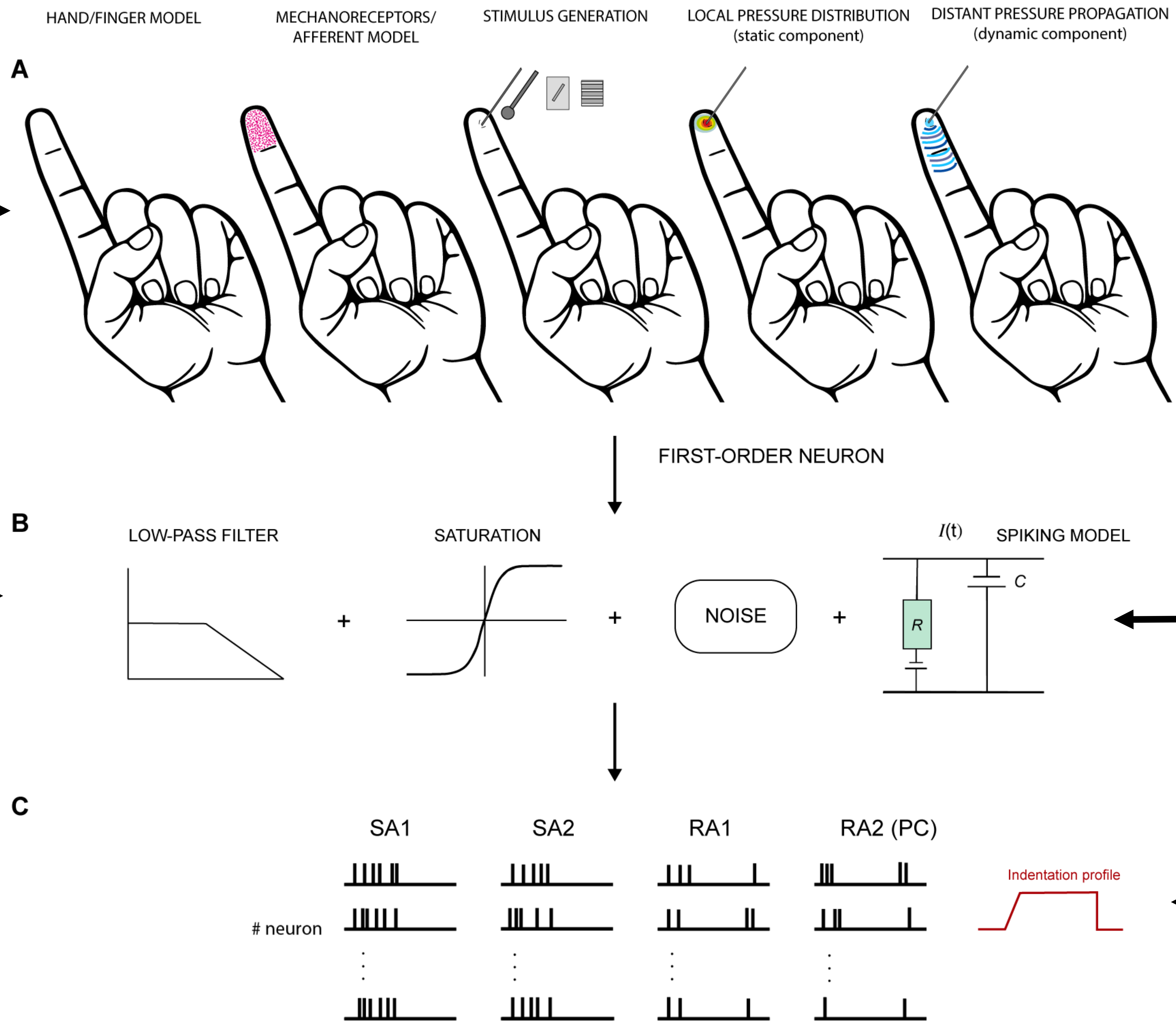
HAND / SKIN MODEL

STIMULUS GENERATION & SKIN RESPONSE

SIGNAL PROCESSING

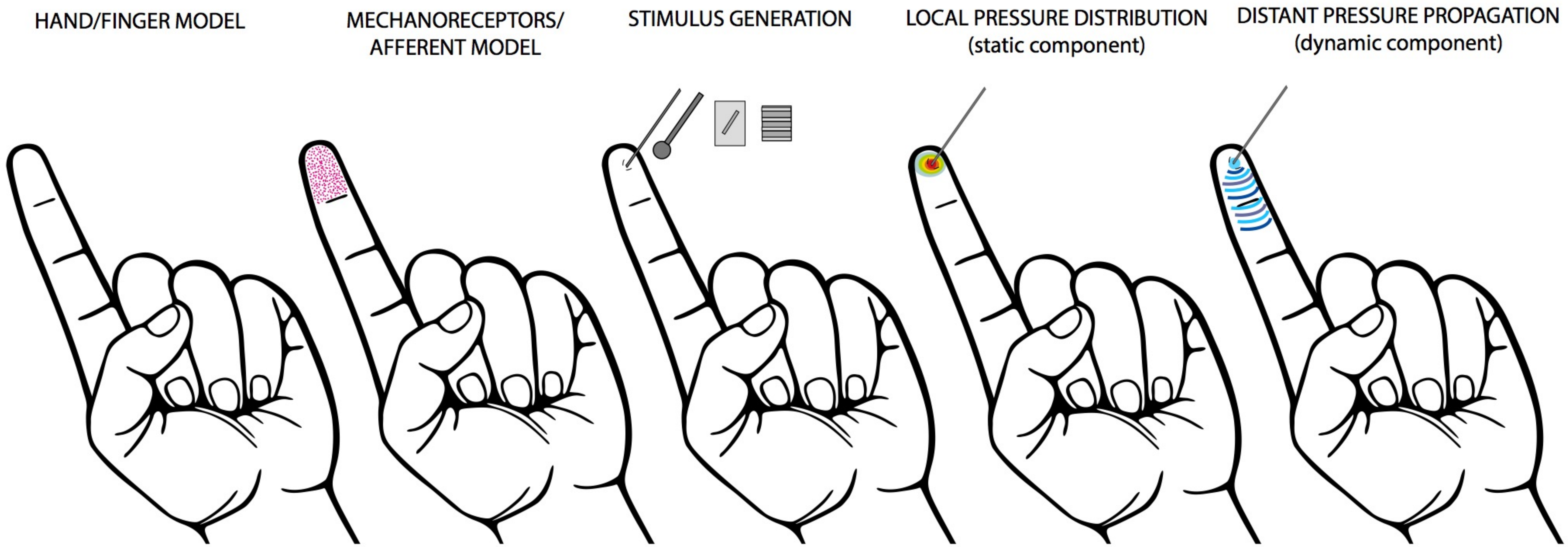
NEURAL MODEL

NEURAL RESPONSE



Deflorio, Di Luca, Wing (2022, in press)

Modelling – 1. Hand/Skin Model and Stimulus Generation



- How to represent skin mechanics?
- CM vs FEM

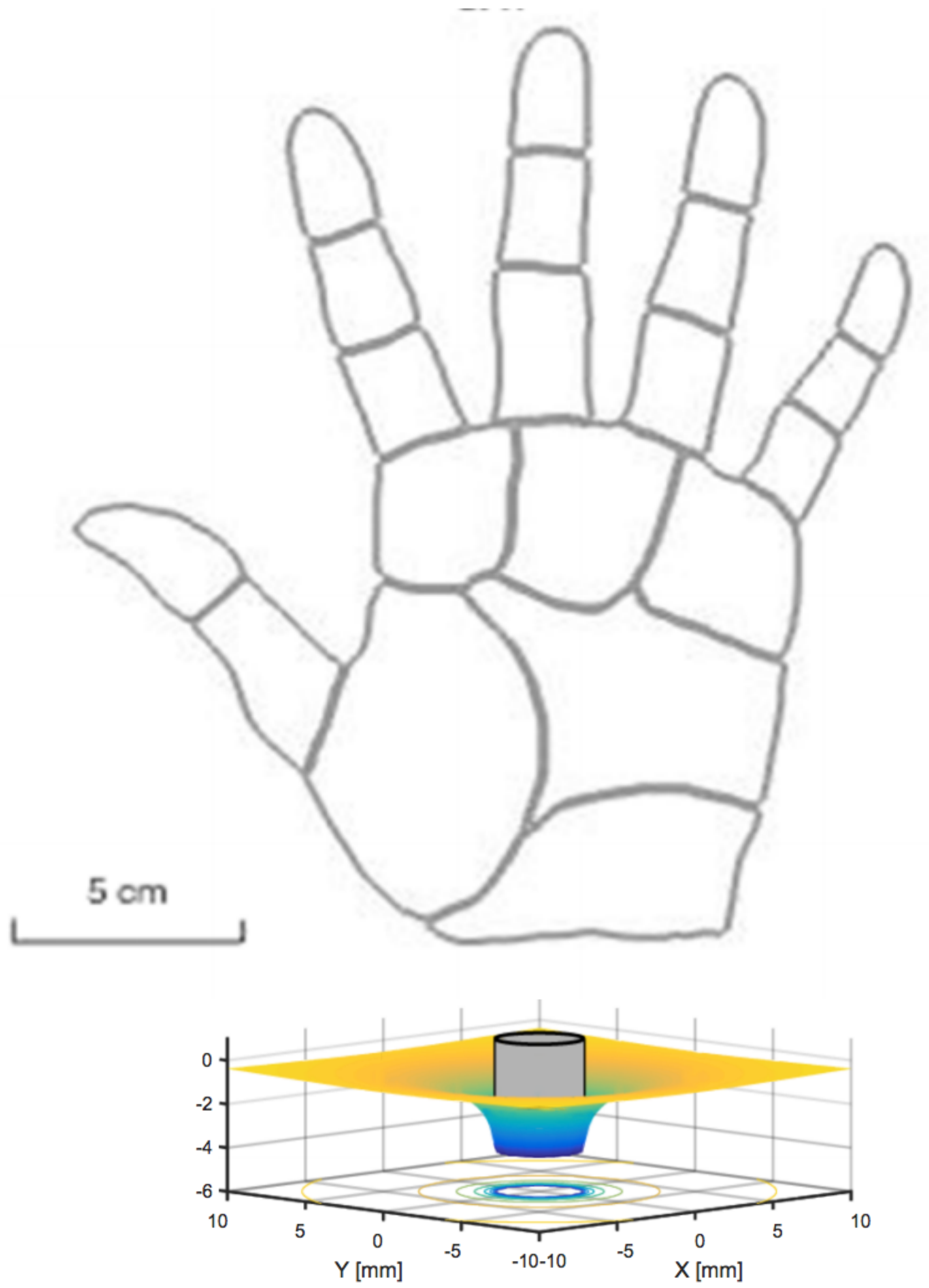
- Which fibers to include?
- Which properties?

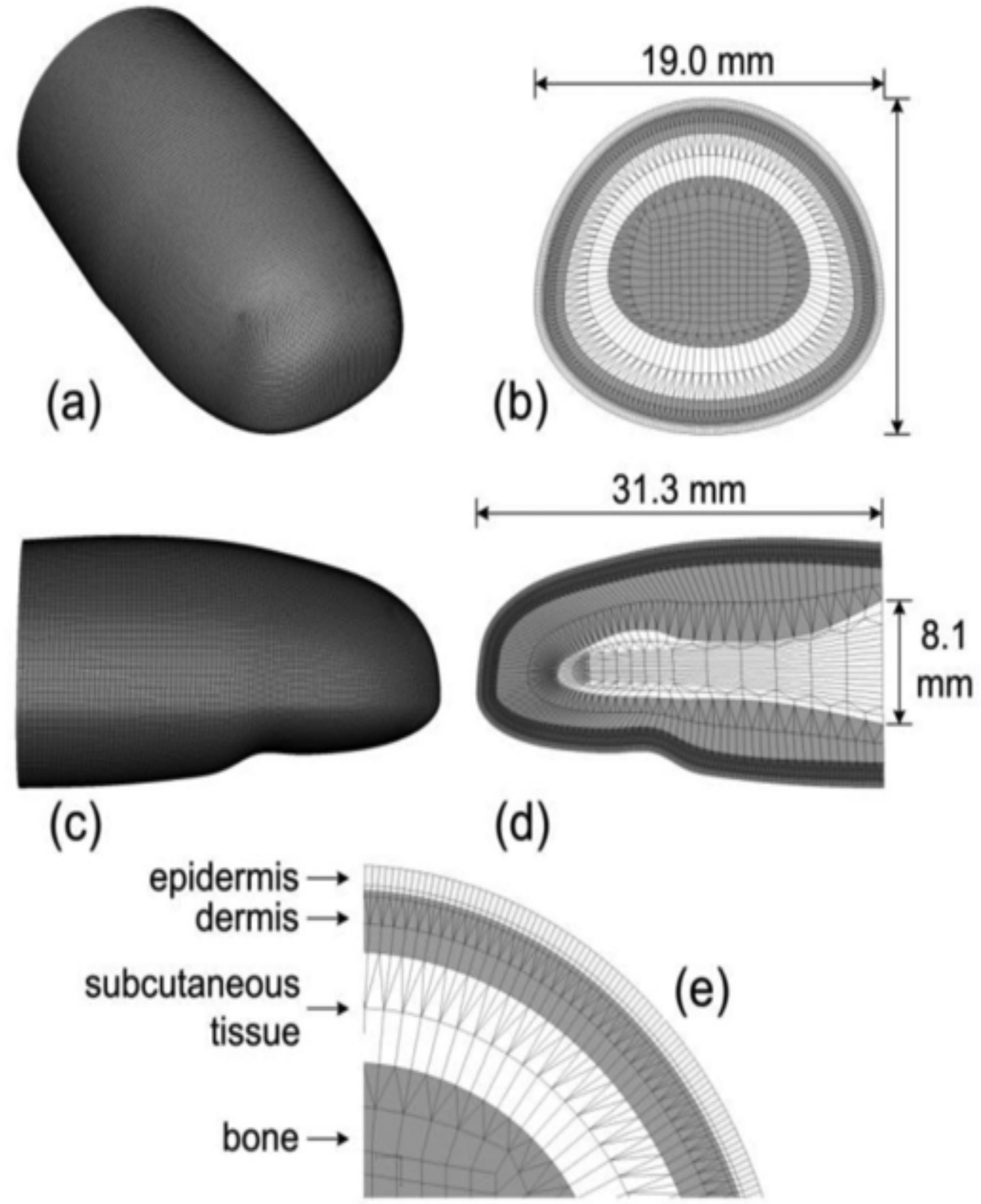
- How to create virtual stimuli?

- How to reproduce the skin response?

Continuum Mechanics and Finite Element Modelling

- To calculate the stresses acting on each receptor which will represent the input to the neural model





CM

- Continuous Mass
- Assume all the elements have same properties
- **Skin treated as homogeneous, elastic body**
- **Analytical solution**

Saal et al., 2017

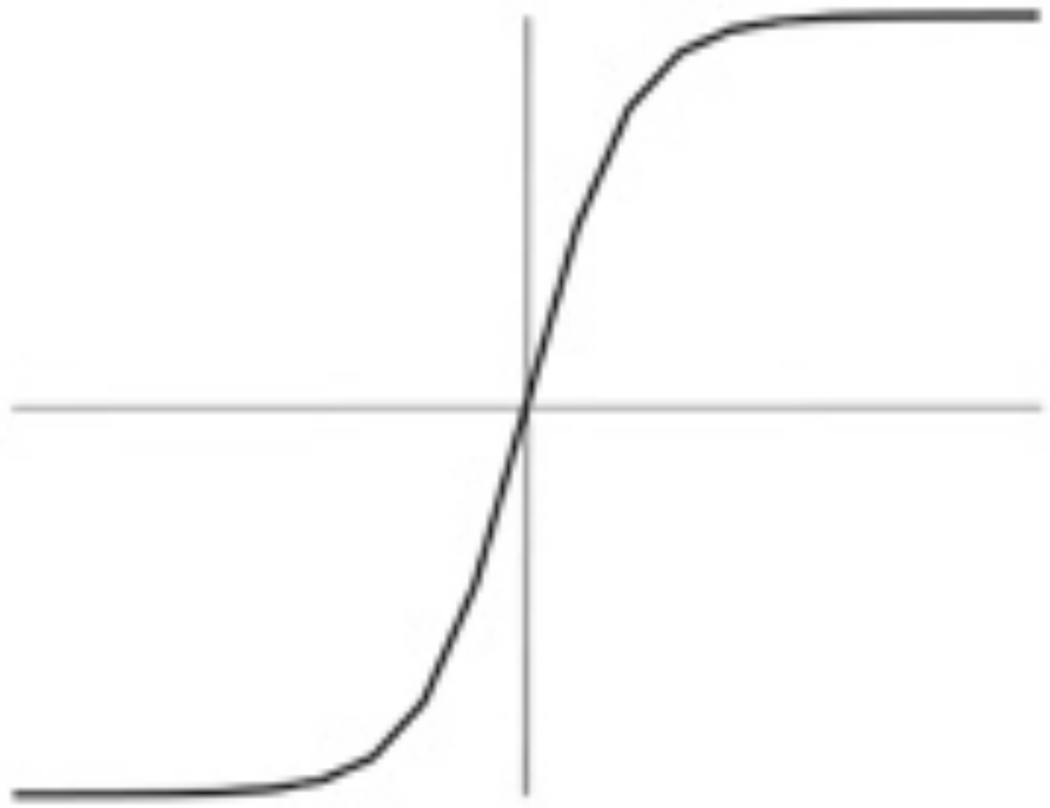
FEM

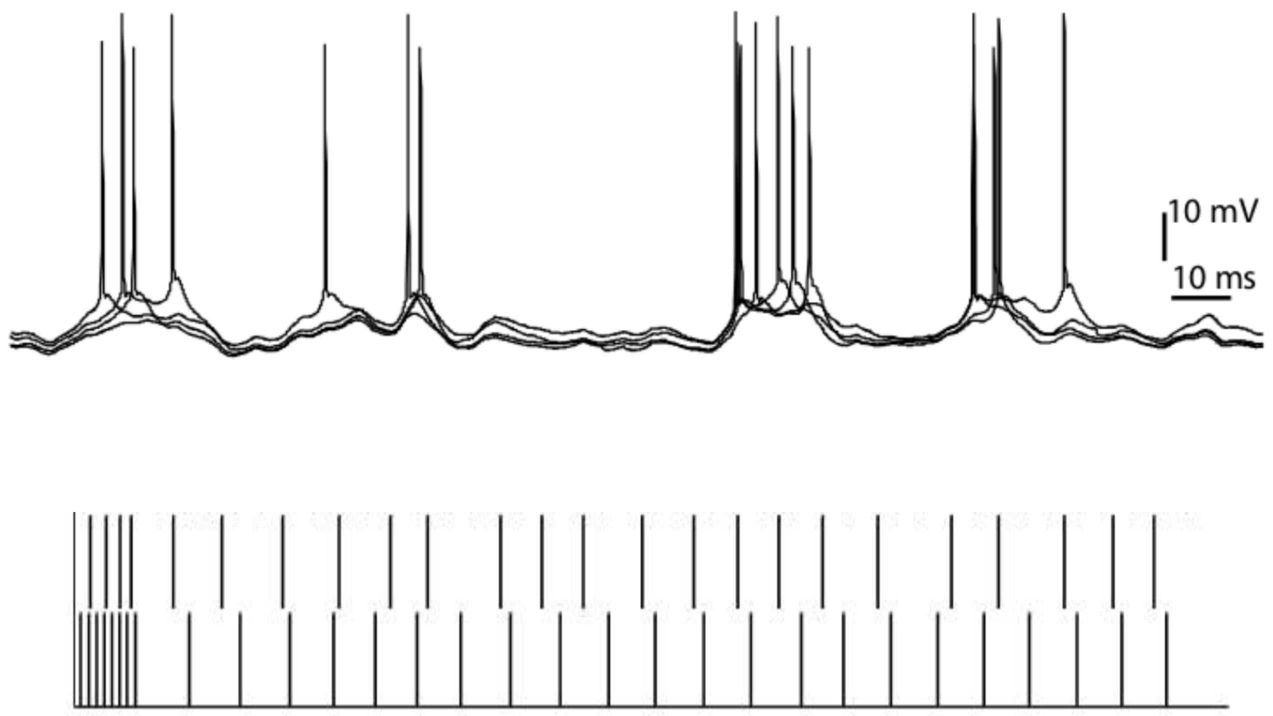
- Discrete partitioning
- Takes into account the properties of the different elements
- **Skin treated as non-homogeneous, viscoelastic body**
- **Non-analytical solution**

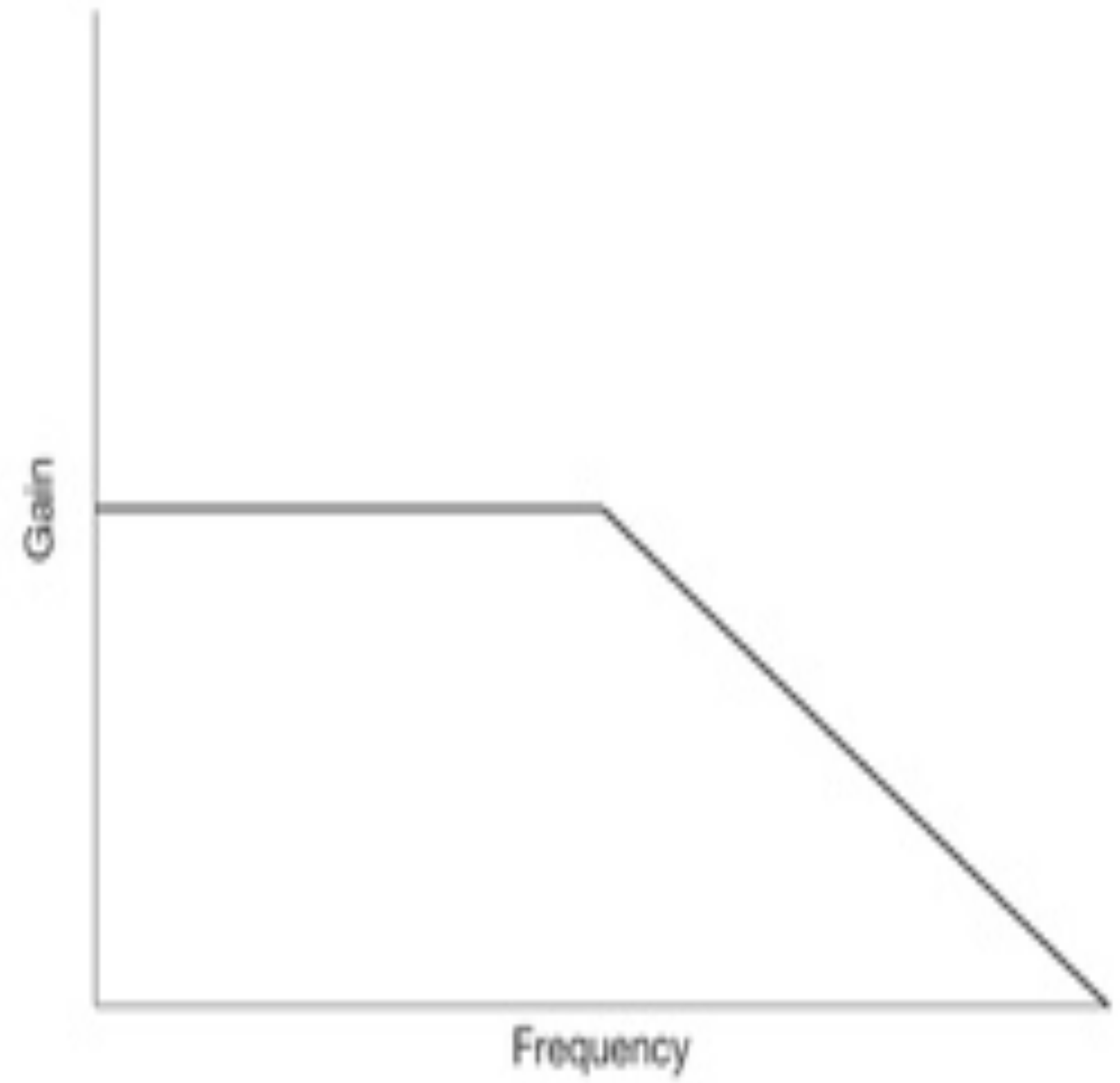
Gerling et al., 2014

Modelling – 2. Signal Processing

- The main goal of signal processing is to reproduce the known response properties of tactile neurons







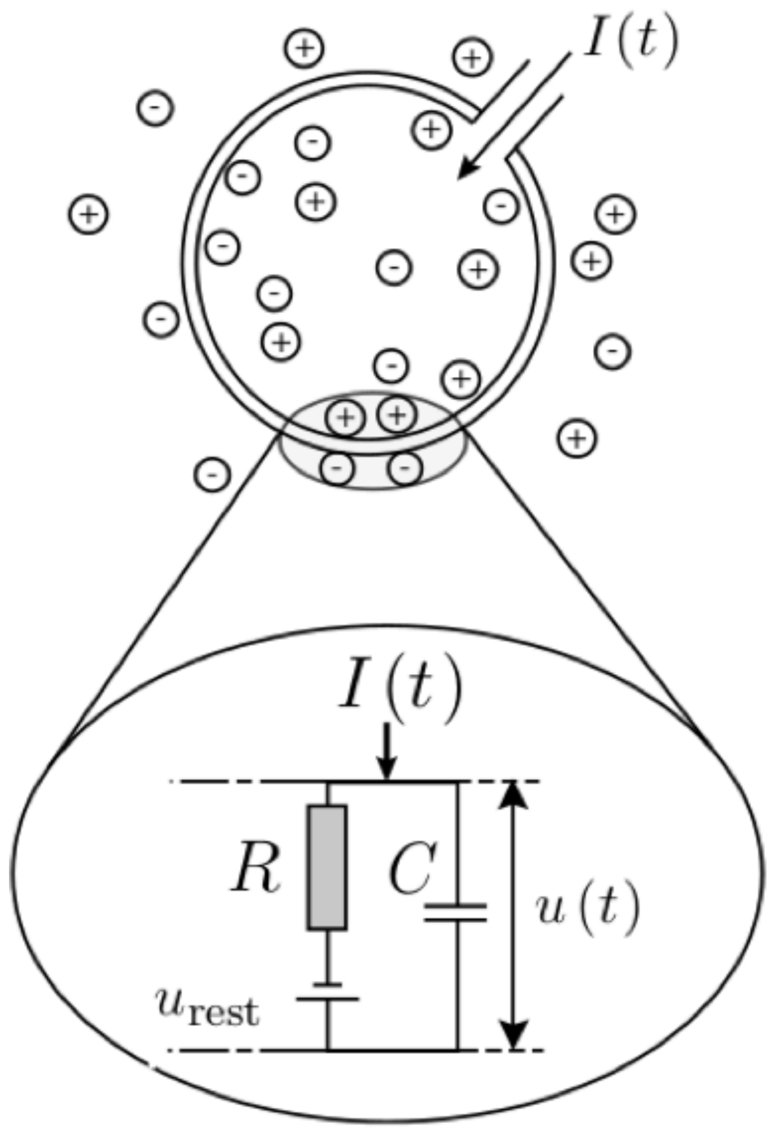
Saturation function: to reproduce the saturation at high intensities

Temporal Noise: to reproduce the stochastic behaviour of neurons

Low-pass filter: to account for the non-responsiveness of neurons above certain frequencies

Modelling – 3. Neural Models

- The goal of a neural model is to generate spike trains in a realistic and efficient way.



Models	biophysically meaningful	tonic spiking	phasic spiking	tonic bursting	phasic bursting	mixed mode	spike frequency adaptation	class 1 excitable	class 2 excitable	spike latency	subthreshold oscillations	resonator	integrator	rebound spike	rebound burst	threshold variability	bistability	DAP	accommodation	inhibition-induced spiking	inhibition-induced bursting	chaos	# of FLOPS
integrate-and-fire	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-	-	5
integrate-and-fire with adapt.	-	+	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	+	-	-	-	-	10
integrate-and-fire-or-burst	-	+	+		+	-	+	+	-	-	-	-	+	+	+	-	+	+	-	-	-		13
resonate-and-fire	-	+	+	-	-	-	-	+	+	-	+	+	+	+	-	-	+	+	+	-	-	+	10
quadratic integrate-and-fire	-	+	-	-	-	-	-	+	-	+	-	-	+	-	-	+	+	-	-	-	-	-	7
Izhikevich (2003)	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	13
FitzHugh-Nagumo	-	+	+	-		-	-	+	-	+	+	+	-	+	-	+	+	-	+	+	-	-	72
Hindmarsh-Rose	-	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	120
Morris-Lecar	+	+	+	-		-	-	+	+	+	+	+	+	+		+	+	-	+	+	-	-	600
Wilson	-	+	+	+			+	+	+	+	+	+	+	+	+	+		+	+				180
Hodgkin-Huxley	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	1200

Izhikevich, 2004

Modelling – 3. Neural Models

- Often neural models use differential equations to describe how variables change over time.
- In particular, if v(t) > thresh → fire

Izhikevich model (2003)

$$v' = 0.04v^2 + 5v + 140 - u + I \quad (1)$$
$$u' = a(bv - u) \quad (2)$$

with the auxiliary after-spike resetting

$$\text{if } v \geq 30 \text{ mV}, \text{ then } \begin{cases} v \leftarrow c \\ u \leftarrow u + d. \end{cases} \quad (3)$$

- I = input (current)
- v = membrane potential
- u = membrane recovery for inactivation of Na+ and activation of K+)
- a = timescale of u
- b = sensitivity of u to subthreshold fluctuation of v
- c = after-spike reset value of v
- d = after-spike reset value of u

Leaky Integrate-and-fire model (Lapicque, 1907)

$$v' = I + a - bv, \text{ if } v \geq v_{\text{thresh}}, \text{ then } v \leftarrow c$$

- I = input (current)
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https://neuronaldynamics.epfl.ch/online.html
Izhikevic (2003, 2004)

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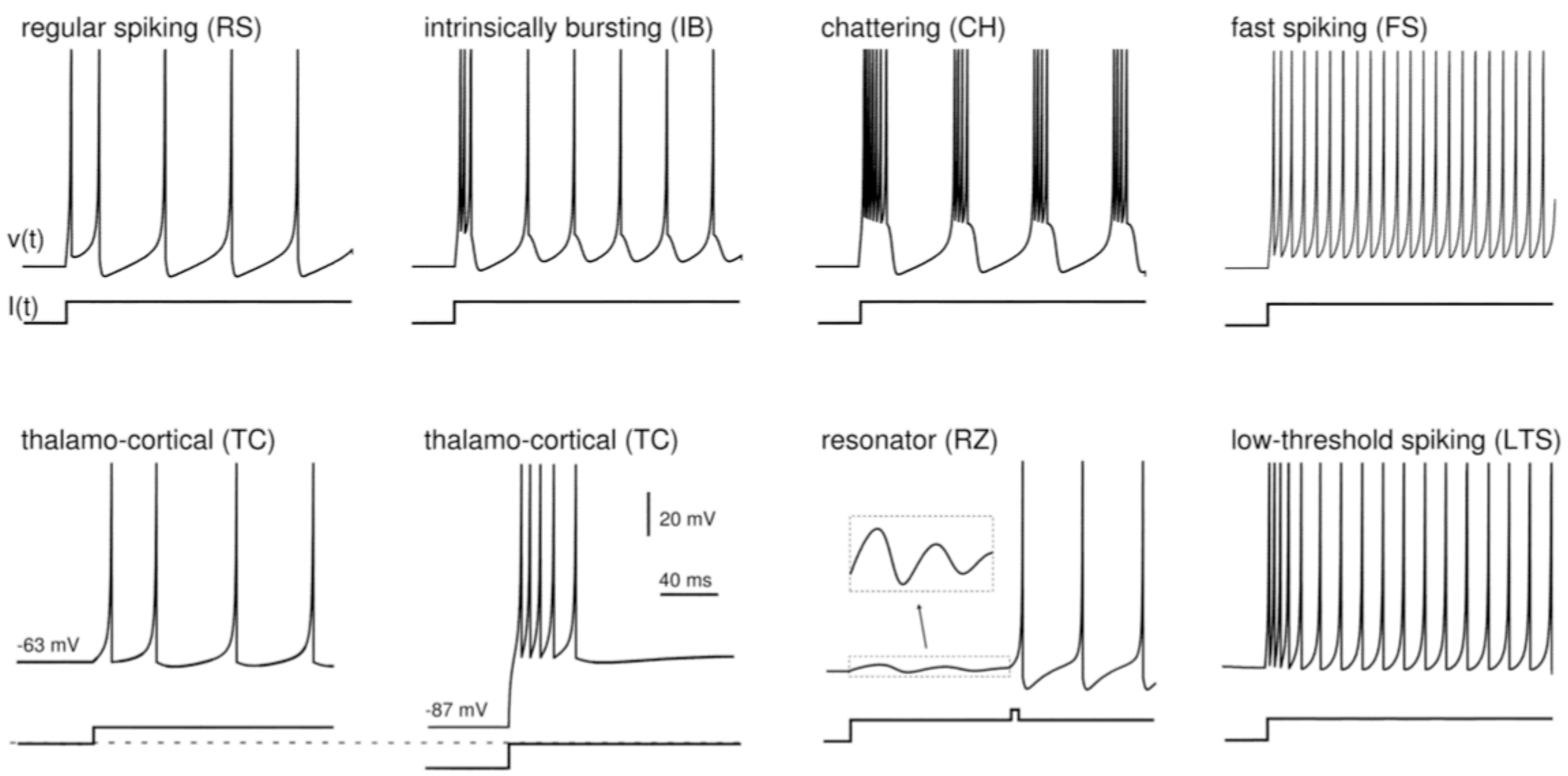

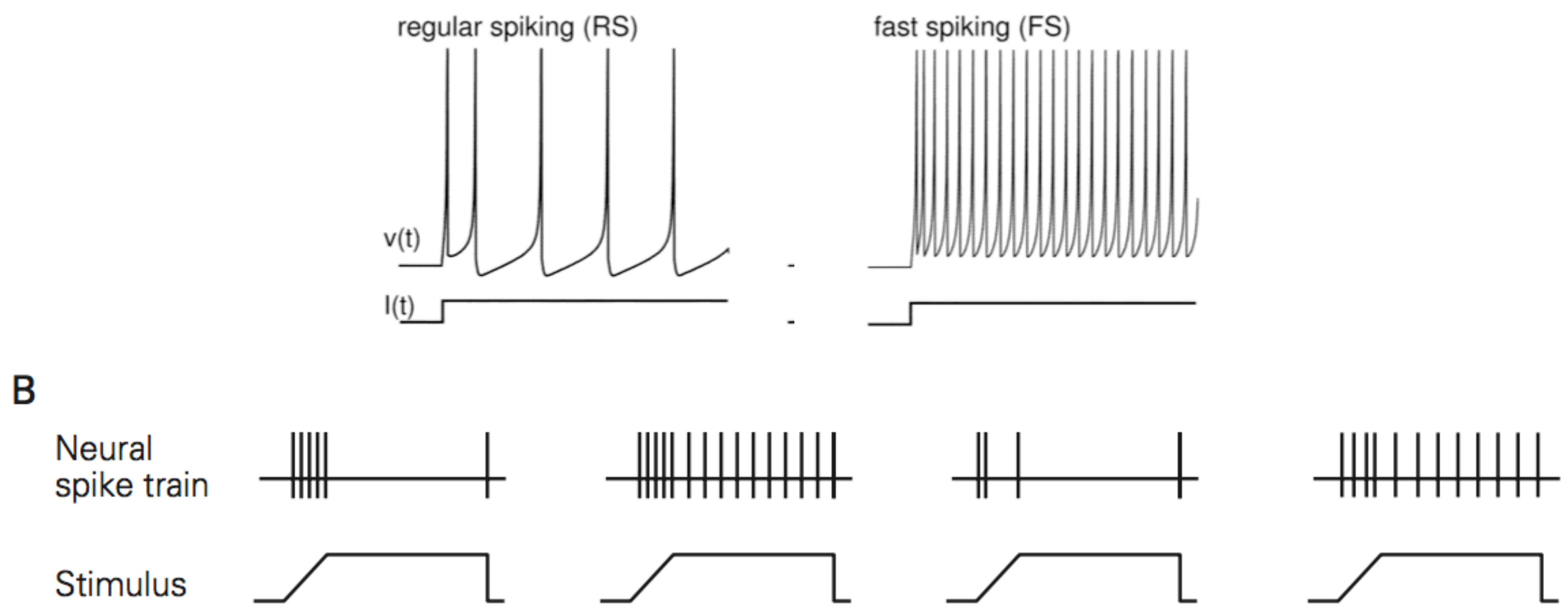

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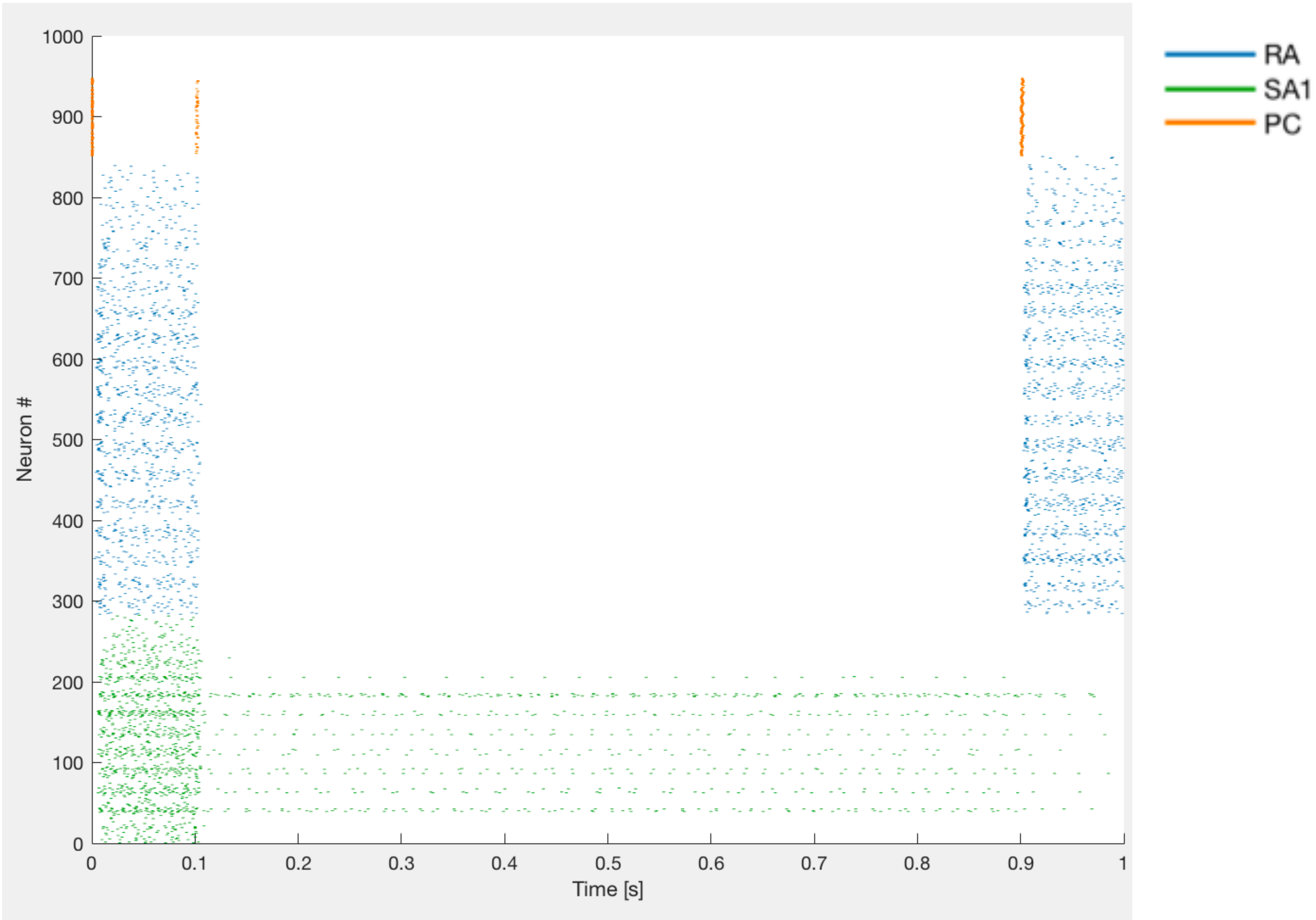
Izhikevic (2003, 2004)

Modelling – 4. Output



Saal et al. (2017)

Modelling – Applications (1)

How is the information about edge orientation extracted so efficiently as to enable rapid object manipulation?

- **Previous studies show that shape information can be extracted from the spatial variation of the response of the tactile fibers** (e.g. Phillips and Johnson, 1981)

However..

- mean firing rates over long time intervals and only for a few recorded afferents.

- not clear whether such a spatial code can be accurate and fast enough.

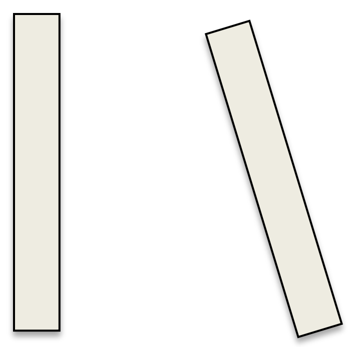
Modelling – Applications (1)

How is the information about edge orientation extracted so efficiently as to enable rapid object manipulation?

Delhaye and colleagues (2019):

- Simulation of the entire population of SA1 and RA1 fibers (with Saal et al. model, 2017)
- Classification approach to test how and when the information about edge orientation arises

VIRTUAL TASK



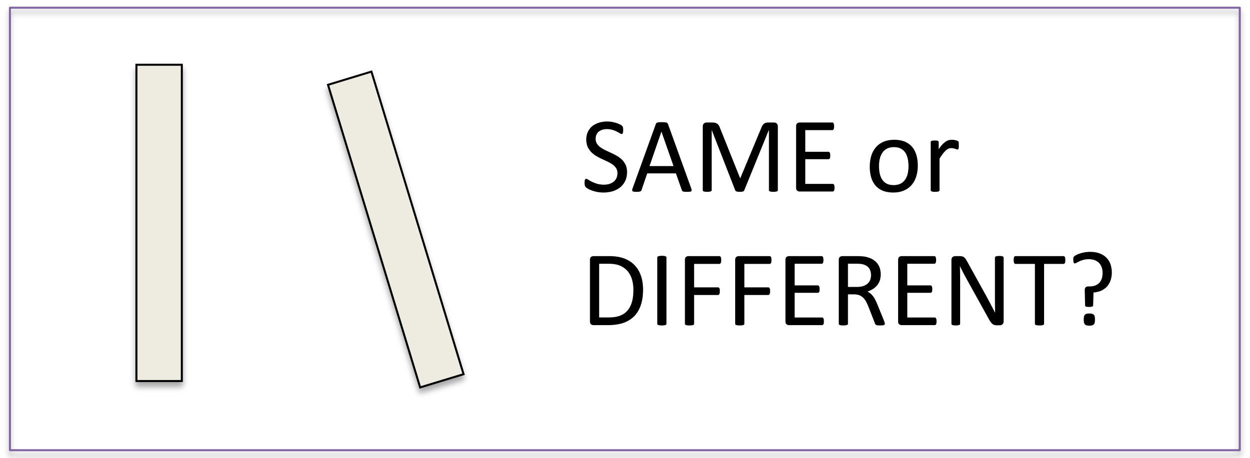
SAME or DIFFERENT?

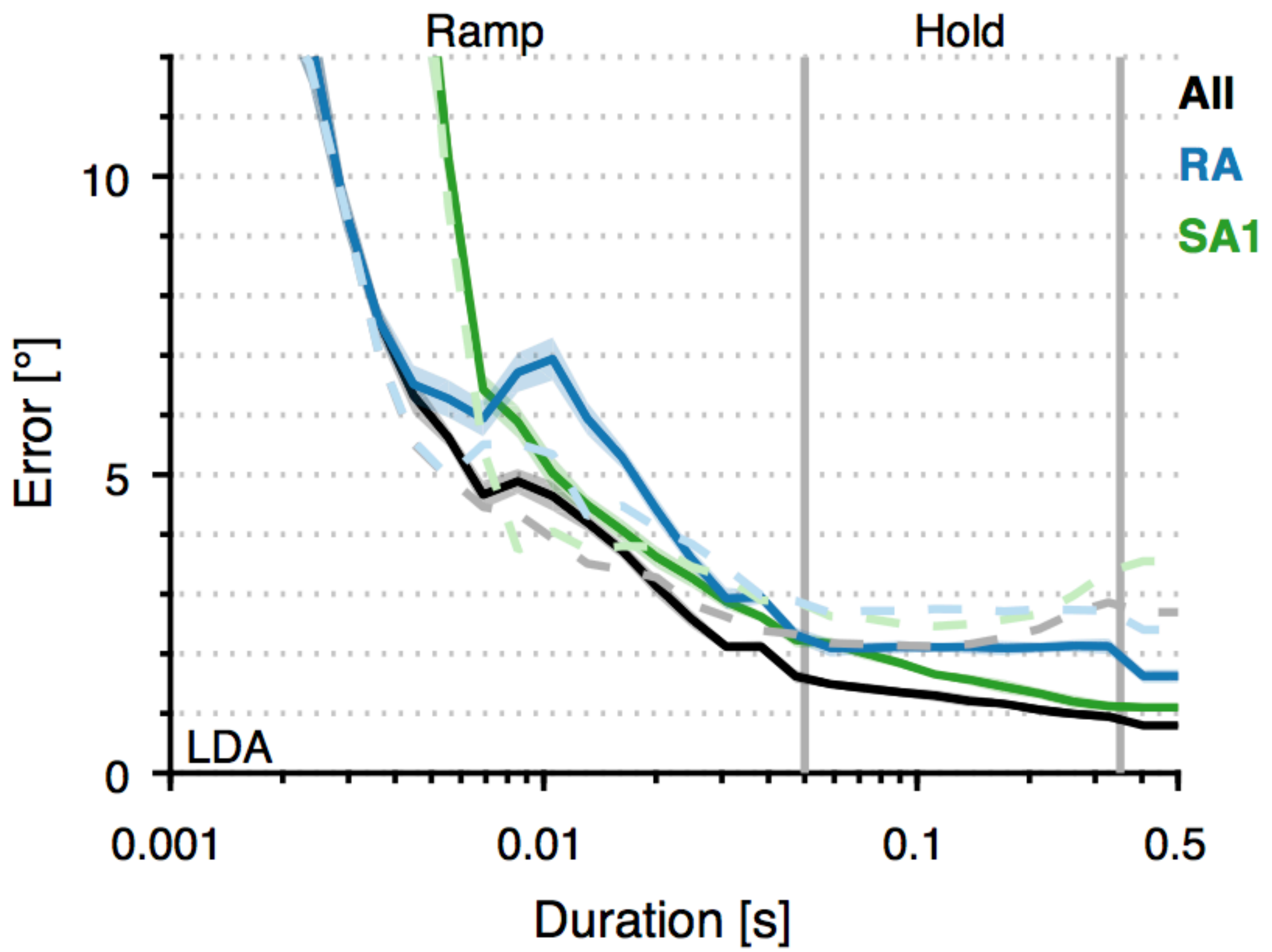
SIMULATION

- Rectangular edges 1.6 mm wide and 6 length (3.2, 4.8, 6.4, 8, or 9.6 mm)
- 30 equally spaced orientations from 0° to 45°
- 5 indentation depths (0.8, 1.2, 1.6, 2, 2.4 mm)
- 5 times each

Modelling – Applications (1)

How is the information about edge orientation extracted so efficiently as to enable rapid object manipulation?





- Edge orientation can be accurately decoded within 10 milliseconds from the firing rate variations between afferent
- A spatial code can be fast enough to support shape detection and fast object manipulation

Modelling – Applications (2)

Is tactile sensitivity affected by neurobiological factors that change with aging?

- **Tactile perception is impaired with aging. At the same time, aging is associated with a reduced skin elasticity and lower tactile neuron density.**

But…

Are those factors linked to the deterioration of tactile sensitivity observed in the elderly?

1. Computational modeling to simulate the response of tactile neurons and predict performance of the two groups.
2. Psychophysical experiment to test model predictions.

Modelling – Applications (1)

Is tactile sensitivity affected by neurobiological factors that change with aging?

Deflorio, Di Luca, Wing (2022, in review):

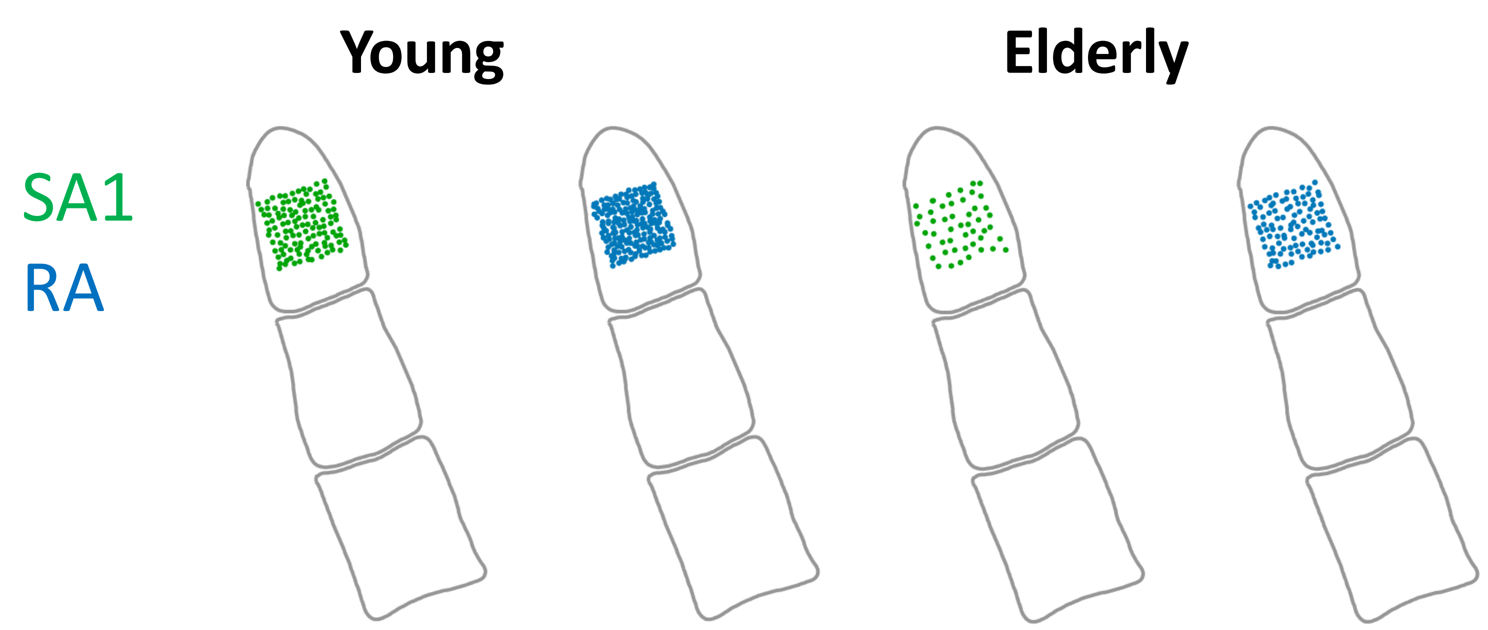
- Simulation of the entire population of SA1 and RA1 fibers (with Saal et al. model, 2017) in response to a single pin or two pins.
- Classification approach to predict the performance of young and elderly group
- Psychophysical experiment to test model predictions

VIRTUAL TASK

2-pins is FIRST or SECOND?

SIMULATION

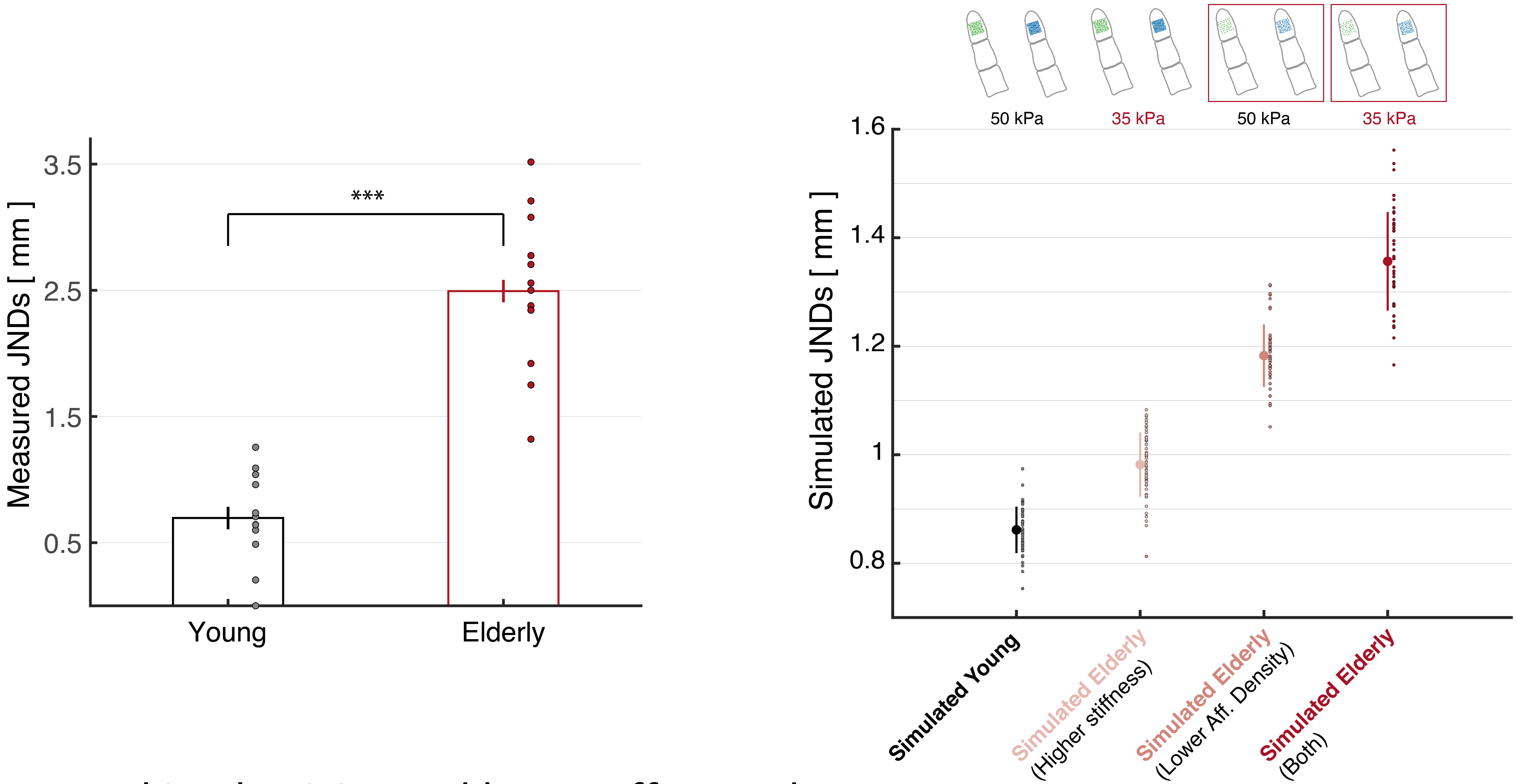
- Single pin and two-pins at 7 different separation levels (from 0.1 to 2 mm)



Skin Elasticity: Young 50 kPa; Elderly 35kPa

Modelling – Applications (2)

Is tactile sensitivity affected by neurobiological factors that change with aging?



- Lower skin elasticity and lower afferent density predict a decrease in discrimination performance.
- Performance decreases even more if the two modifications happen together.
- **The model suggests how elderly touch impairment (and their sensory experience) could be explained (in part) by skin and neuronal changes.**

Modelling – Limitations

- Based on a limited number of fibres from microneurography recordings, often monkeys

- Generally, models are a simplification of real-world objects to meet computational demands and/or lack of knowledge:
  - not all the types of fibres are included
  - not all the neurons' properties are included
  - skin is simplified
  - validated on a single task and may lack generalizability to different ones

- Models data need to be assessed with real data

Reading List

- Izhikevich, E. M. (2003). Simple model of spiking neurons. *IEEE Transactions on neural networks*, *14*(6), 1569-1572.

- Izhikevich, E. M. (2004). Which model to use for cortical spiking neurons?. *IEEE transactions on neural networks*, *15*(5), 1063-1070.

- Brunel, N., & Van Rossum, M. C. (2007). Lapicque's 1907 paper: from frogs to integrate-and-fire. *Biological cybernetics*, *97*(5), 337-339.

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