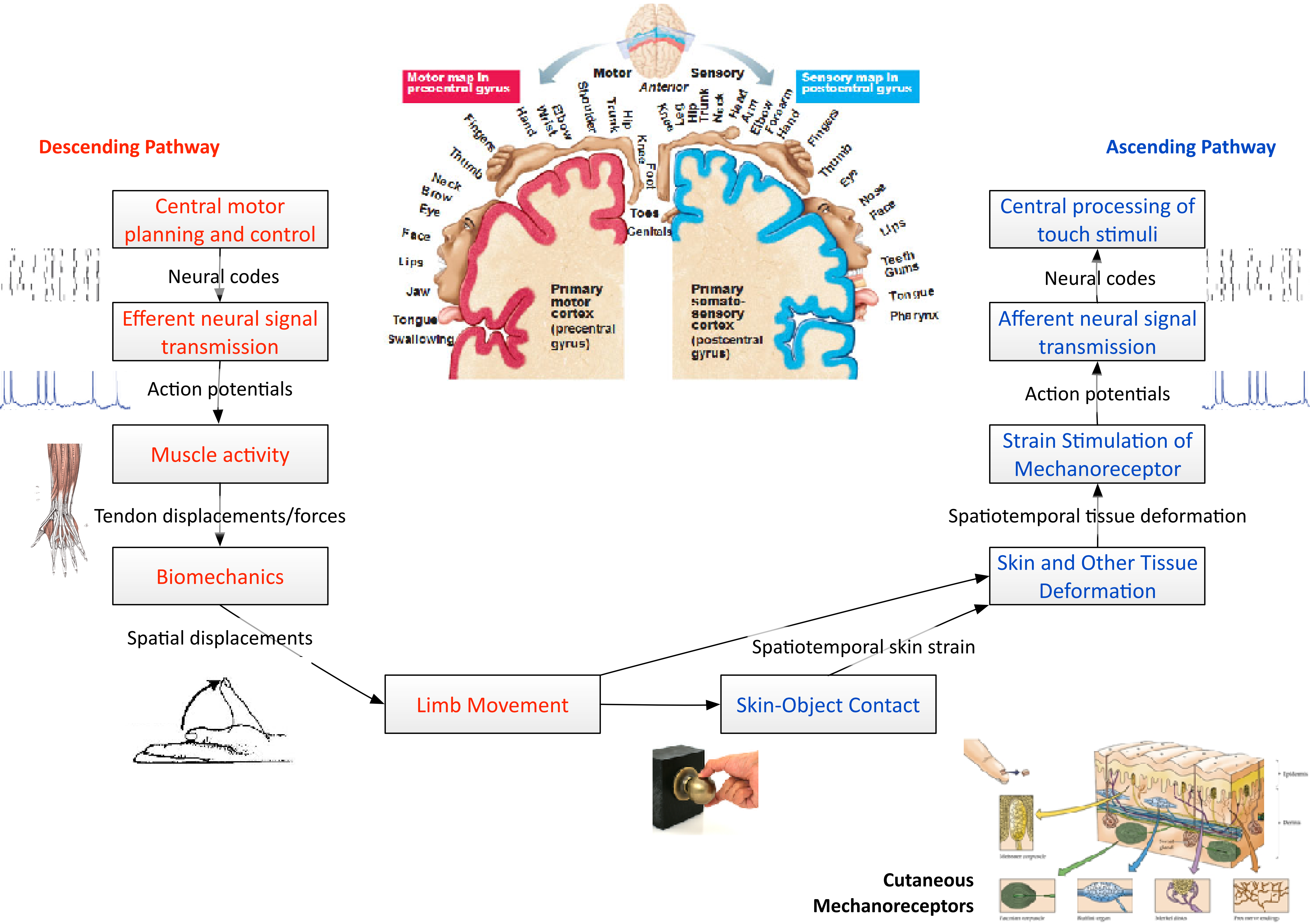
Psychosensory analysis of touch

David Gueorguiev

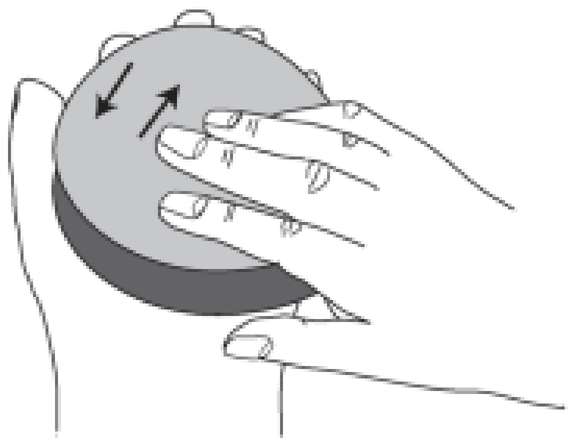
GDR TACT Marseille Juin 2024



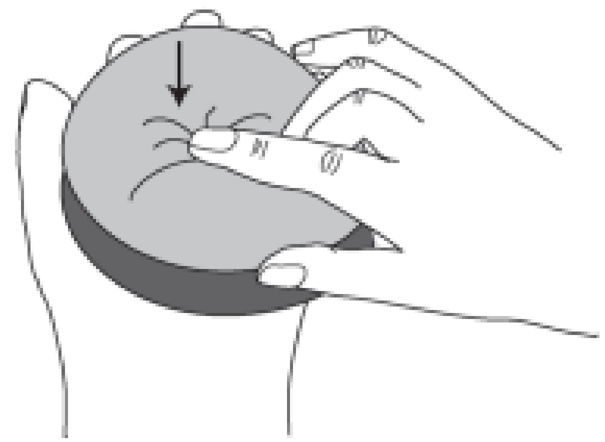
Descending Pathway
Central motor planning and control
Neural codes
Efferent neural signal transmission
Action potentials
Muscle activity
Tendon displacements/forces
Biomechanics
Spatial displacements
Limb Movement
Skin-Object Contact
Spatiotemporal skin strain
Ascending Pathway
Central processing of touch stimuli
Neural codes
Afferent neural signal transmission
Action potentials
Strain Stimulation of Mechanoreceptor
Spatiotemporal tissue deformation
Skin and Other Tissue Deformation
Motor map in precentral gyrus
Sensory map in postcentral gyrus
Motor
Sensory
Anterior
Primary motor cortex (precentral gyrus)
Primary somato-sensory cortex (postcentral gyrus)
Cutaneous Mechanoreceptors

Motions for haptic exploration

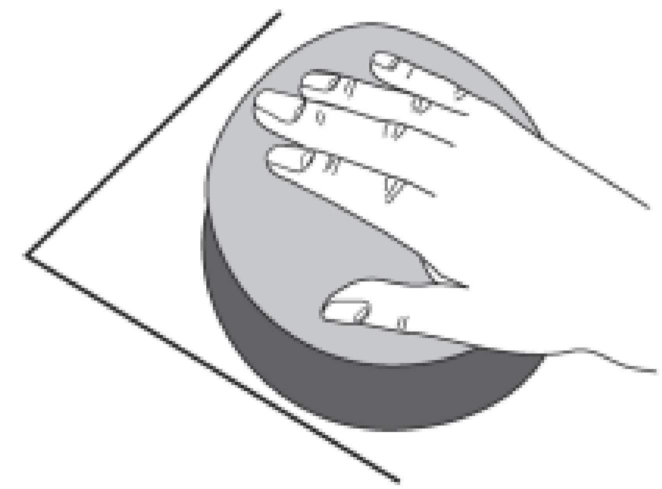
Lateral Motion:
Texture



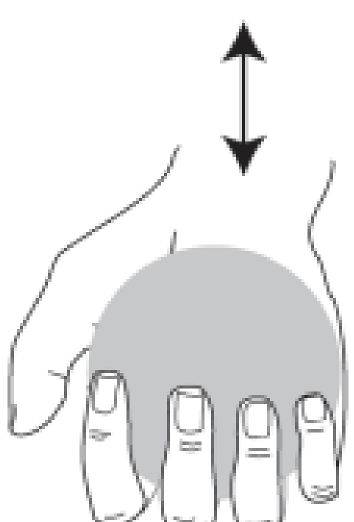
Pressure:
Hardness



Static Contact:
Temperature

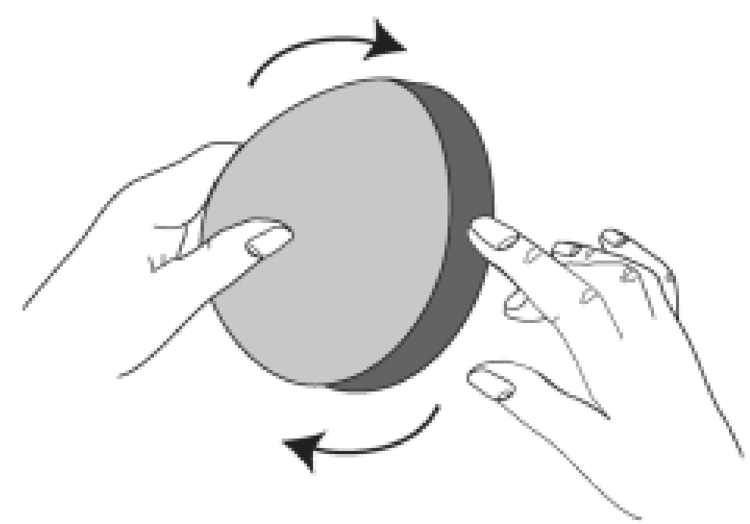


Unsupported Holding:
Weight

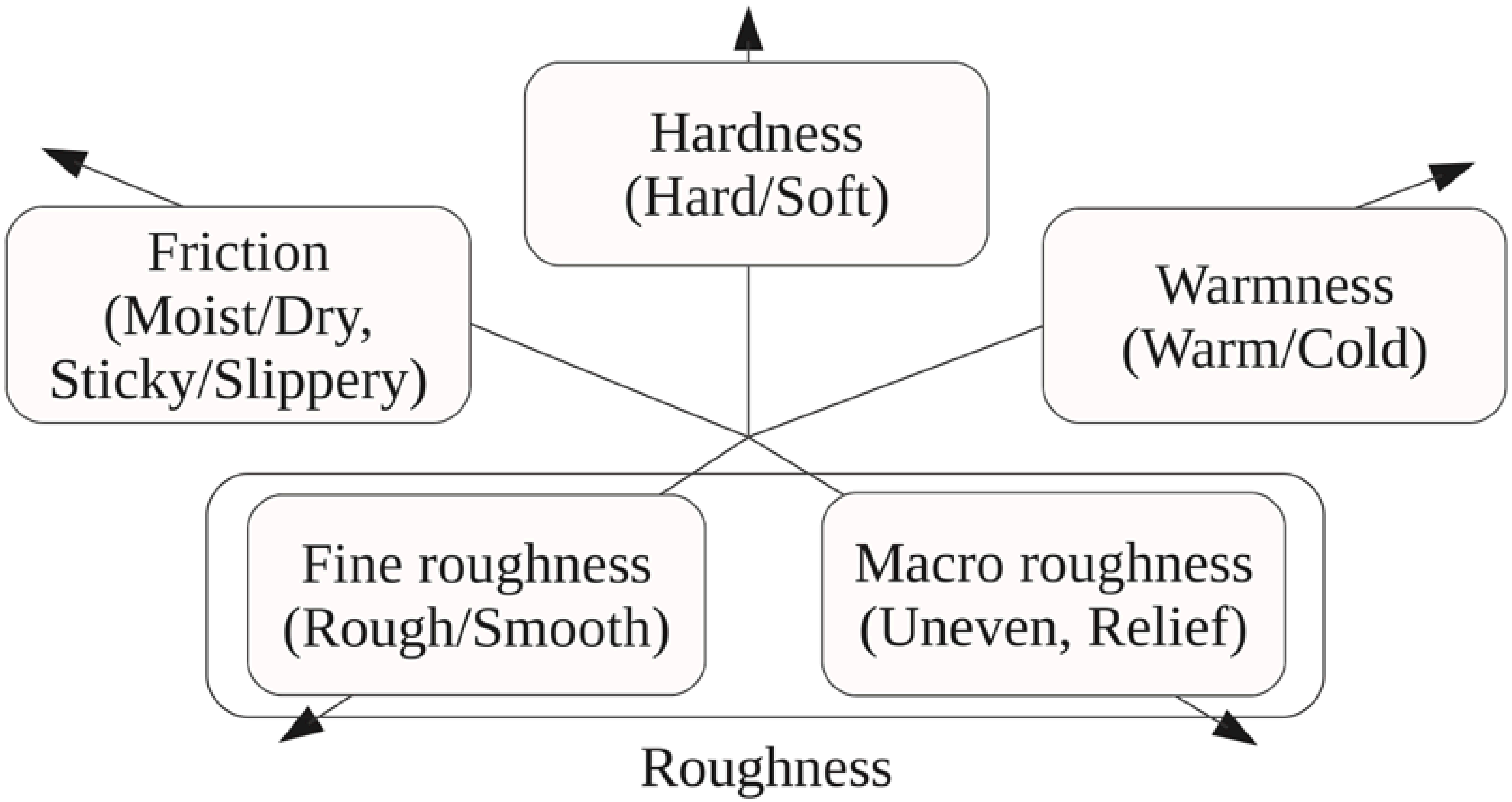


Enclosure:
Global Shape, Volume

Contour Following:
Global Shape, Exact Shape



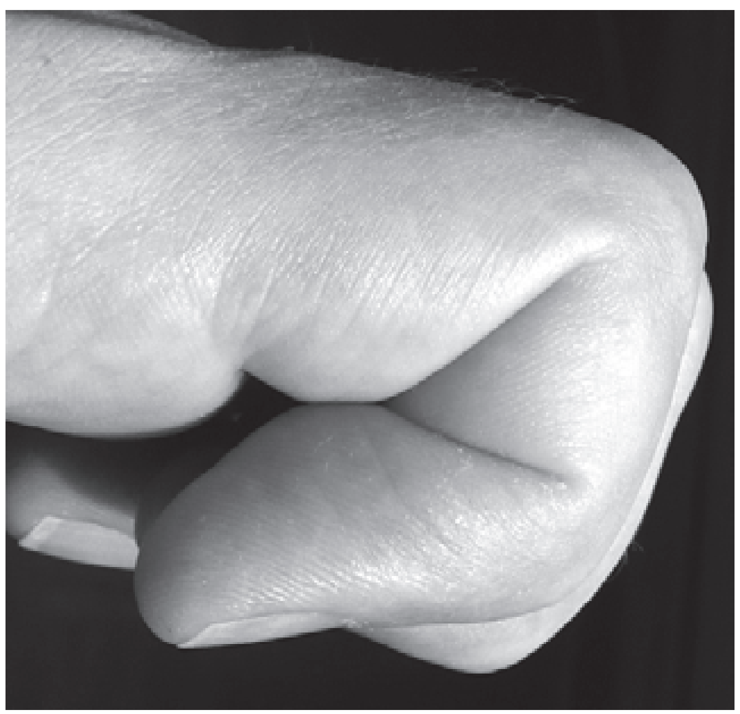
Psychophysical tactile dimensions

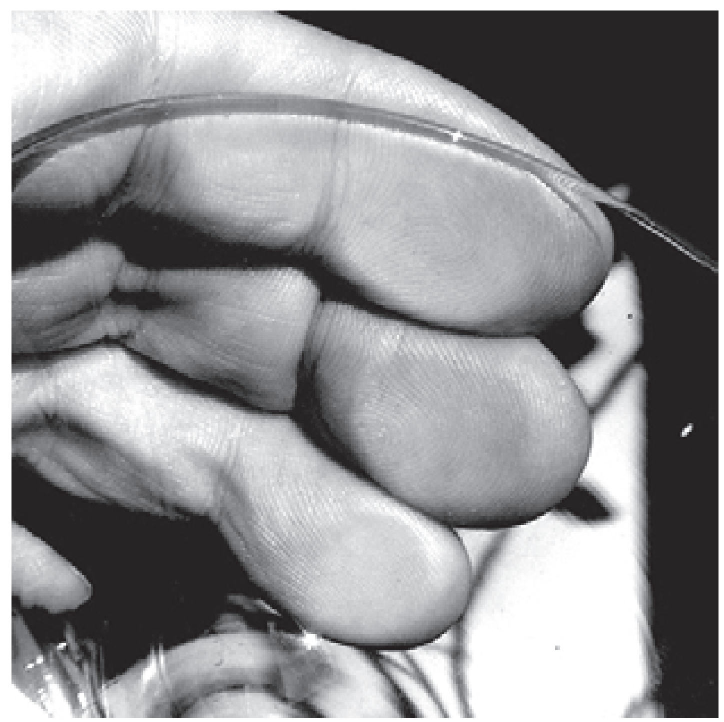


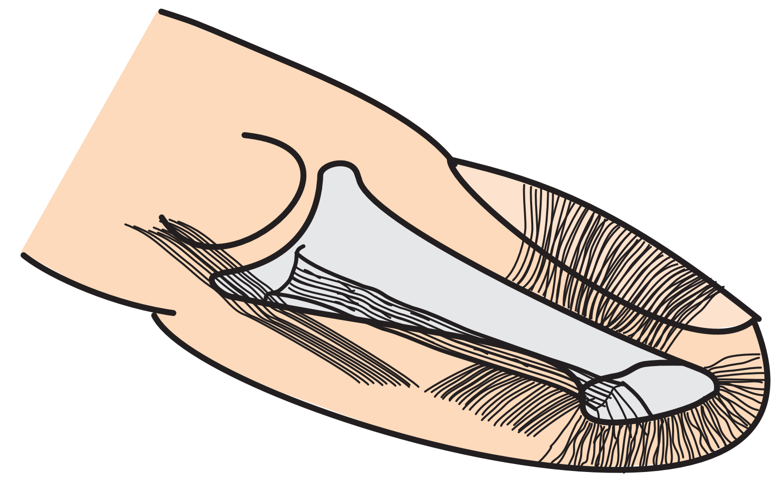
Okamoto, S., Nagano, H., & Yamada, Y. (2012). Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics*, *6*(1), 81-93.

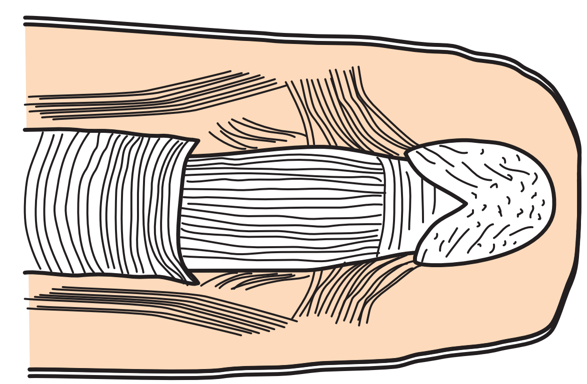
Fingertip biomechanics

Anatomy

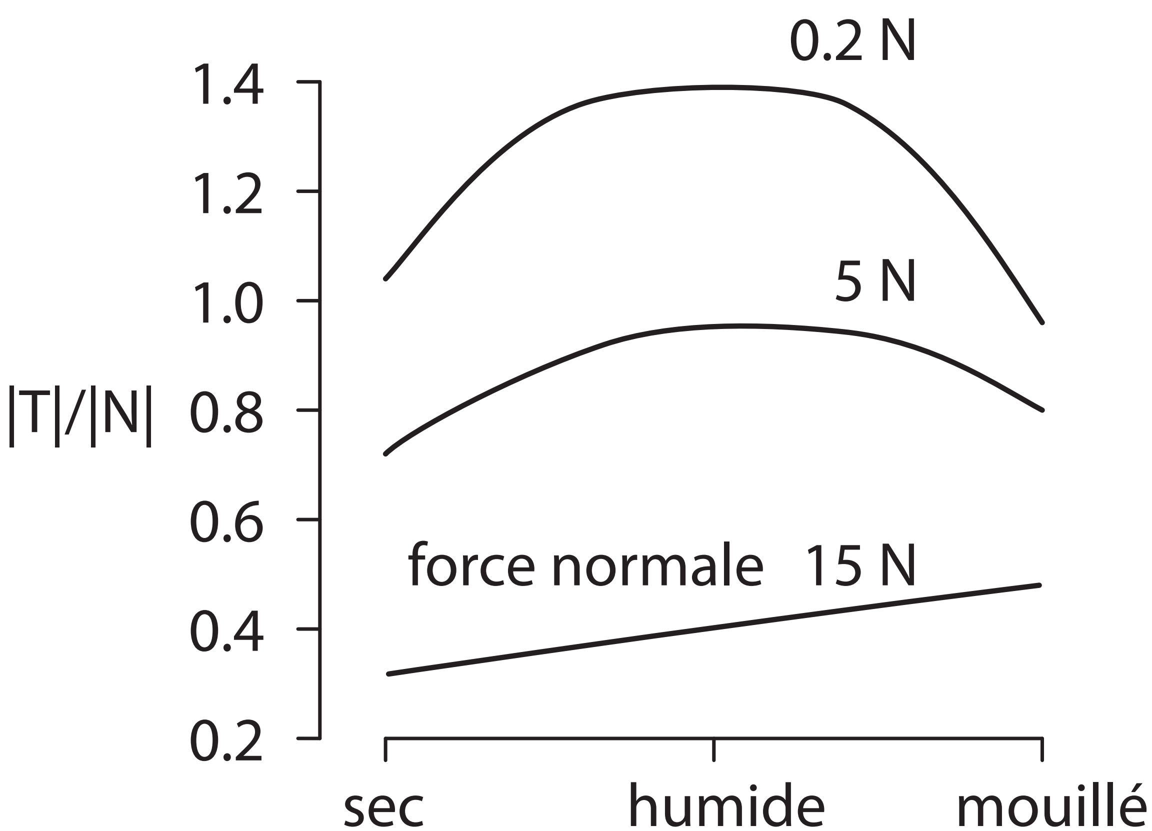


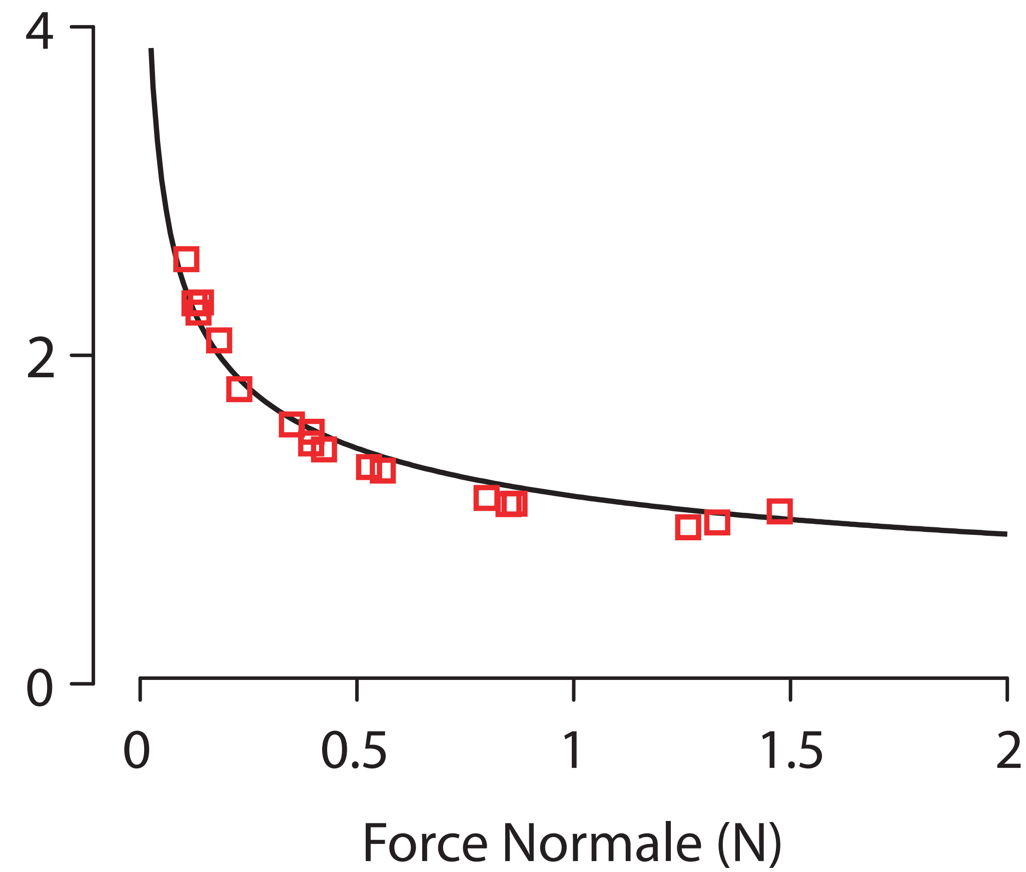






Friction

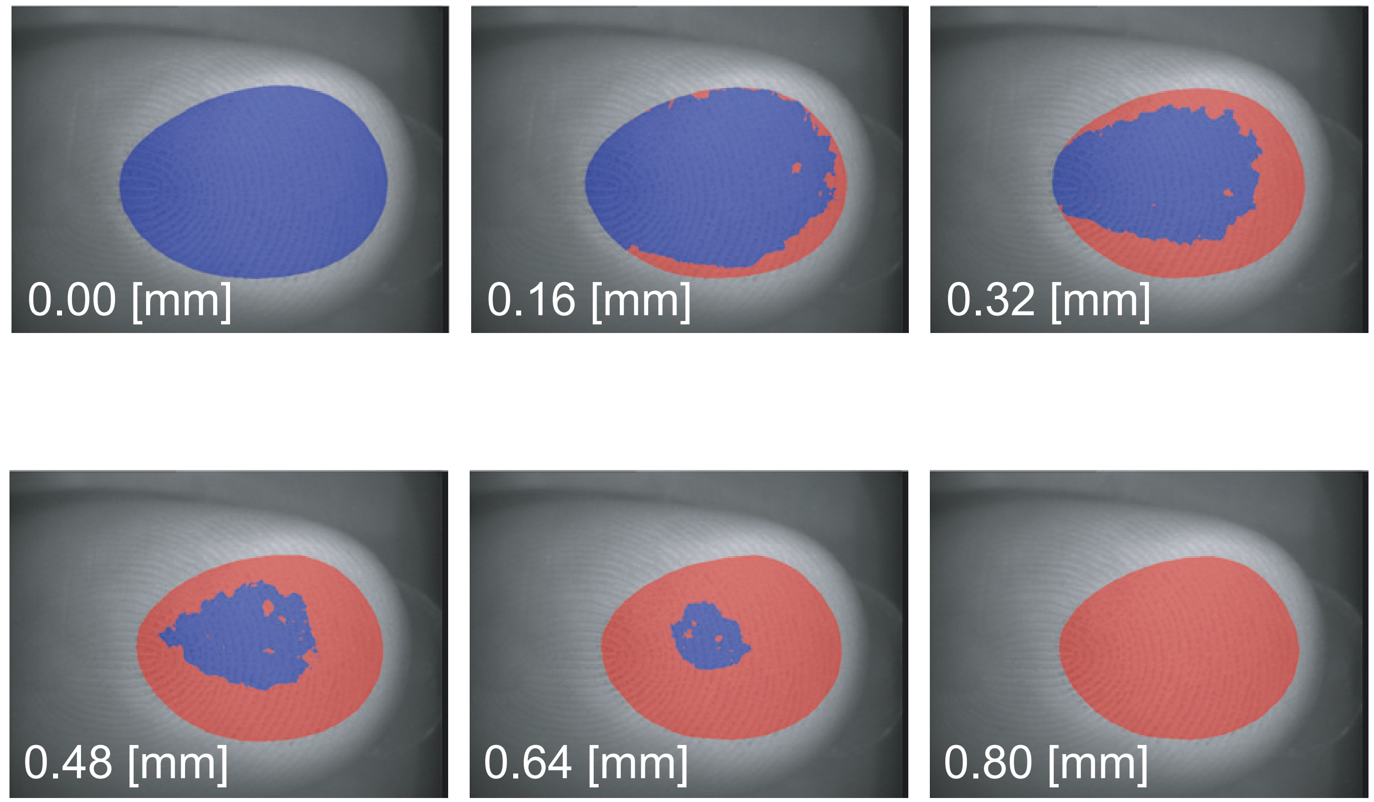


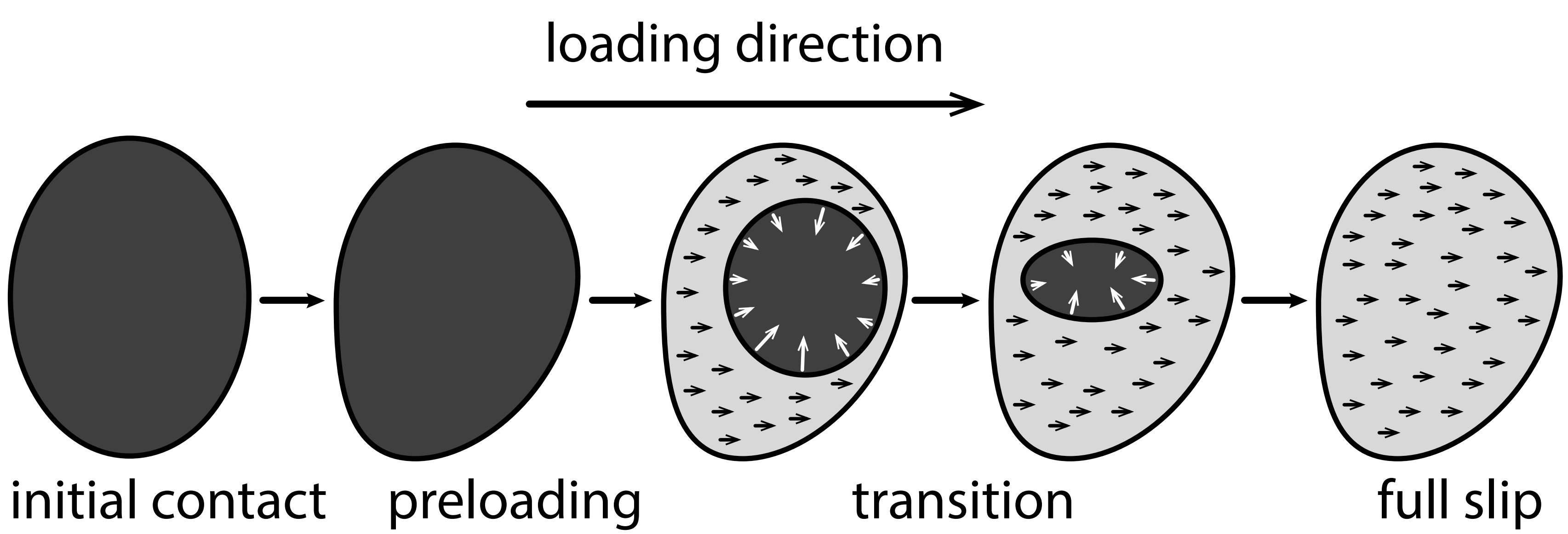


- Hertzian spherical contact
- Proportional to the real contact area
- Large influence of humidity

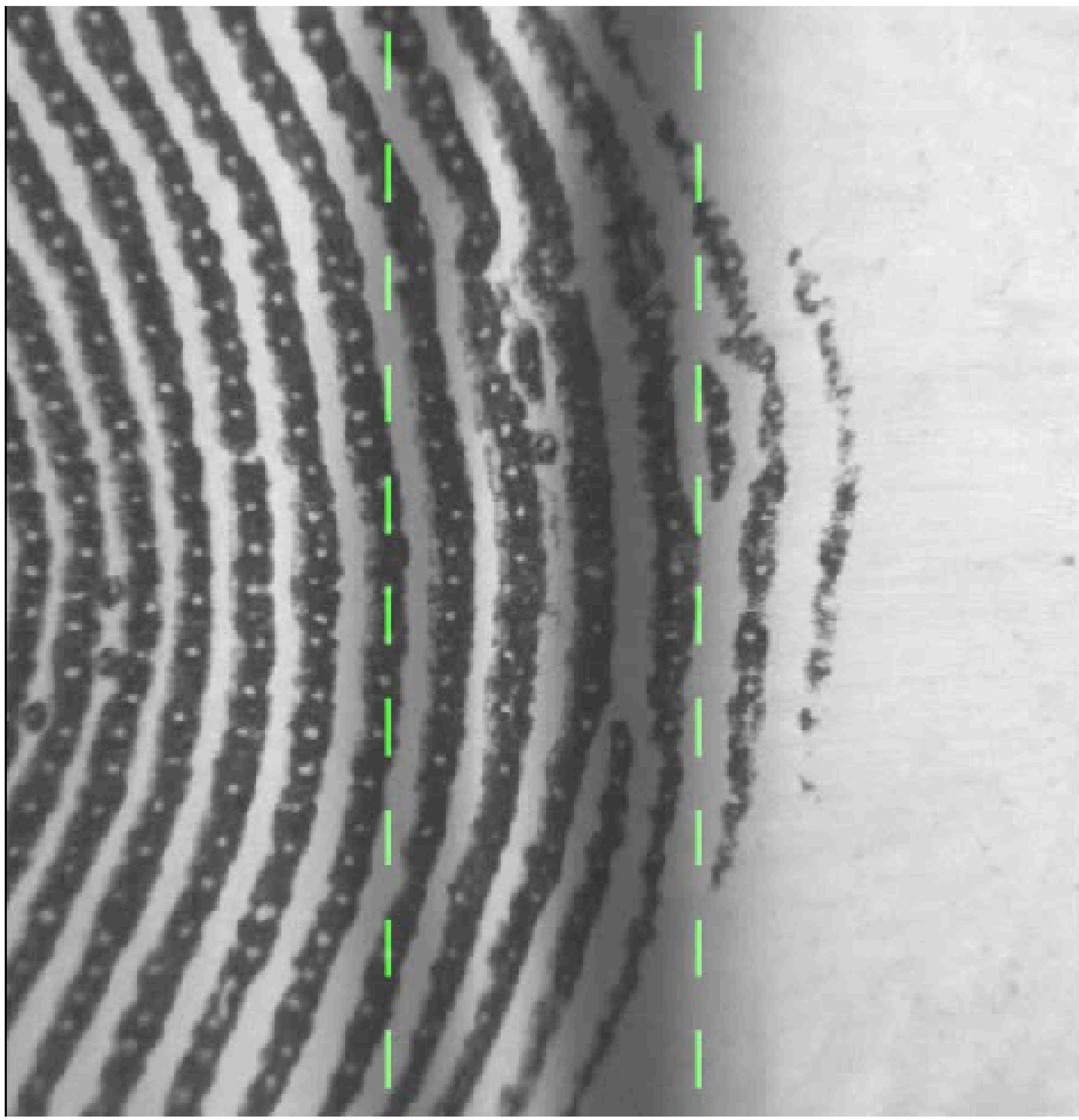
T. André, P. Lefèvre, and J.-L. Thonnard. A continuous measure of fingertip friction during precision grip. Journal of Neuroscience Methods,

Contact area starts to slip



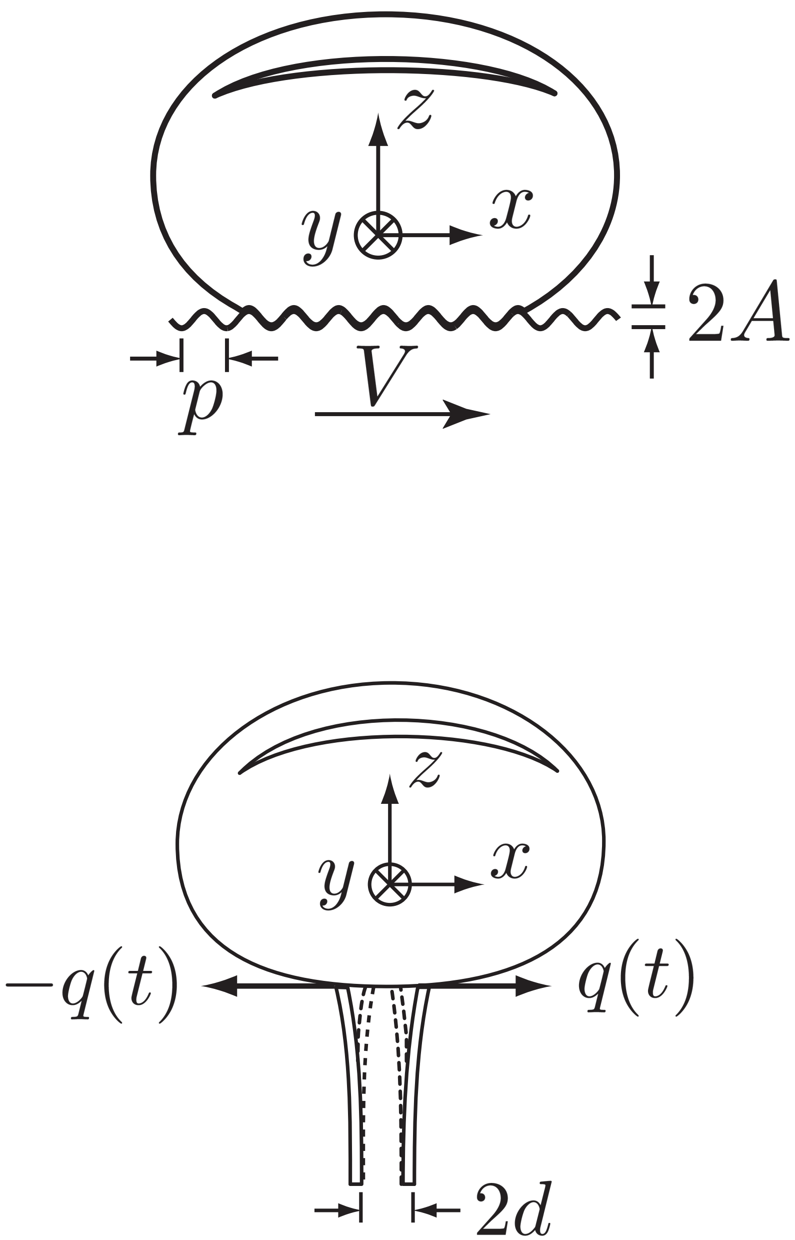


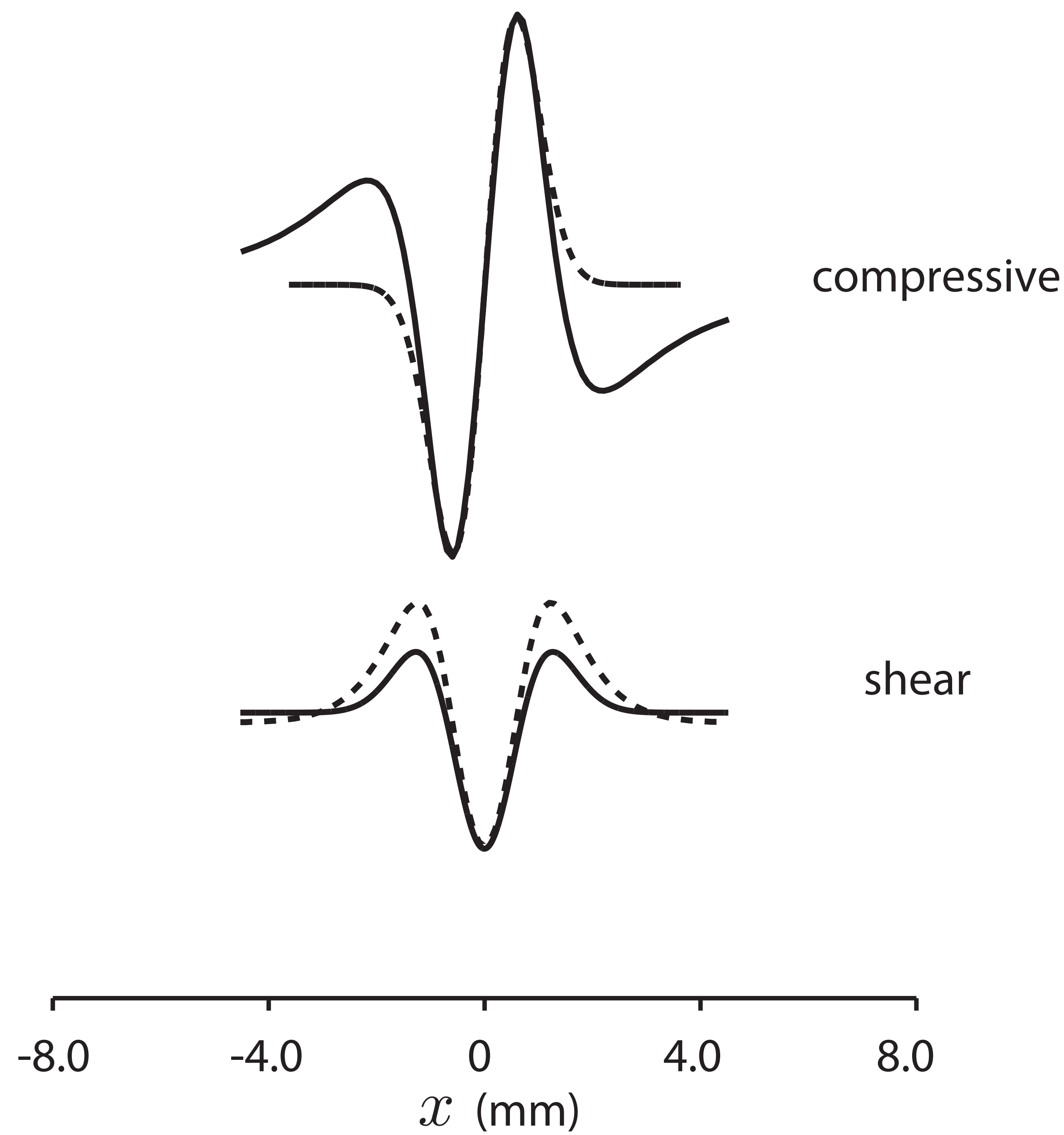
M. Tada, M. Mochimaru, et T. Kanade, “How does a fingertip slip ? - Contact mechanics of a fingertip under tangential loading,” dans EuroHaptics 2006



Courtesy of Vincent Hayward

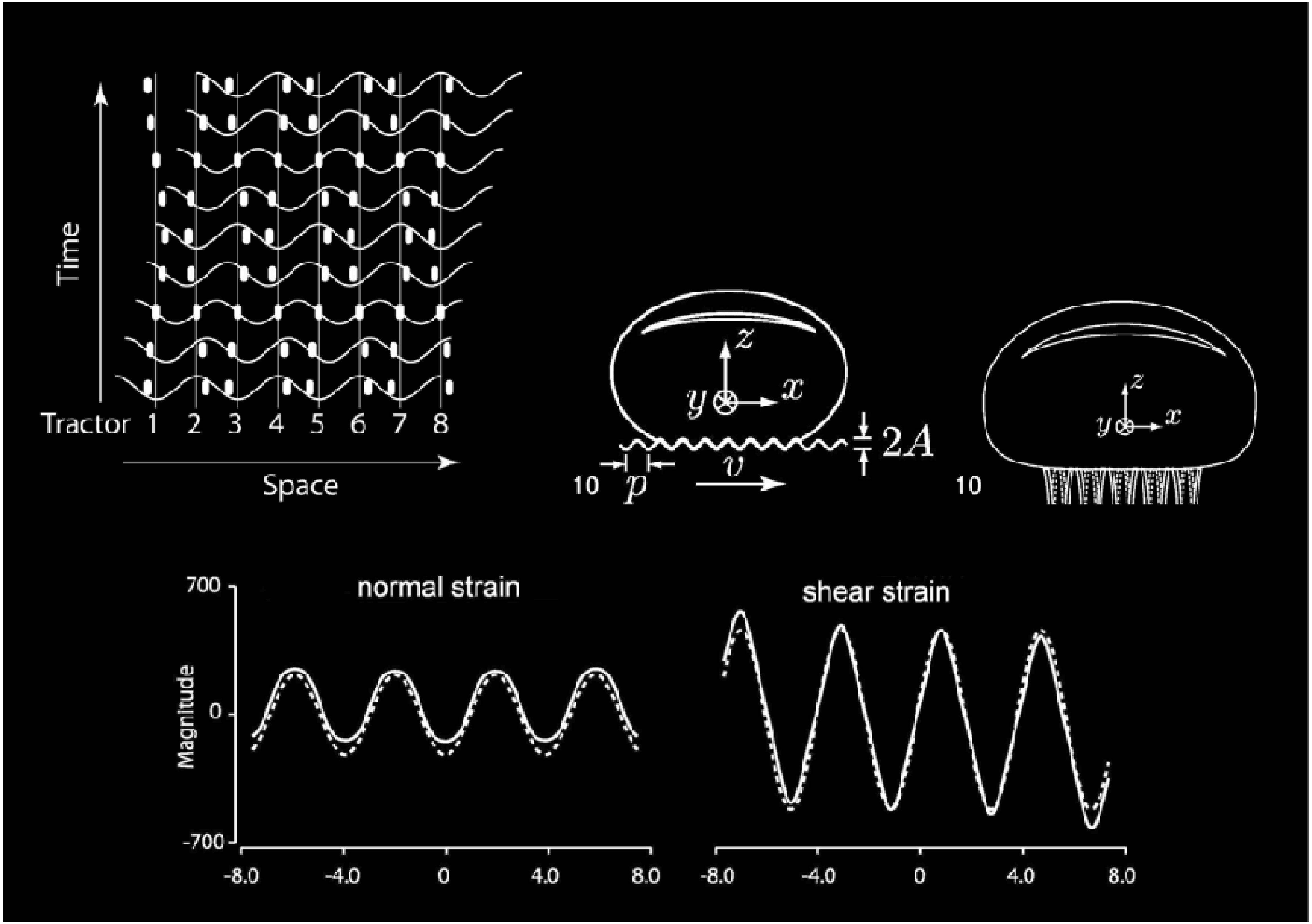
Spatial filtering by the skin





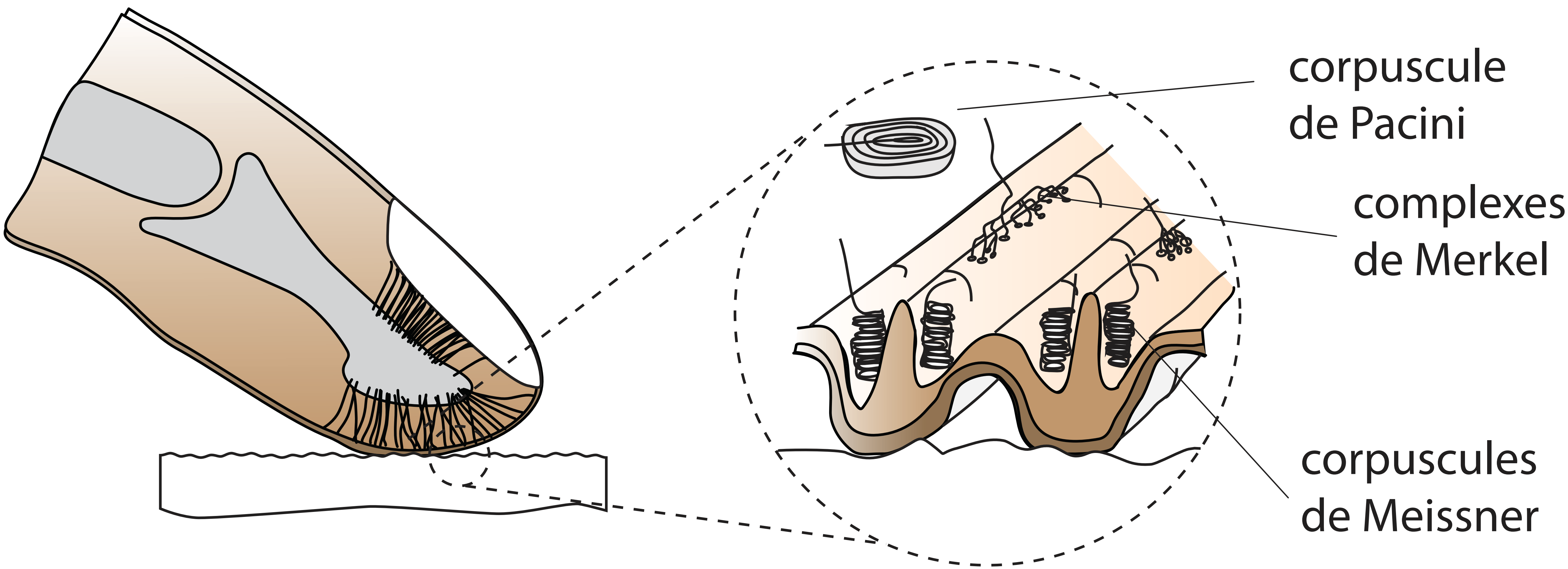
Wang, Qi, and Vincent Hayward. "Tactile synthesis and perceptual inverse problems seen from the viewpoint of contact mechanics."
ACM Transactions on Applied Perception (TAP) 5.2 (2008): 7.

Spatial filtering by the skin



Wang, Qi, and Vincent Hayward. "Tactile synthesis and perceptual inverse problems seen from the viewpoint of contact mechanics."
ACM Transactions on Applied Perception (TAP) 5.2 (2008): 7.

Nervous system


corpuscule
de Pacini
complexes
de Merkel
corpuscules
de Meissner

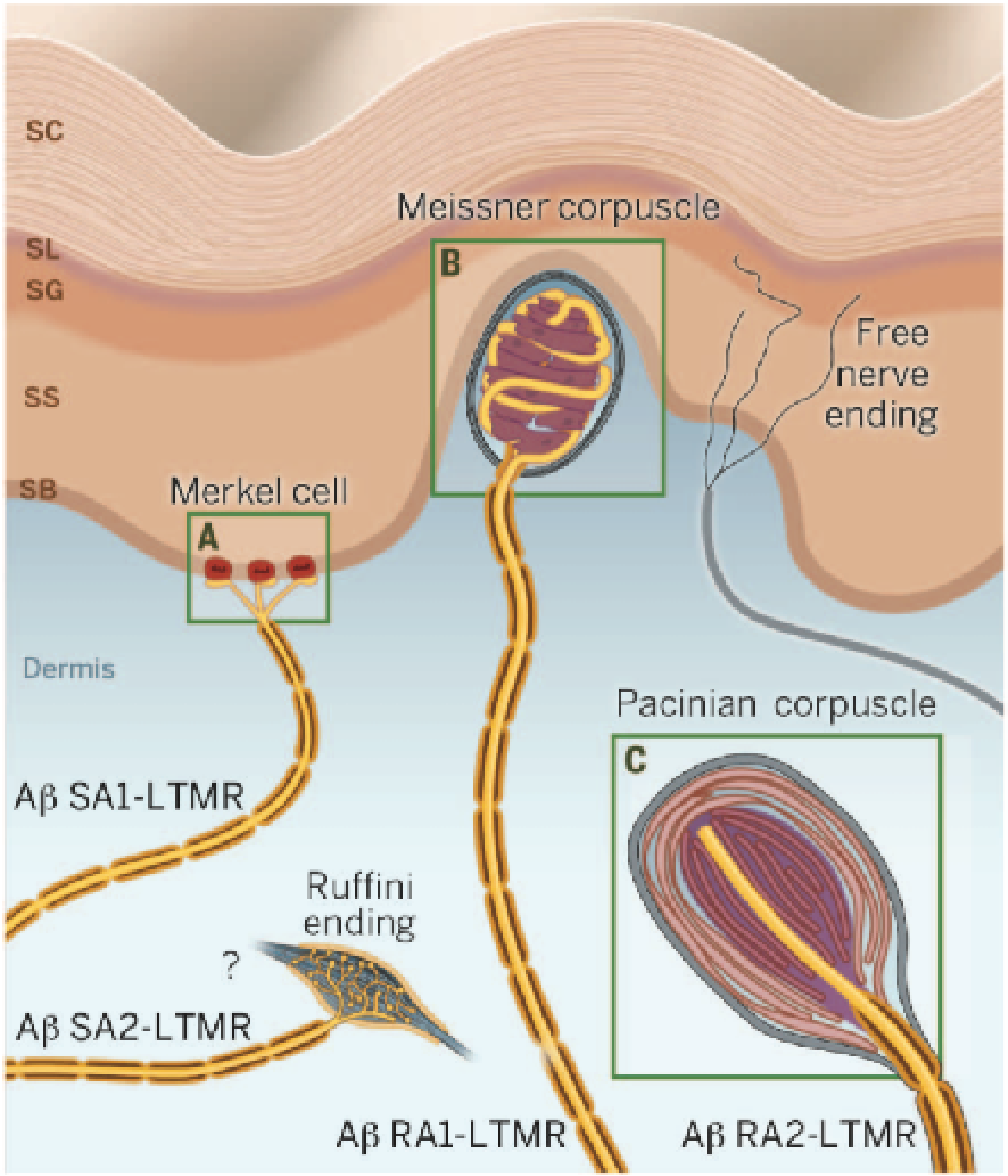


Fig. 1. LTMR innervation of glabrous skin. Glabrous skin is innervated by Aβ LTMRs, including Aβ SA1-LTMRs terminating in Merkel cells, Aβ SA2-LTMRs hypothesized to end in Ruffini endings, Aβ RA1-LTMRs innervating Meissner corpuscles, and Aβ RA2-LTMRs ending in Pacinian corpuscles. Green boxed regions are shown in greater detail in Fig. 3 (here, the letters "A," "B," and "C" correspond to panels with the same names in Fig. 3). SC, stratum corneum; SL, stratum lucidum; SG, stratum granulosum; SS, stratum spinosum; SB, stratum basale.

Zimmerman, Amanda, Ling Bai, and David D. Ginty. "The gentle touch receptors of mammalian skin." *Science* 346.6212 (2014): 950-954.

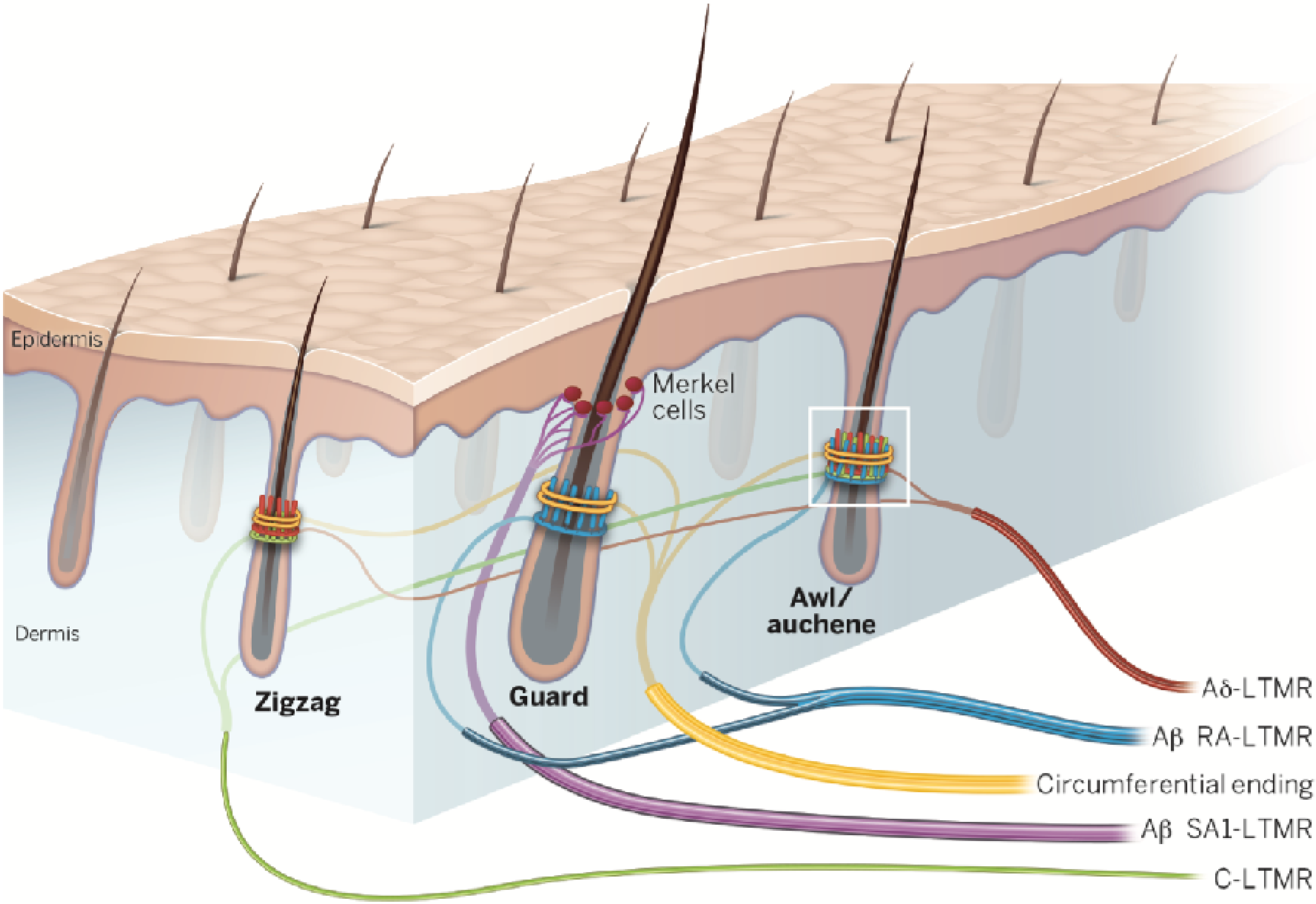


Fig. 2. LTMR innervation of hairy skin. Hairy skin in rodents is innervated by distinct combinations of LTMRs. Touch domes of Merkel cells and associated Aβ SA1-LTMRs are found above the level of the sebaceous glands of guard hair follicles. Guard hairs are also innervated by Aβ RA-LTMR lanceolate endings. Awl/auchene hairs are innervated by all three types of lanceolate-ending LTMRs: Aβ RA-LTMRs, Aδ-LTMRs, and C-LTMRs. Zigzag hairs, the most numerous, are innervated by Aδ-LTMRs and C-LTMRs. Circumferential endings encircle the longitudinal lanceolate endings of all three types of hair follicles. The white boxed region is shown in greater detail in Fig. 4.

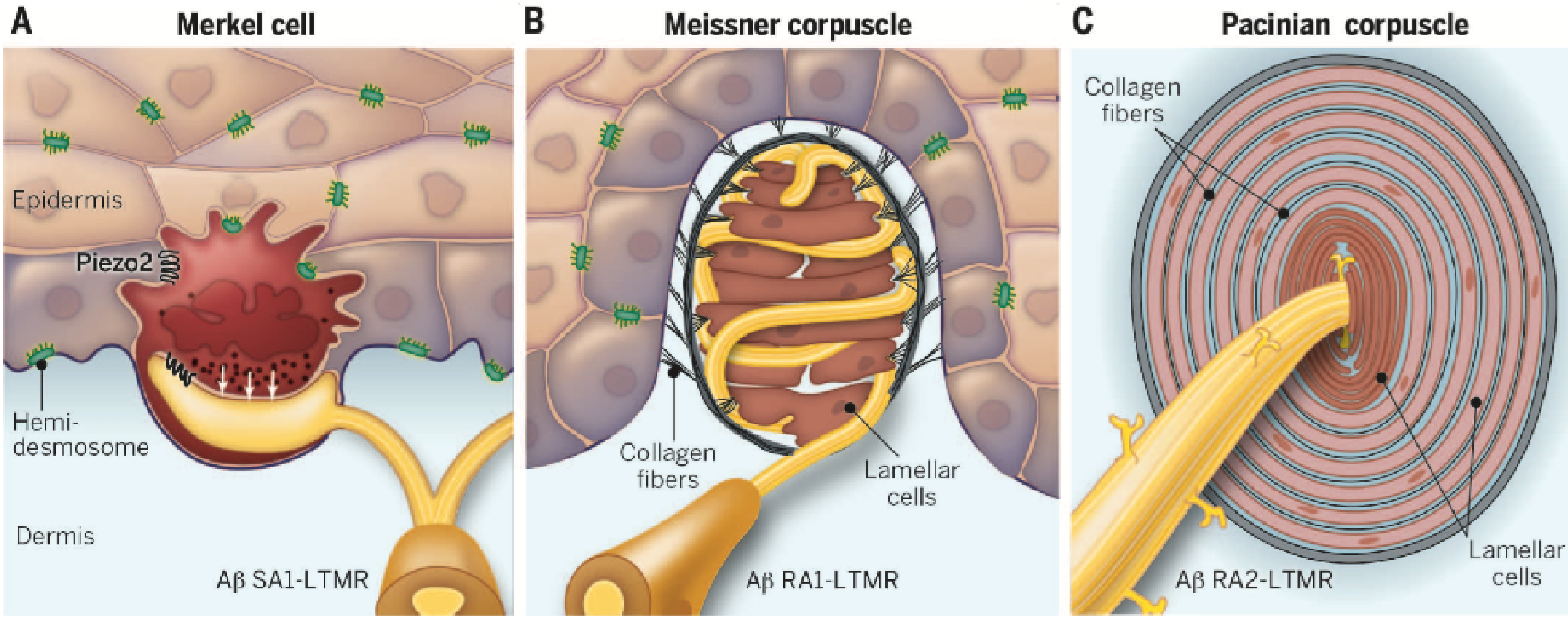
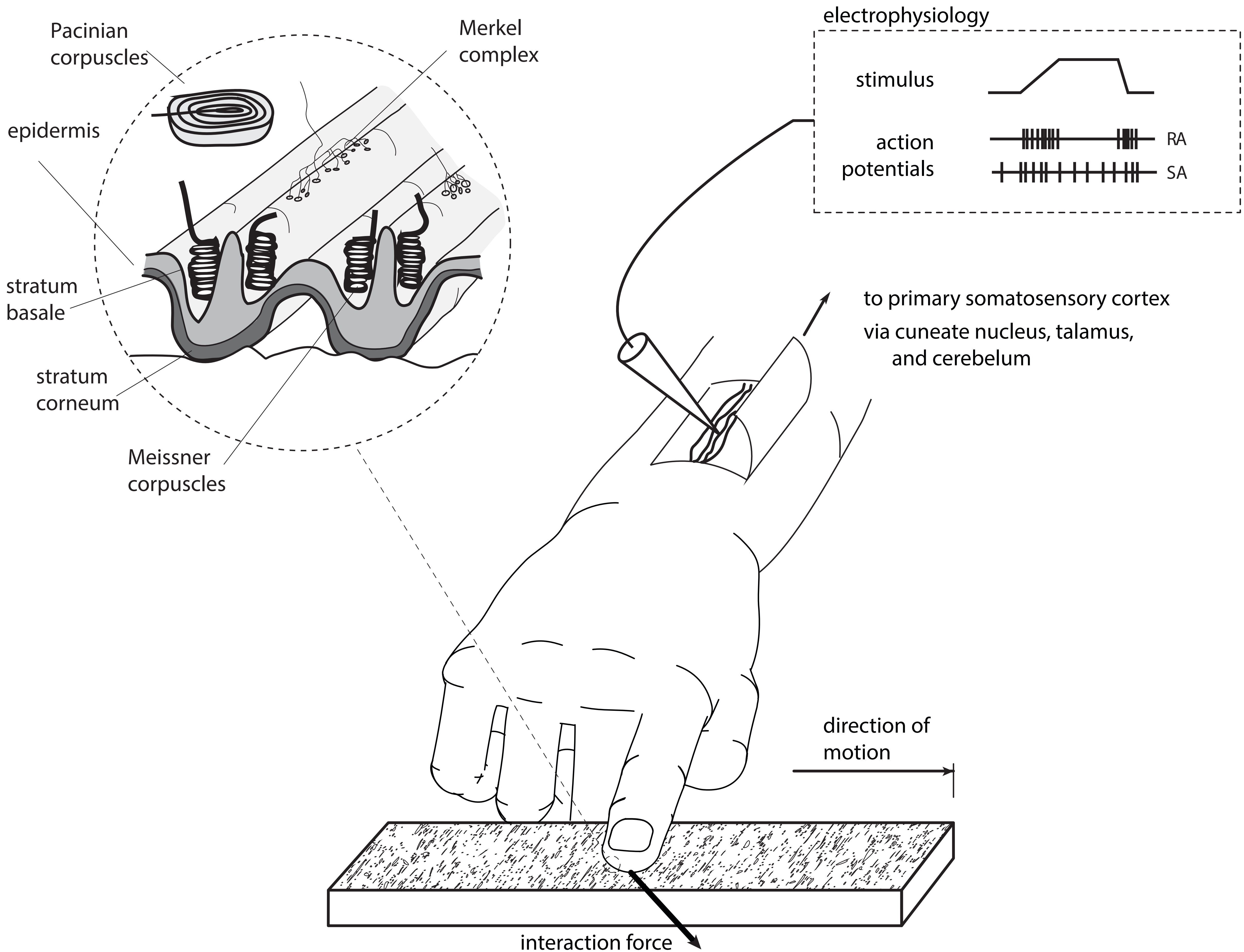
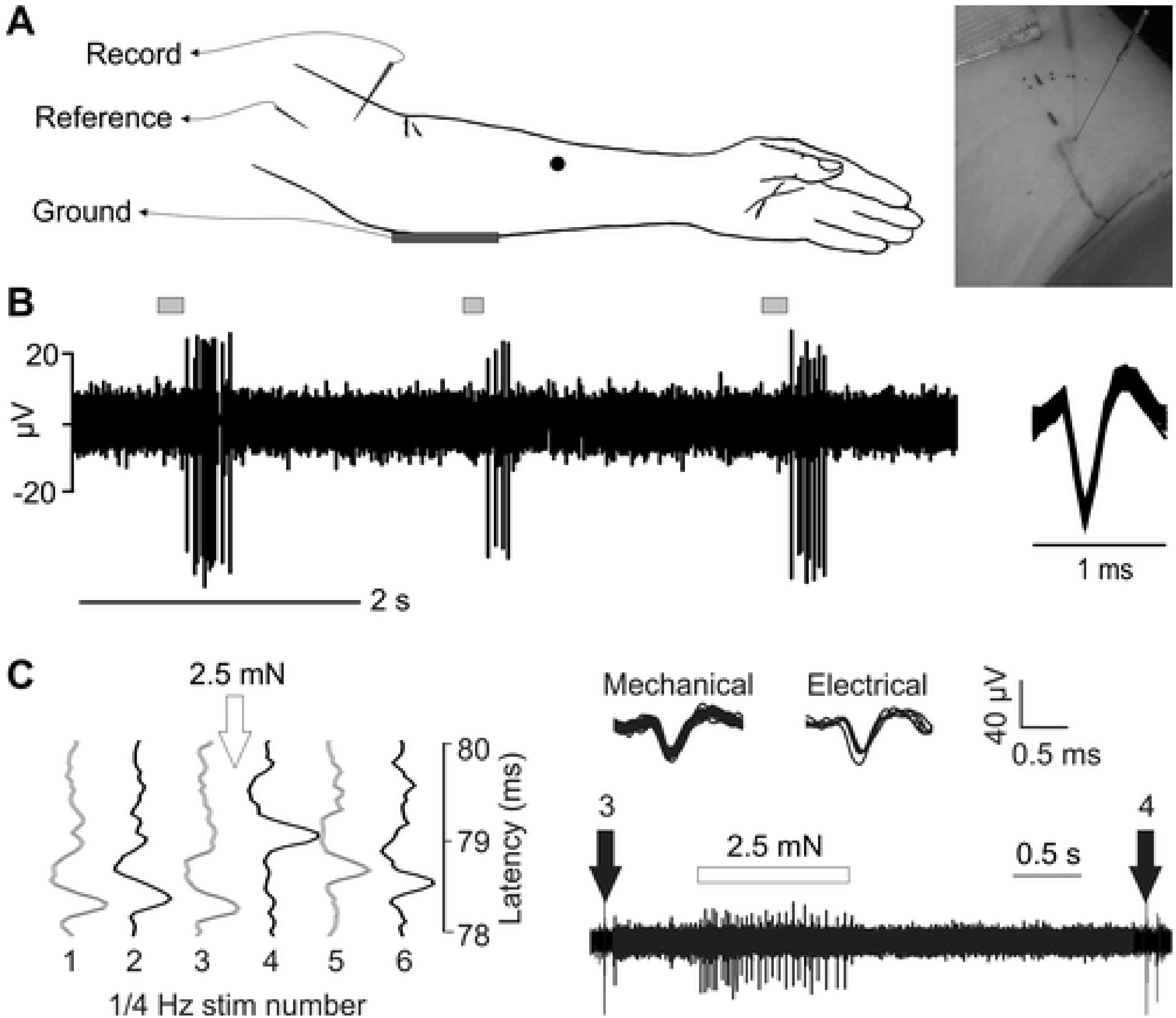


Fig. 3. LTMR end organs of glabrous skin. (**A**) Merkel cells are located within the basal layer of the epidermis, innervated by a single Aβ SA1-LTMR. Cytoplasmic protrusions of the Merkel cell and hemidesmosomes physically link Merkel cells to surrounding epithelial cells. Dense-core vesicles are located inside the Merkel cell in close proximity to the enlarged axon terminal and are thought to be involved in signaling between the Merkel cell and the neurite. Recent evidence revealed Merkel cells to be mechanically sensitive and to play an active role in mechanotransduction (white arrows). (**B**) Meissner corpuscles are located within dermal papillae and are innervated by one or more Aβ RA1-LTMRs. The external capsule is linked to both the lamellar cells and the epidermis via collagen fibers. (**C**) Pacinian corpuscles are located in the deep dermis, contain layered lamellar cells, and are innervated by a single Aβ RA2-LTMR. Axonal protrusions project from the neurite into the cleft between inner-core lamellar cells and are thought to be the sites of generator potentials. Longitudinal and circumferential collagen fibers anchor the inner core and outer zone, respectively.



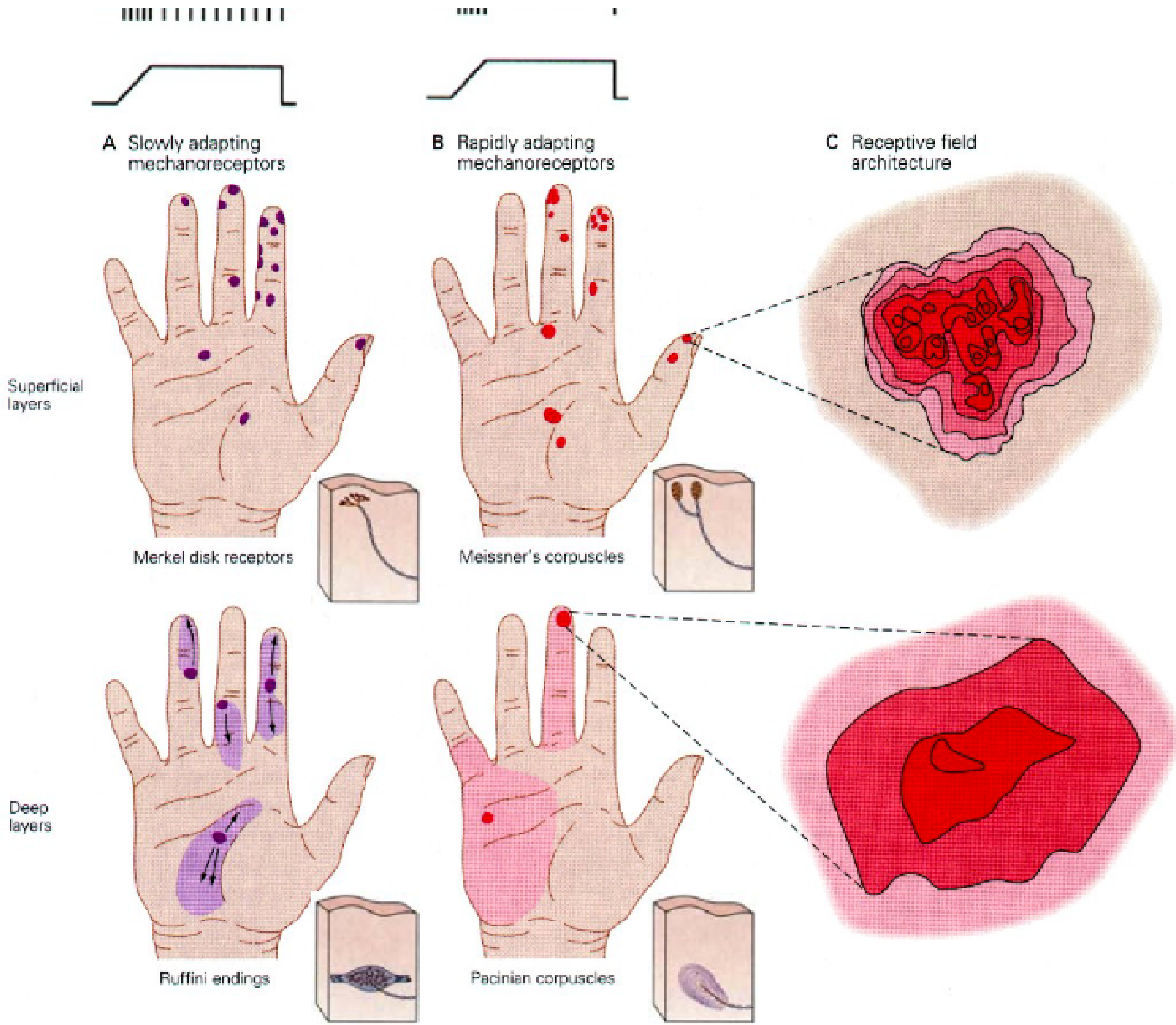
Pacinian corpuscles
Merkel complex
epidermis
stratum basale
stratum corneum
Meissner corpuscles
electrophysiology
stimulus
action potentials
RA
SA
to primary somatosensory cortex
via cuneate nucleus, talamus, and cerebelum
direction of motion
interaction force



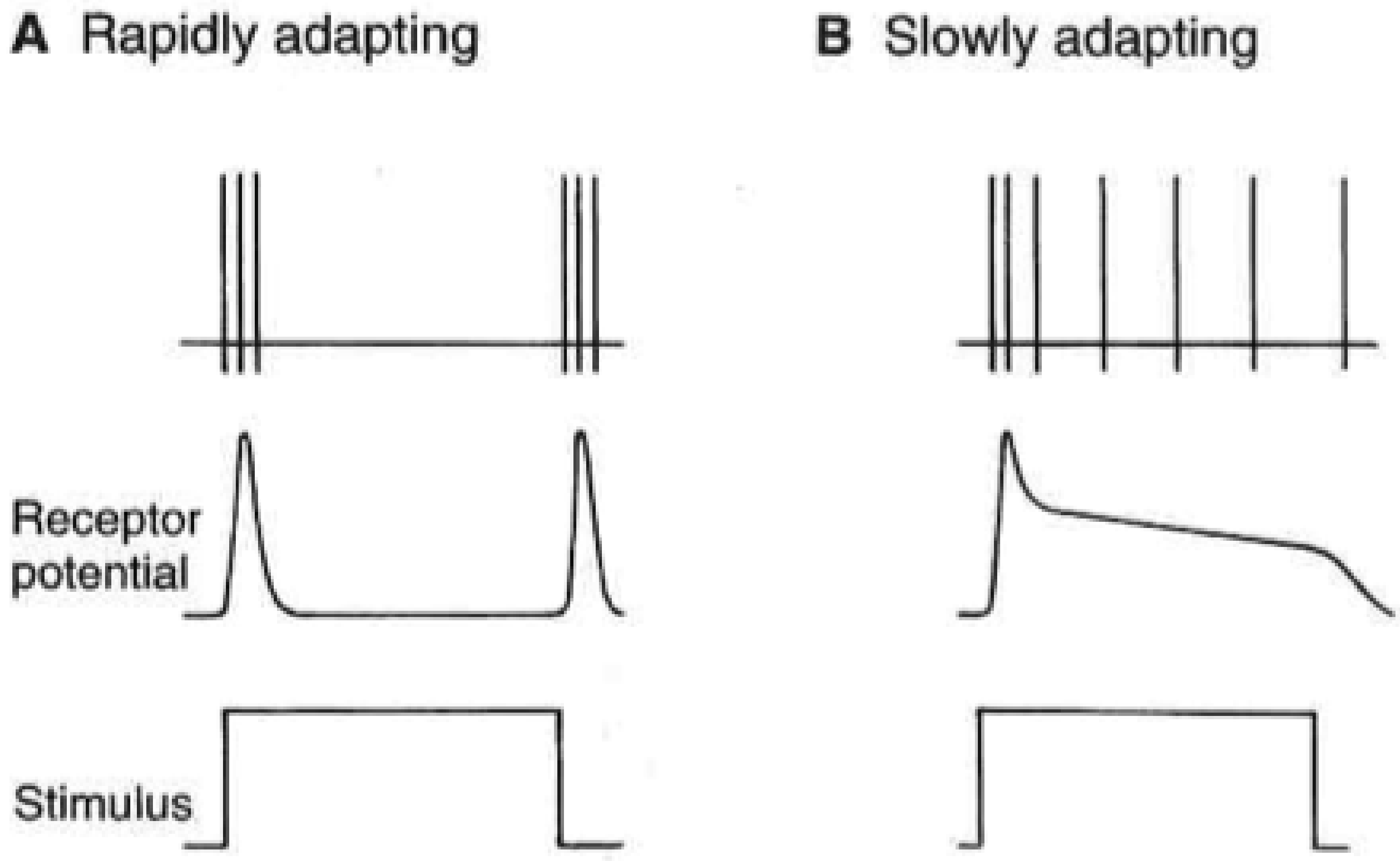
A
Record
Reference
Ground
B
20
μV
-20
2 s
1 ms
C
2.5 mN
80
79
78
Latency (ms)
1
2
3
4
5
6
1/4 Hz stim number
Mechanical
Electrical
40 μV
0.5 ms
3
4
2.5 mN
0.5 s

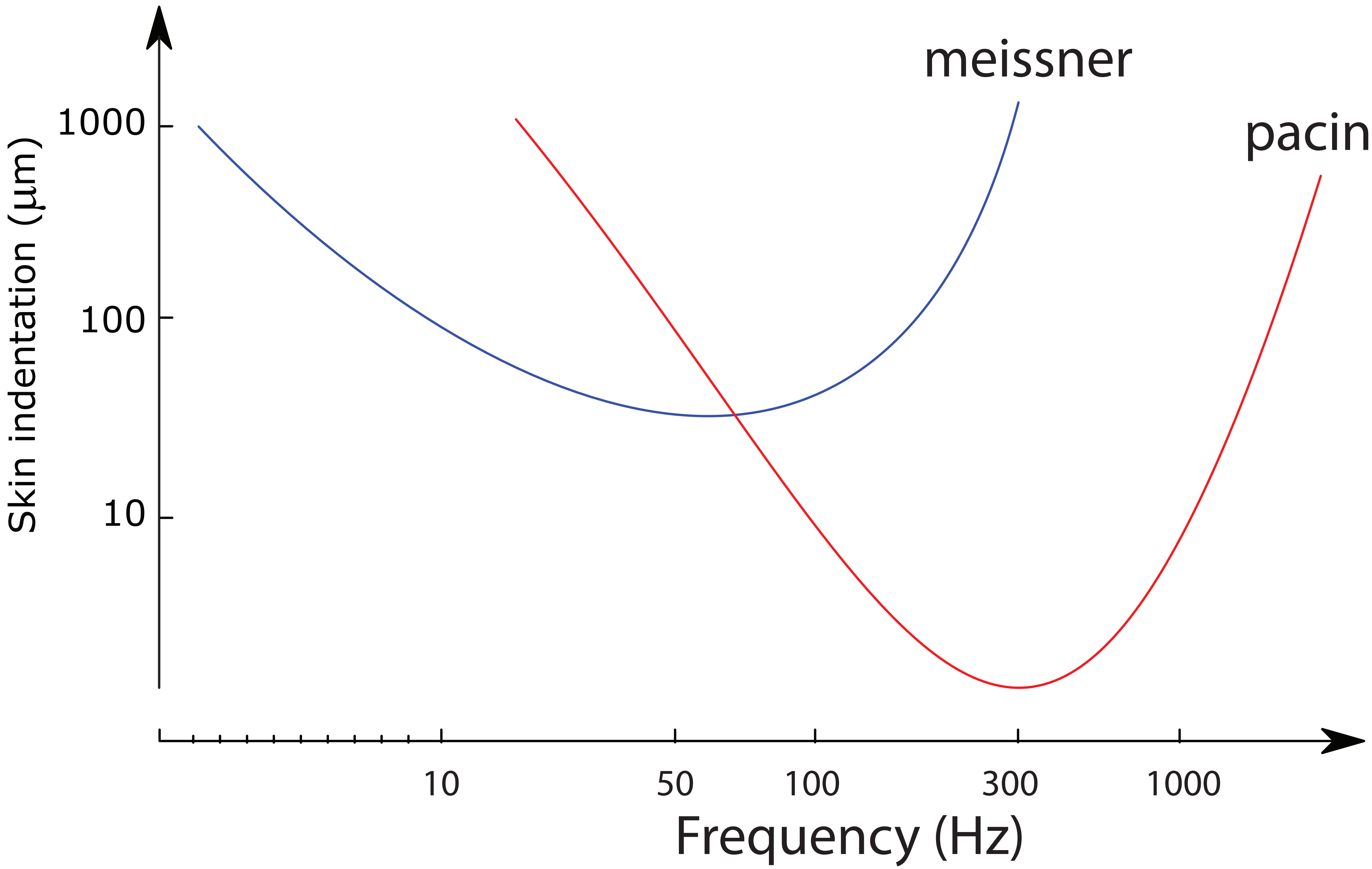
Slowly adapting (SA)

Rapidly adapting (RA)

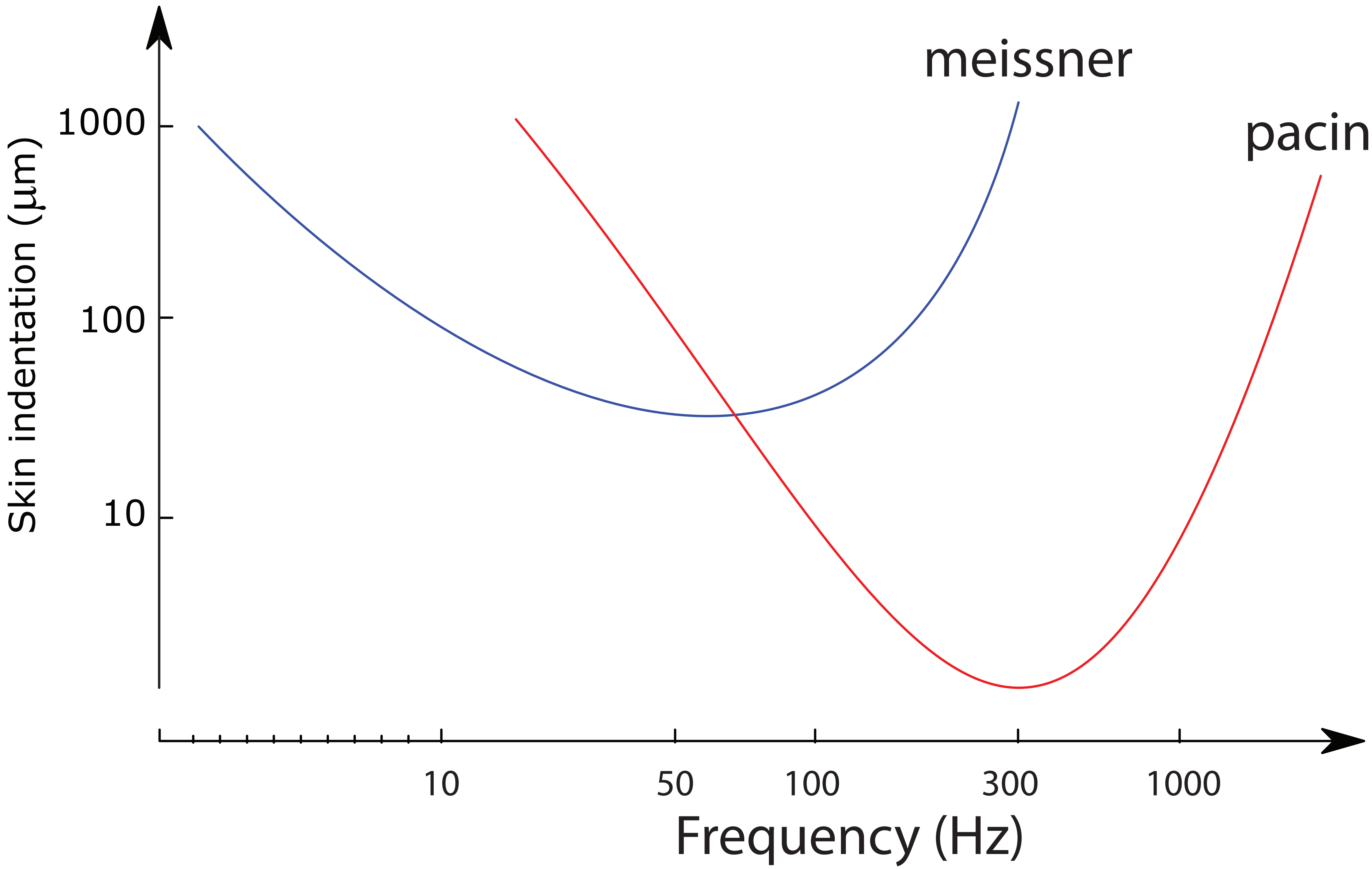


adaptation


A Rapidly adapting
B Slowly adapting
Receptor potential
Stimulus



meissner
pacini
Skin indentation (µm)
1000
100
10
10
50
100
300
1000
Frequency (Hz)

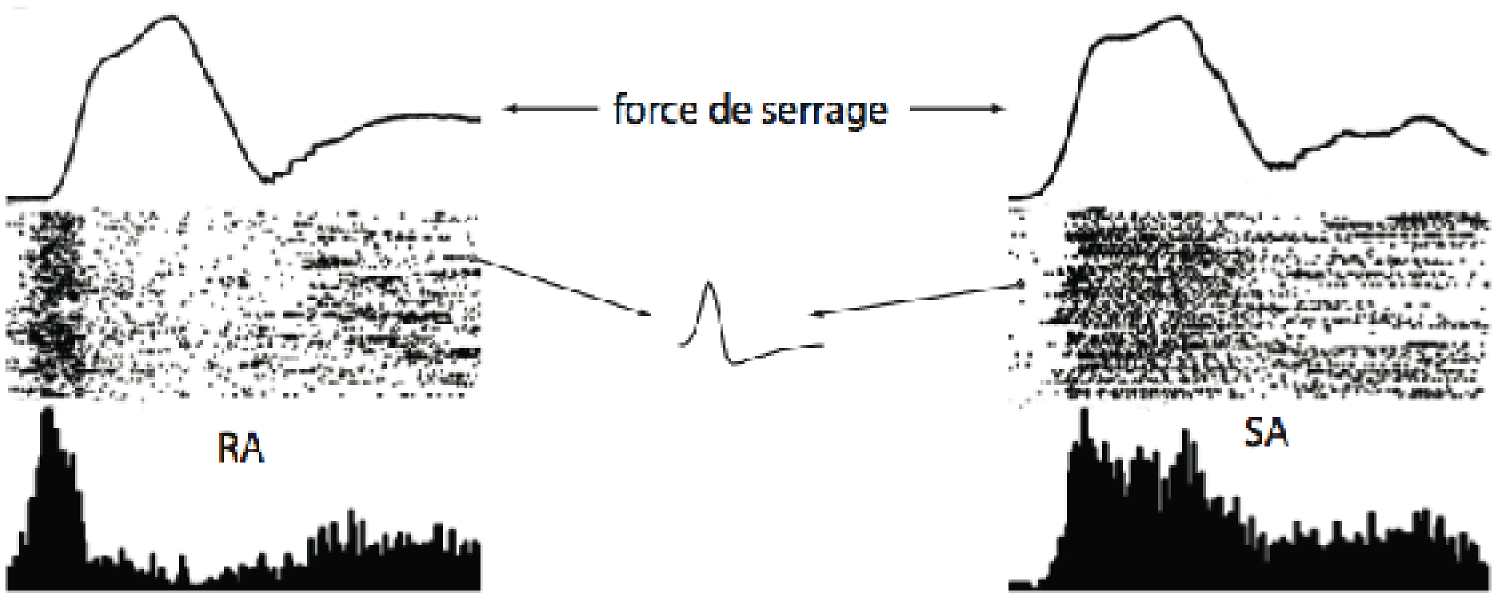


meissner
pacini
1000
100
10
Skin indentation (µm)
10
50
100
300
1000
Frequency (Hz)

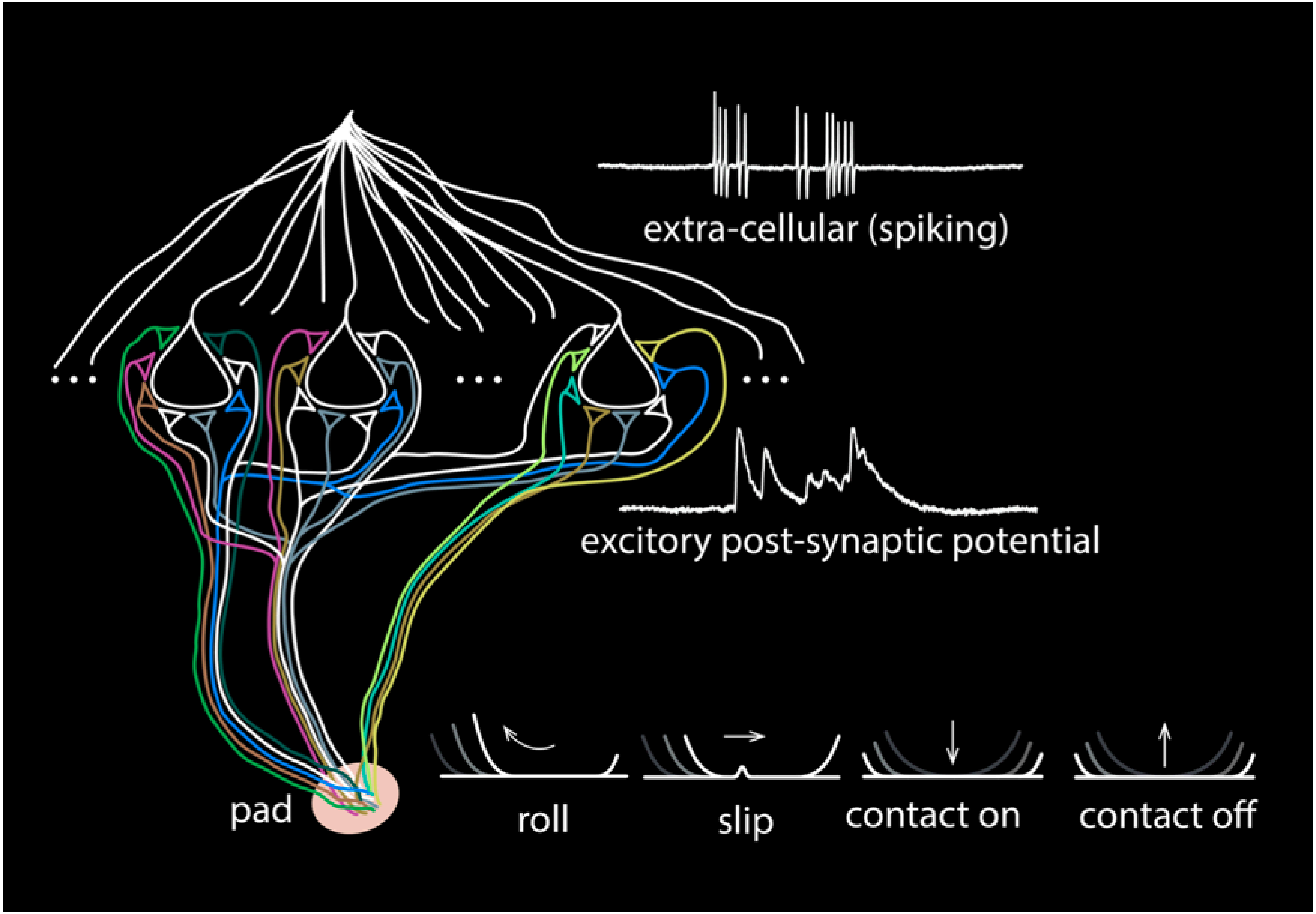
SA **RA**


re07Grip01.Pbo Trial Number:5

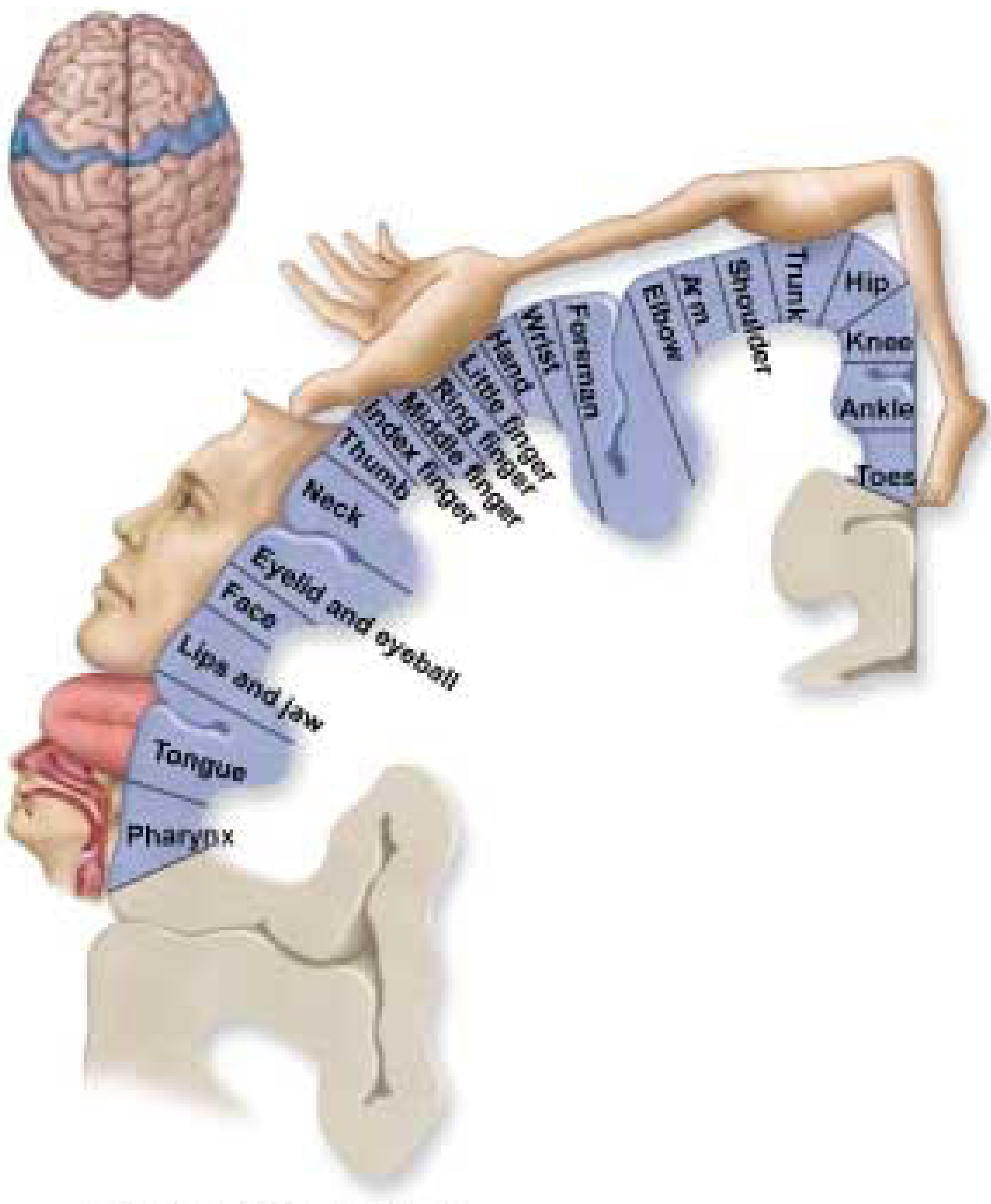

Trial Number:32


force de serrage
RA
SA

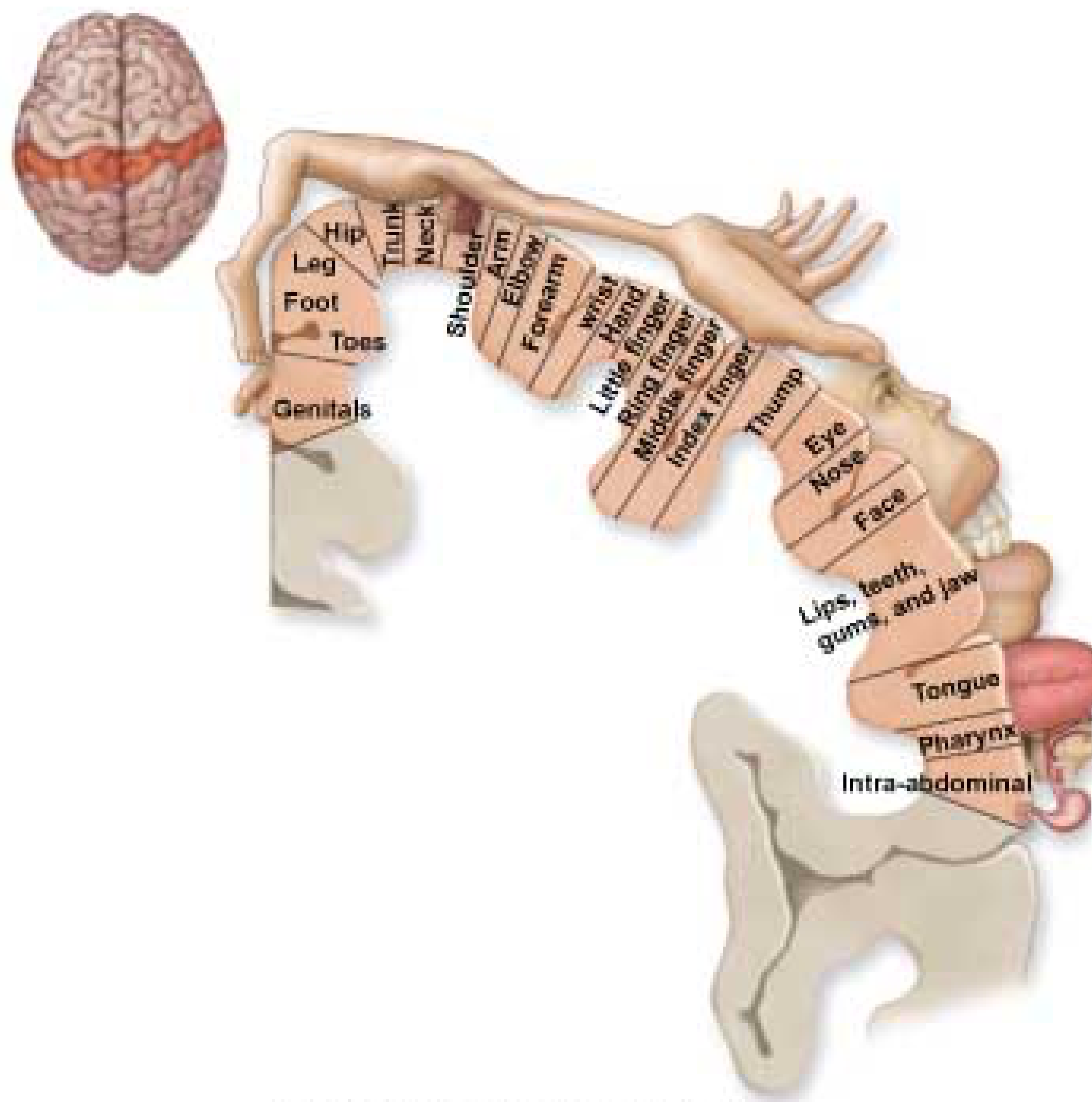
Bottom-up neural pathways



Homonculus somatotopic organisation

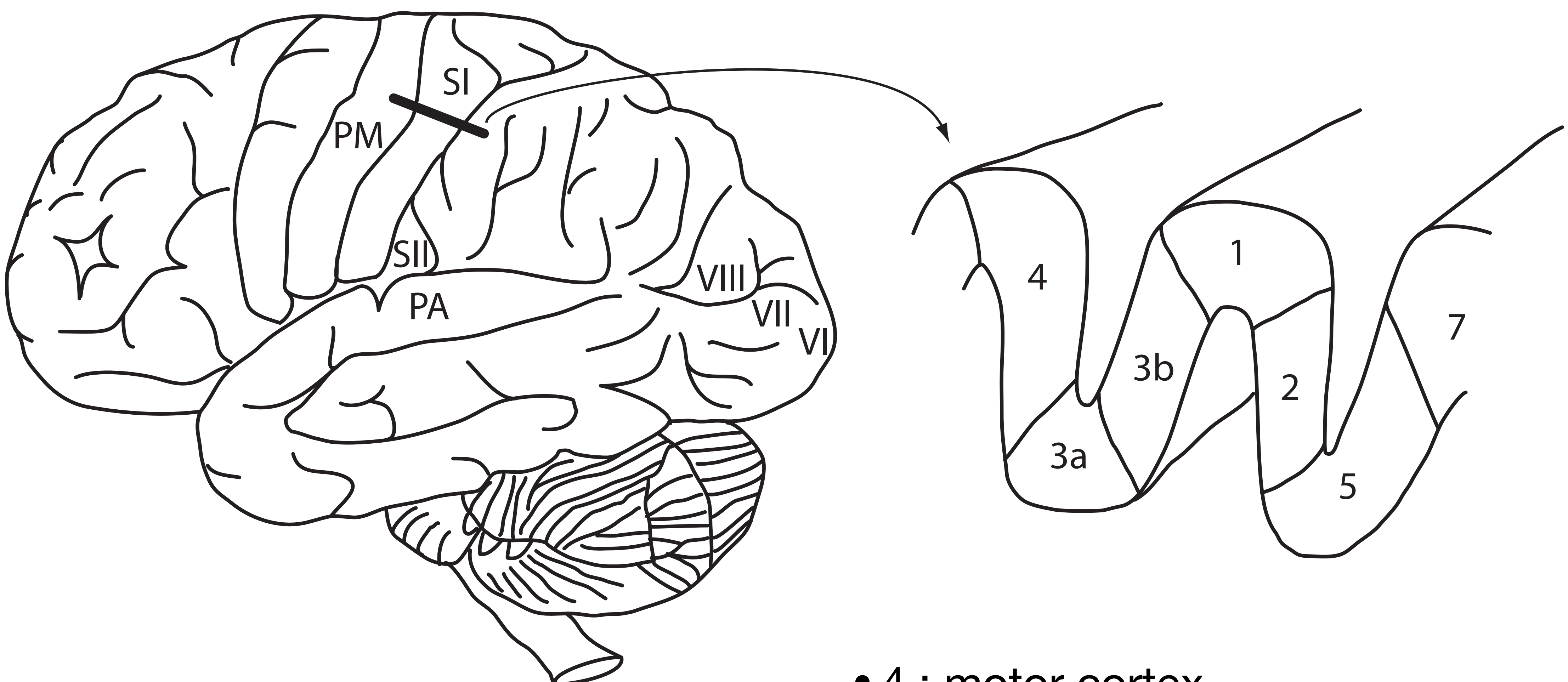


a. Primary motor area



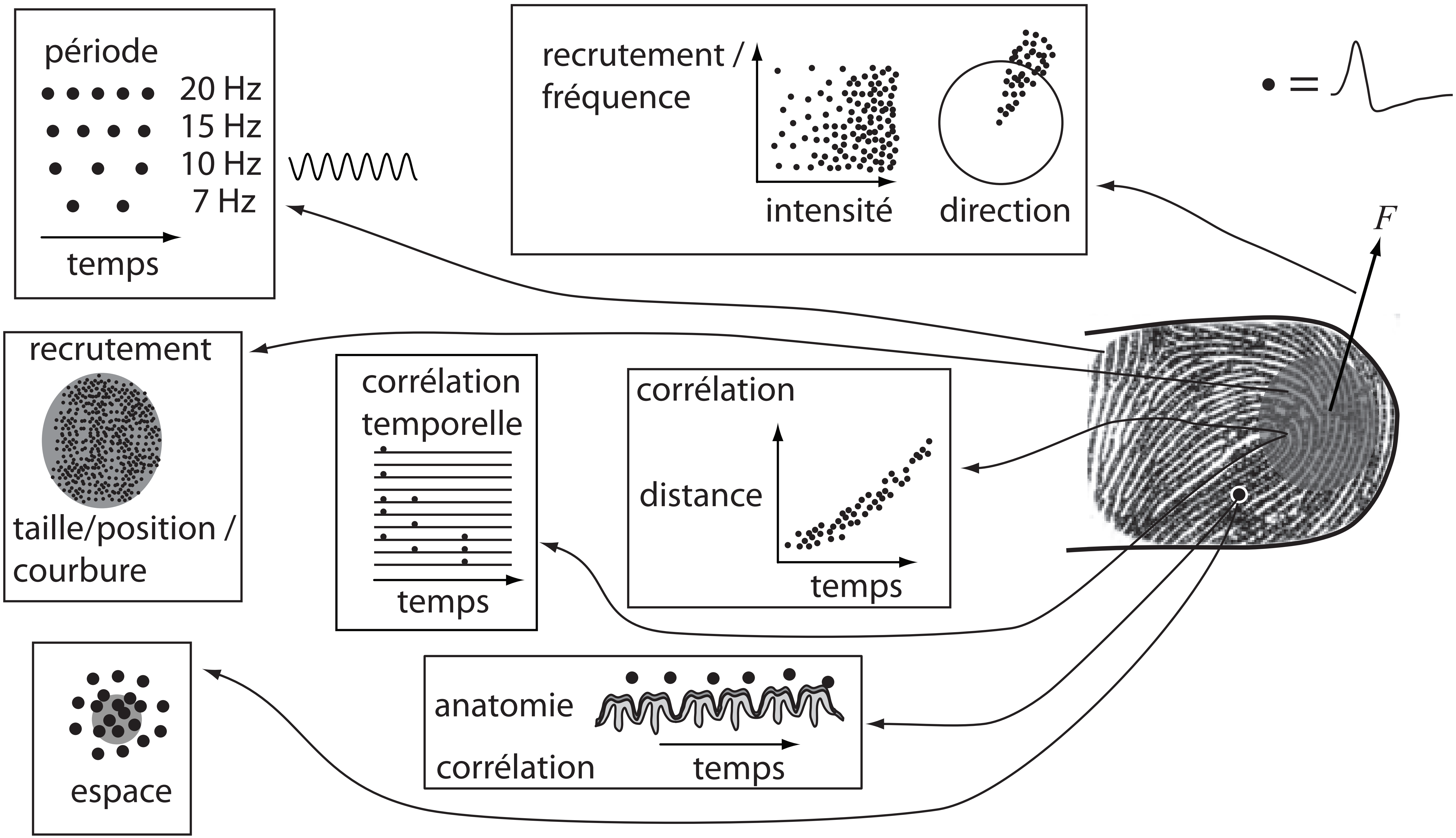
b . Primary somatosensory area

Somatosensory areas



- 4 : motor cortex
- 3a, 3b : primary somatosensory cortex
- 2 : Shape and Size
- 1 : Texture
- 5, 7 : **?**

Neuronal codes

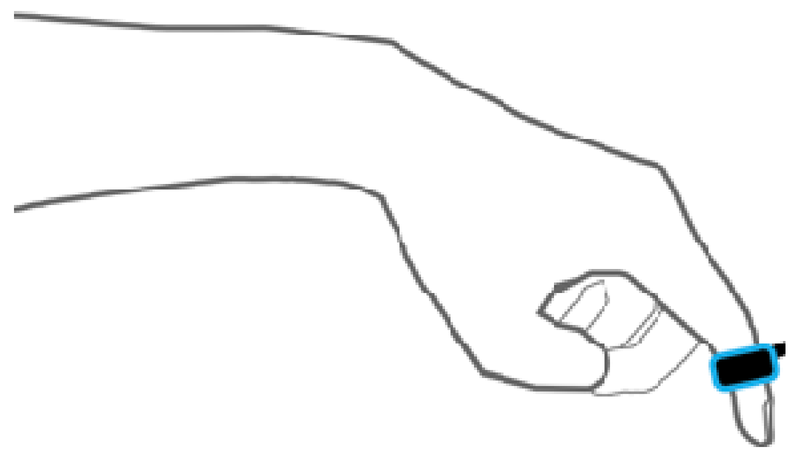


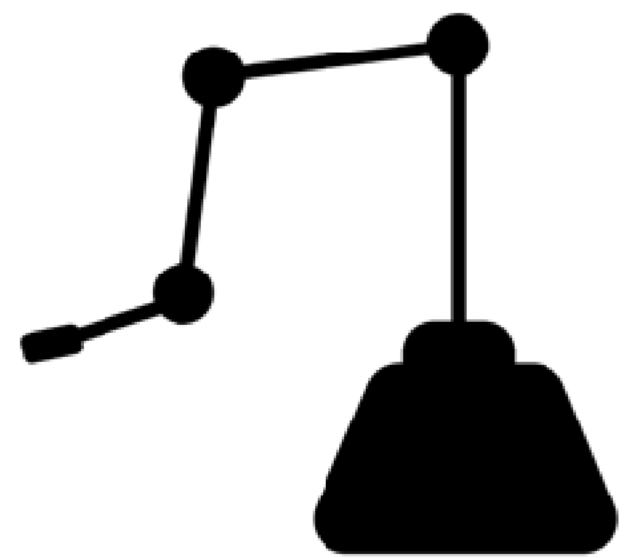
Perception and psychophysics

Which change in intensity produces a sensation?

How to quantify it?

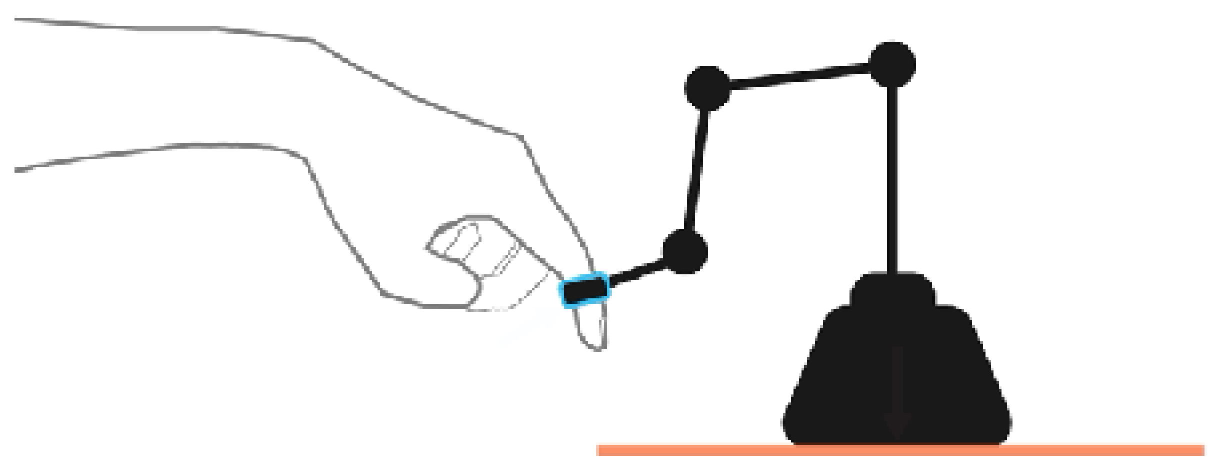
Research on human touch is a major gateway for the progress of haptics and the conception of novel haptic devices.





In turn, haptic devices can help study human touch as they can:

- precisely control stimuli and measure user motion and/or force.
- create stimuli that do not exist in the physical world.



Example GFF devices for haptic perception experiments

Highly reliable

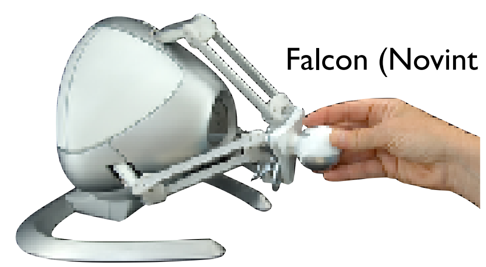
Good position & force resolution

Phantom Omni (3D Systems Inc.)

Phantom Premium (3D Systems Inc.)

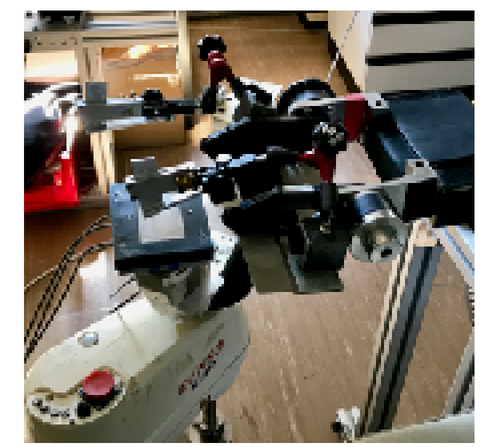
Cheap

Can buy on eBay



Falcon (Novint Inc.)

Custom-built



SMP Force platform (UCLouvain)

Complexity of building and using

Depends on DoF, kinematic structure, materials and fabrication method

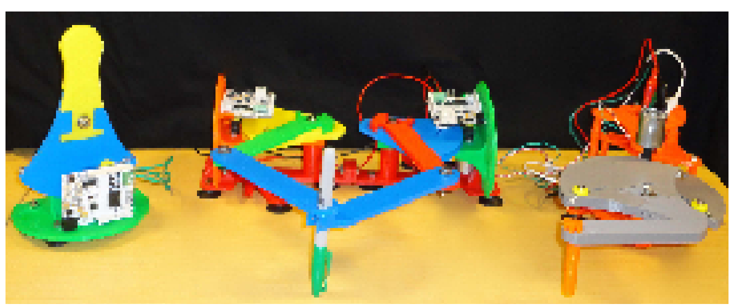
Simple

Low DoF
Serial
Plastic
3D printable

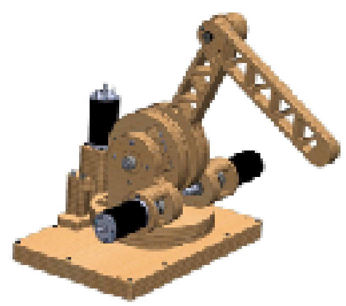
3-4 interviews of trusted contacts who are senior PhDs or post-doc

High DoF
Parallel, Serial & Parallel
Unique engineering featu
Metal
Machined

Complex



1-2 DoF, Serial (mostly), 3D printed plastic

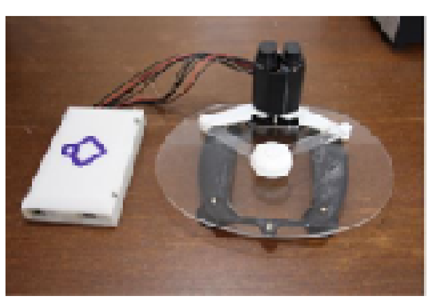


3 DoF, Serial, Wood, Laser cut

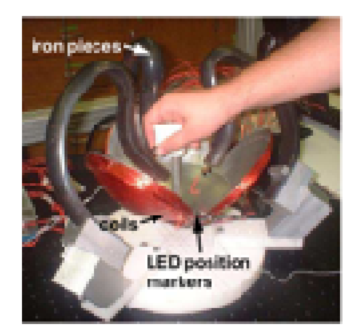
5 DoF, Parallel, Metal

6 DoF, Serial & Parallel, Metal

6 DoF, Parallel, Metal



2 DoF, Parallel, 3D printed plastic



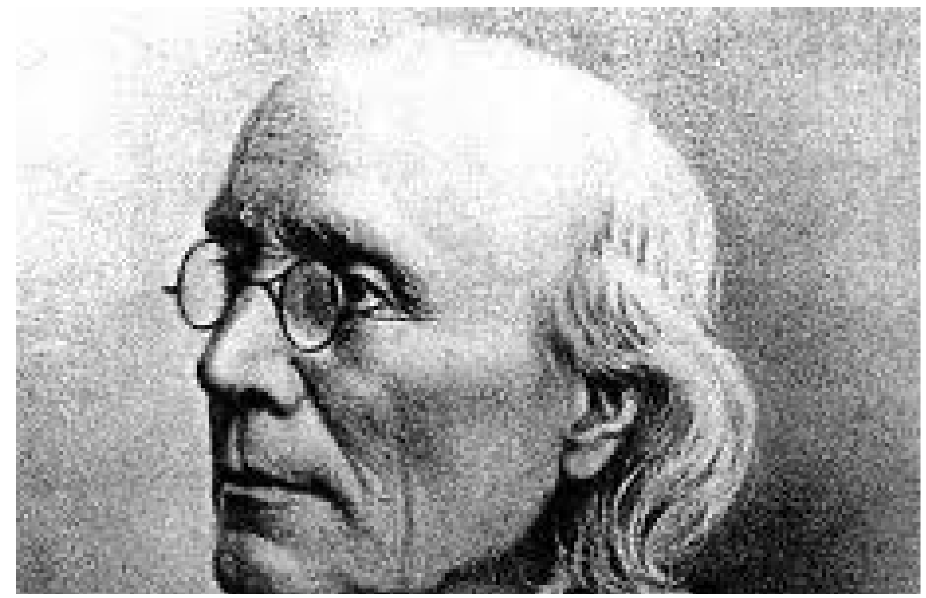
6 DoF, No Links, Magnets, Metal

Perception studies

To study human touch perception, researchers rely on a set of established procedures that are known as psychophysical methods.

The origins of Psychophysics

1830: Ernst *Weber: First experiments on touch and light*



1860: Gustav fechner: *Elements of psychophysics*

Quantitative investigation of the mechanisms that detect and process information in the nervous system

Weber law

$$dp = k\frac{dS}{S}$$

dp = différence de sensation
dS = différence de stimulus
S = valeur de référence du stimulus
k = constante de Weber

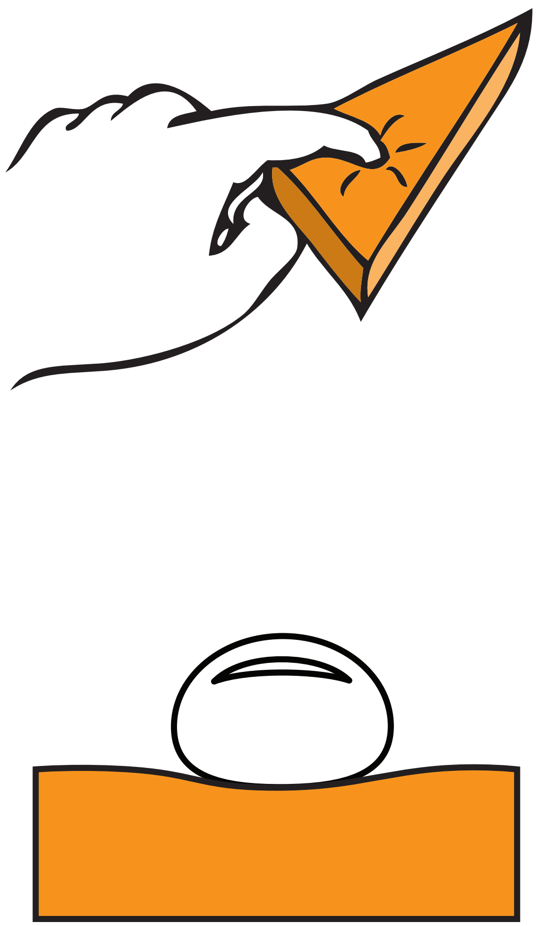
Example

An item weights 100 grams, item B weights 105 grams
An item C weights 200 grams, item D weights 210 grams

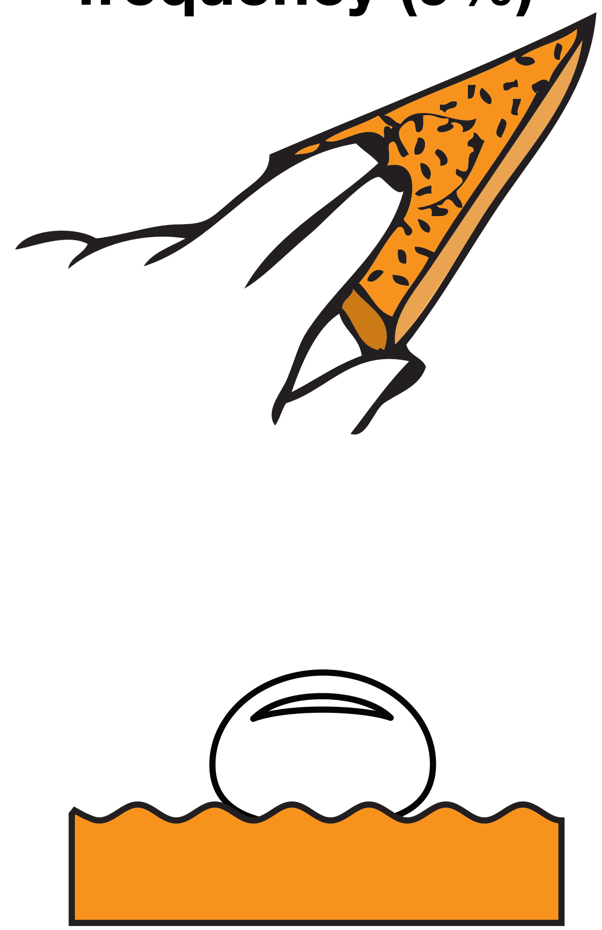
Same perceived difference of sensation, dp

A few Weber fractions

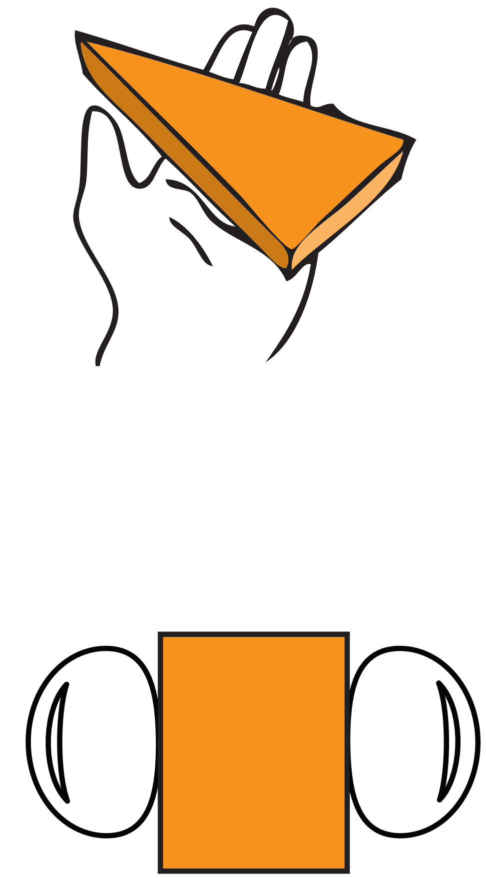
Elasticity (23%)



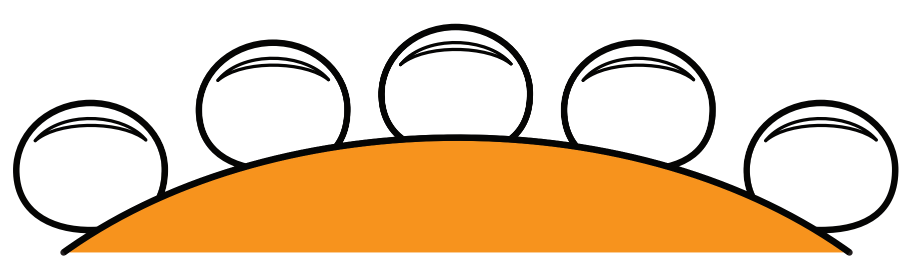
Roughness:
amplitude (15%)
frequency (9%)



weight (7/9%)



Curvature
(10%)



Human haptic sensing and output

Table 3.2 Sensory thresholds of human hand. Unless otherwise stated, the values are for the index fingertip

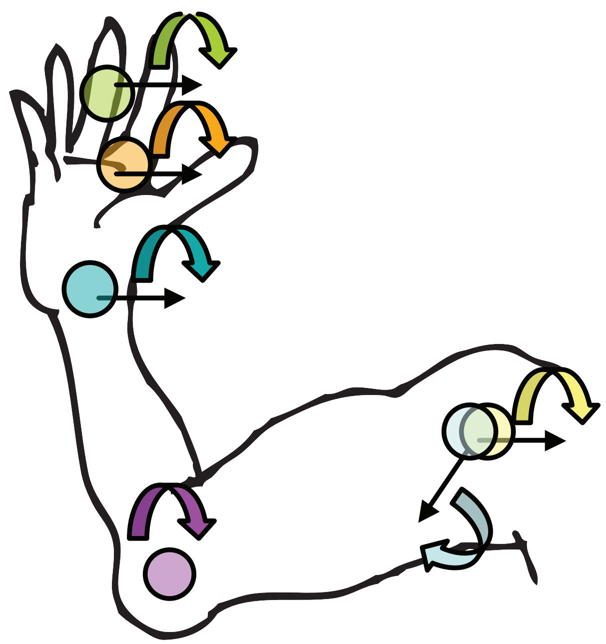
Parameter		Value	Notes
Force	Absolute	0.06 N	
	Differential	7 %	Over a range of 2.5–10 N
		7 %	Elbow muscle. Over a range of 25–400 N
		15–27 %	For forces less than 0.5 N
Pressure	Absolute	0.019 g	Women
		0.055 g	Men
Friction	Accurately scaled	0.43–2.79	Range of friction coefficient
Shear	Accurately scaled	0.15–0.70 N	
Vibration	Intensity (differential)	25 %	Over a range of 10–20 dB sensation level
	Temporal (absolute)	const 28 dB	For 0.4–3 Hz with 1 μm peak
		−5 dB/dec	For 3–30 Hz
		−10 dB/dec	For 30–250 Hz
		+10 dB/dec	For 250–700 Hz
Spatial resolution		1.2 mm	Discrimination of grating orientation
		0.6 mm	Detection of grating
Temporal resolution		5 ms	Successiveness of mechanical pulses

Table 3.4 Output capabilities of human

Parameter		Value	Notes	Reference
Force	Maximum	50/60 N	Finger/wrist	[64]
		100 N	Elbow & shoulder	
	Control	11–15 %		[61]
		1 %	Over 10 to 20 N	[64]
		1 %	Wrist, elbow & shoulder Over 20 to 50 N	
		10 %	Over 5 to 18 N	[47]
	Bandwidth	2–3 Hz		[55]
		5 Hz		[3]
		2–6 Hz		[26, 27]
Motion	Maximum speed	17.6 rad/s		[17]
	Bandwidth	<2 Hz	Active touch for sensing	[36]
		2–4 Hz	Voluntary movements	[44, 51]
		2–7 Hz	Periodic tracking	[5]
		4–8 Hz	Skilled actions: hand writing, typing, tapping, playing musical instruments	[26, 36]
		10 Hz	Reflexive actions	[3, 4]
		<10 Hz		[72]
		8–12 Hz	Finger tremor	[57]

Samur, 2012

Proprioception



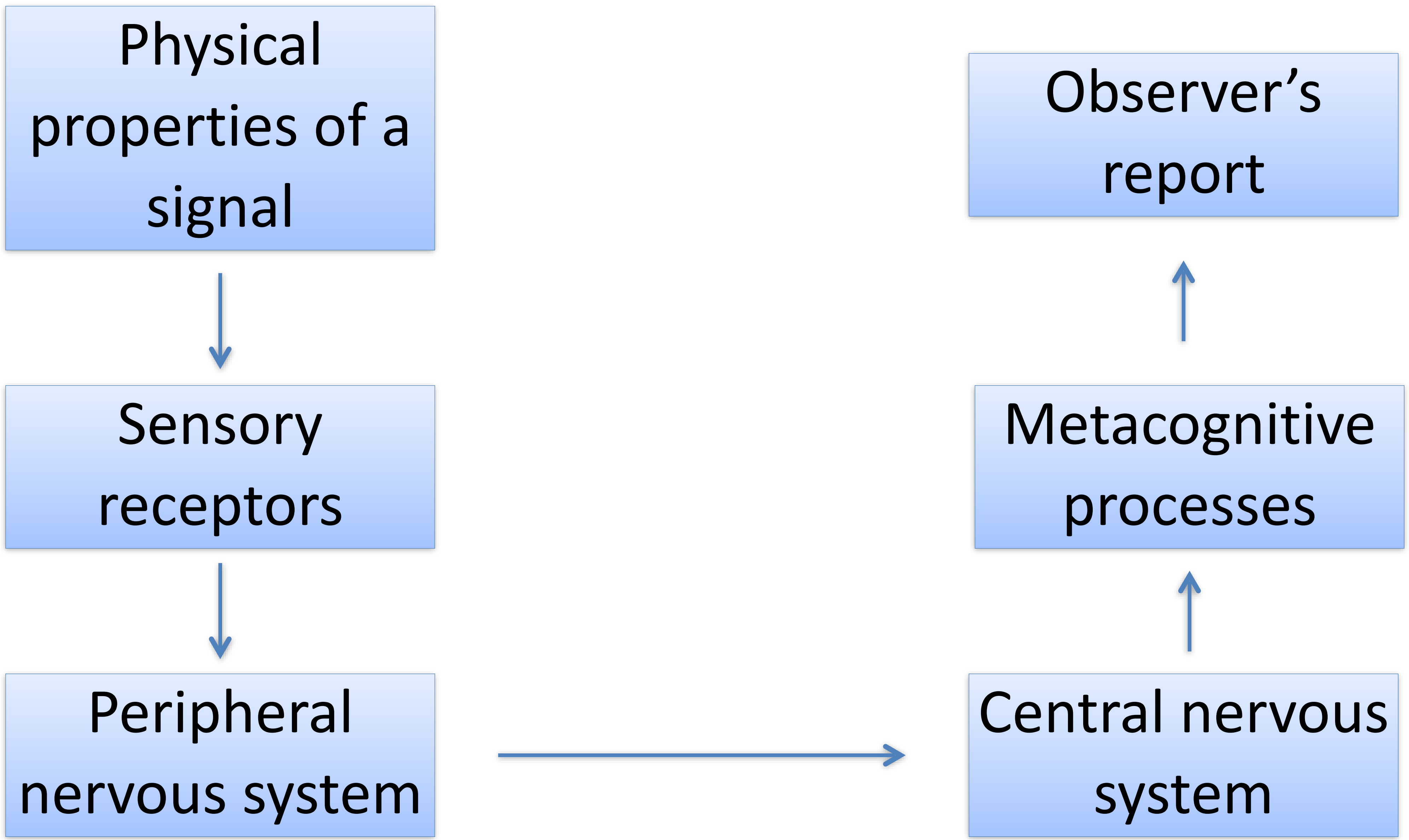
H. Z. Tan, M. A. Srinivasan, B. Eberman, and B. Cheng, "Human factors for the design of force-reflecting haptic interfaces." In Proceedings of the Third International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, American Society of Mechanical Engineers Dynamic Systems and Control Division, 55(1):353-359, 1994.

*L. A. Jones, "Kinesthetic Sensing", unpublished, 2000.

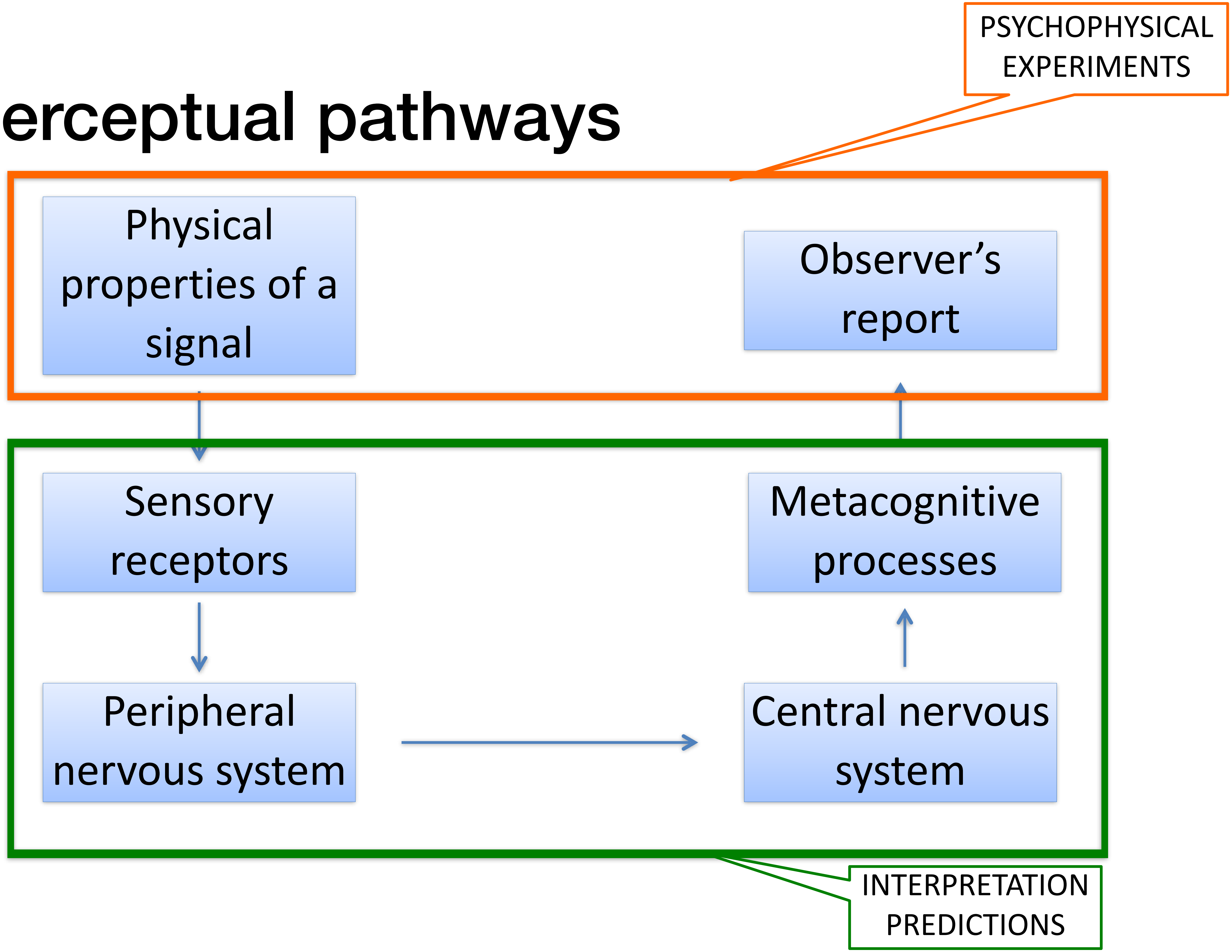
Articulations

● (vert)	Proximal-InterPhalangeal (PIP) Joint	~2.5°/*6.8°
● (orange)	MetaCarpalPhalangeal (MCP) Joint	~2.5°/*4.4°
● (turquoise)	Poignet	2.0°
● (violet)	Coude	2.0°
● (jaune)	Epaule (avant)	0.8°
● (bleu clair)	Epaule (coté)	0.8°

Perceptual pathways



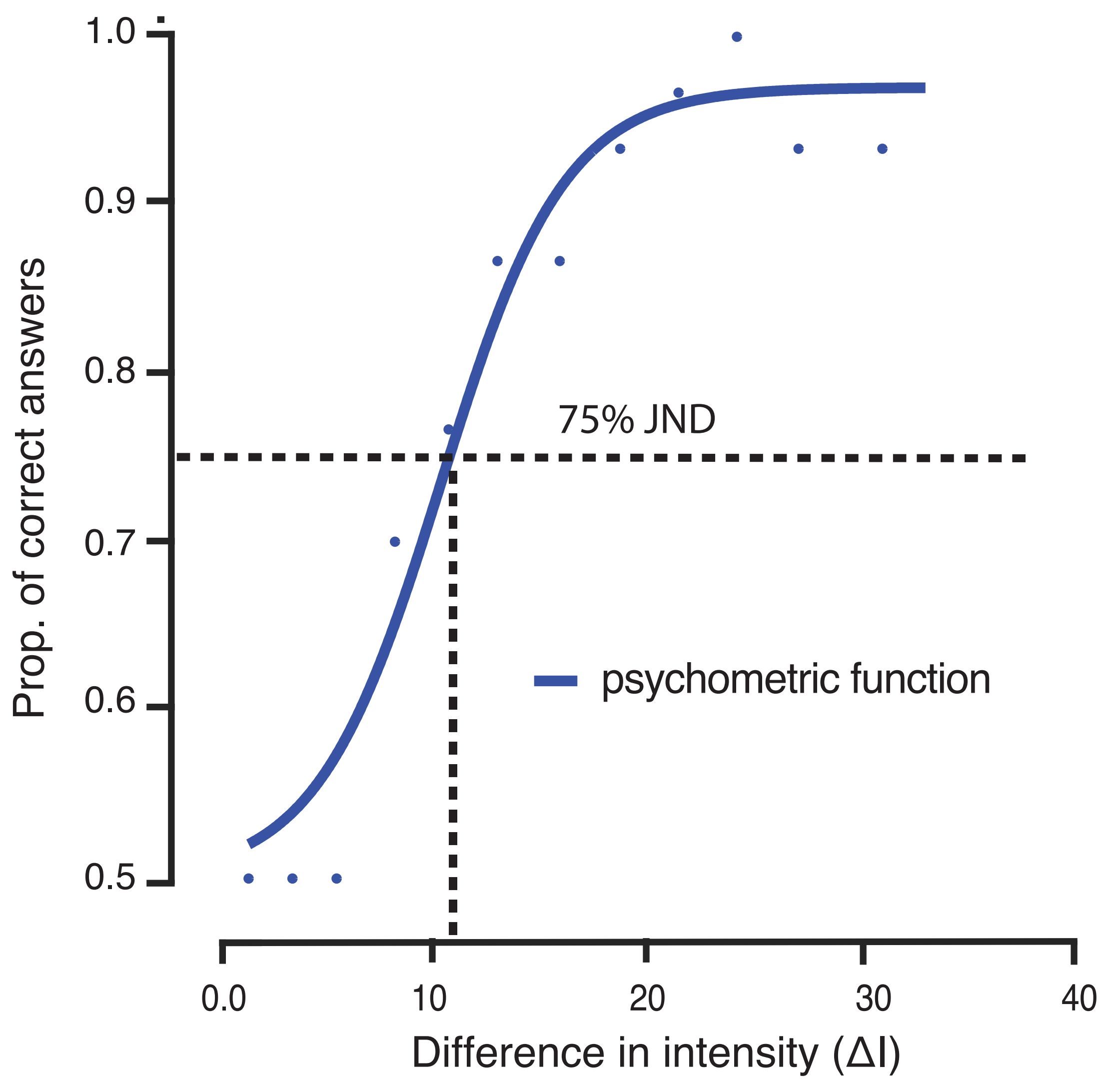
Perceptual pathways



Psychometric function

The probability for humans to detect differences within a given feature of a physical stimulus, e.g. force, stiffness, weight etc.

Here, the difference that is perceived 75% of the time is around 75%



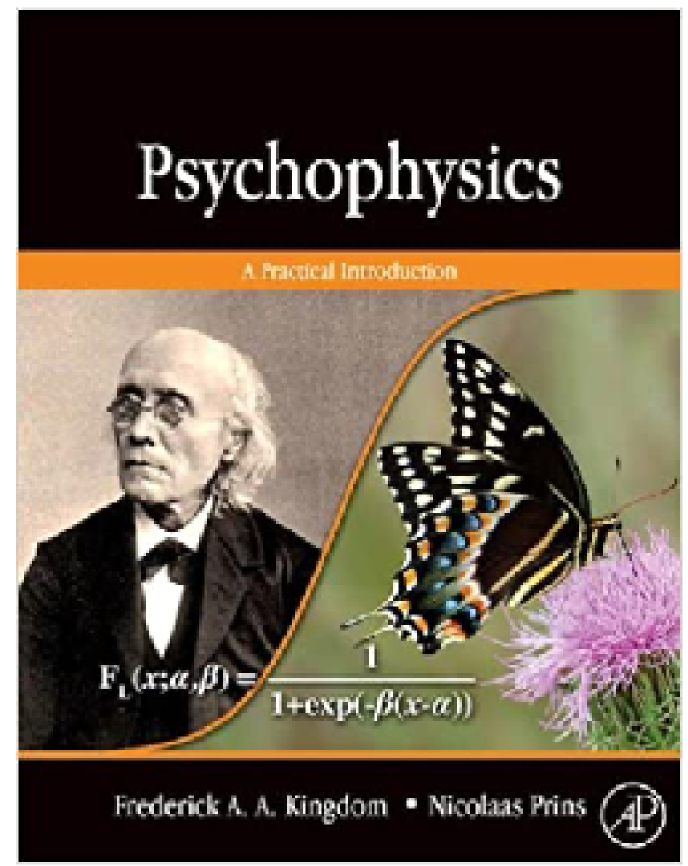
Just noticeable difference = sensory threshold (ex: 75% JND)

-> the difference between the changed stimulus and the reference is perceived 75% of the time.

References for choosing and experimental method

Application of Psychophysical
Techniques to Haptic Research

Jones and Tan, 2013



Kingdom and Prins,
several editions

Three classical psychophysical procedures

Three classical methods (among many others)

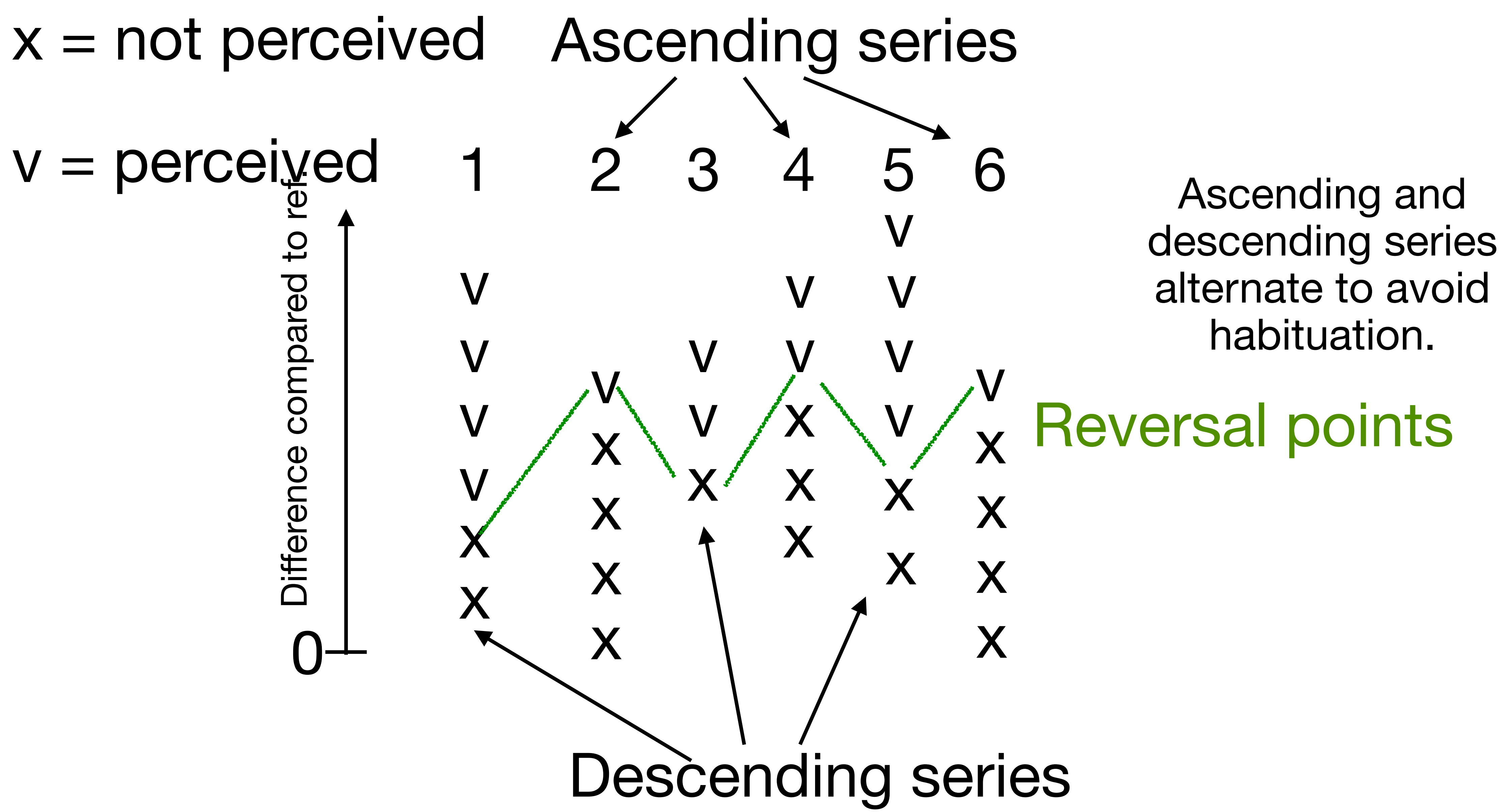
- Method of the limits - fast but prone to bias
- Constant stimuli - robust but time-consuming
- Adaptive method - Optimized for JND tracking

Method of the limits

- Increasing series
  - The stimulus is increased until detection
- decreasing series
  - The stimulus is decreased until unnoticed
- At least 4 series

The sensory threshold is estimated as the average of the reversal points

The method of limits in practice



Method of the limits:

In practice, the method of the limits is often used to obtain a quick first estimate of the sensory threshold. This first estimate is then used to calibrate a more thorough method, usually a constant stimuli or adaptive.

212 IEEE TRANSACTIONS ON HAPTICS, VOL. 2, NO. 4, OCTOBER-DECEMBER 2009

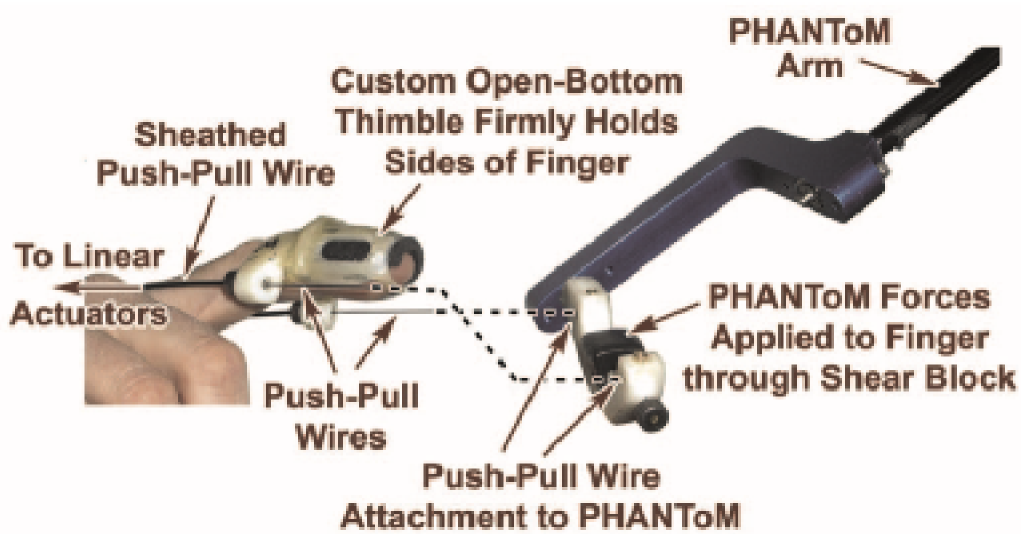
Fingerpad Skin Stretch Increases the Perception of Virtual Friction

William R. Provancher, *Member, IEEE*, and Nicholas D. Sylvester

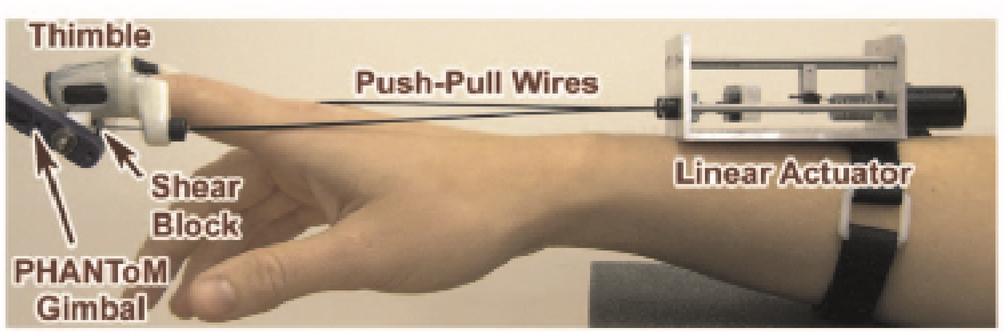
Abstract—This research focuses on the relative importance of fingerpad skin stretch on the perception of friction. It is hypothesized that the perceived magnitude of friction rendered by traditional force feedback can be increased through the addition of fingertip skin stretch. Perceptual data are presented from two separate tests performed on nine male subjects. The first experiment determines the perceptual thresholds for friction based on a modified Karnopp friction model where friction is rendered as purely a kinesthetic resistance via a PHANToM force feedback device. JNDs of 0.056-0.150 corresponding to static coefficients for friction of $\mu_s = 0.2$-0.8 were established. The second experiment evaluates possible changes in the perceived friction magnitude due to imposing small amounts of tangential skin stretch (0.25-0.75 mm) to the fingerpad in combination with force feedback (kinesthetic resistance). Our results show that even these small amounts of skin stretch lead to a statistically significant increase in perceived friction ($p < 0.01$). This significant finding will enable the hapticians to more realistically and accurately render friction via a combination of kinesthetic resistance and tactile feedback.

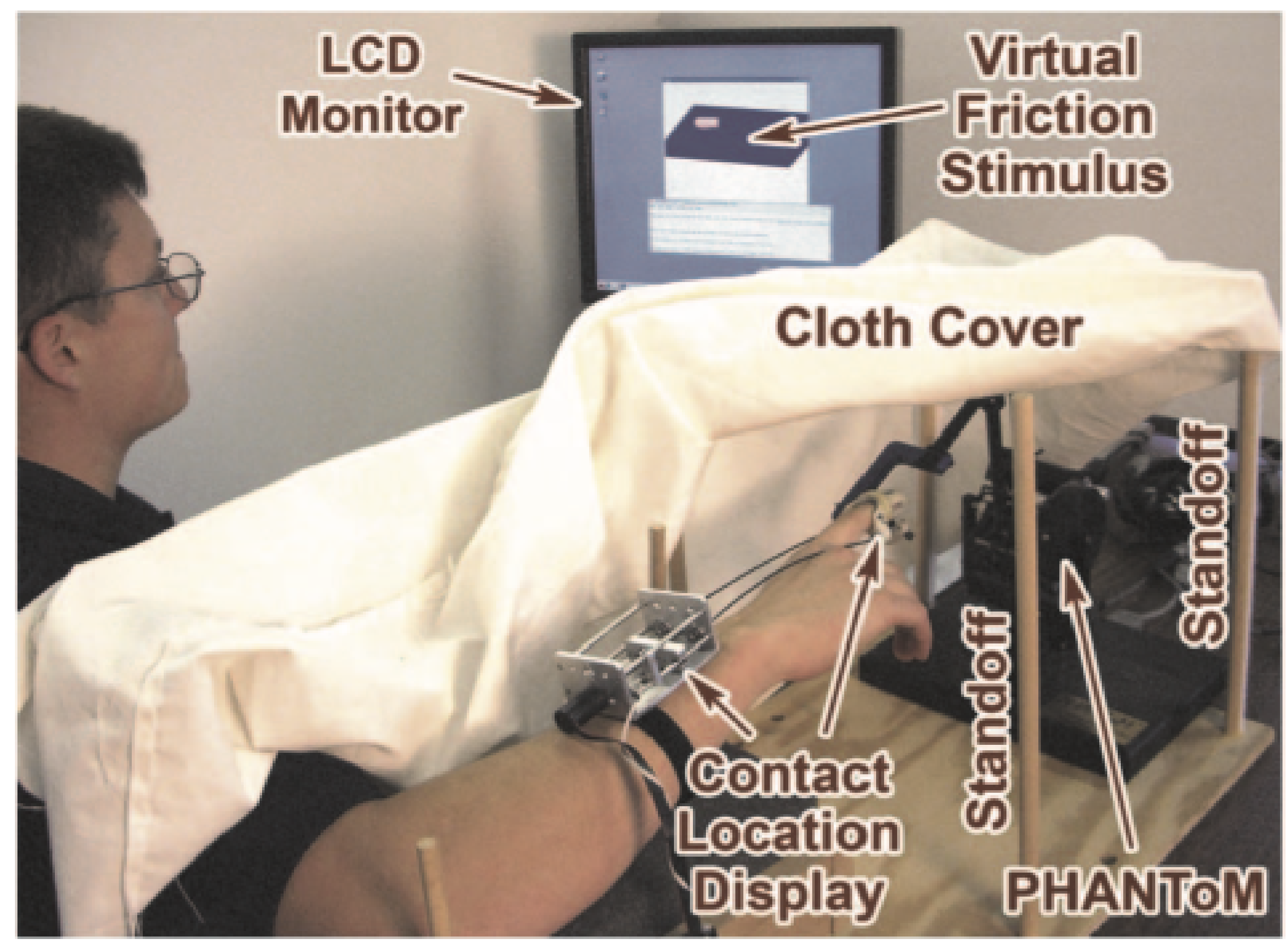
Index Terms—Tactile display, perception and psychophysics, haptic rendering, friction, skin stretch.

Experimental setup and GFF-device:



(a)





Constant stimuli method

Random presentation of a pre-defined set of stimuli based on:

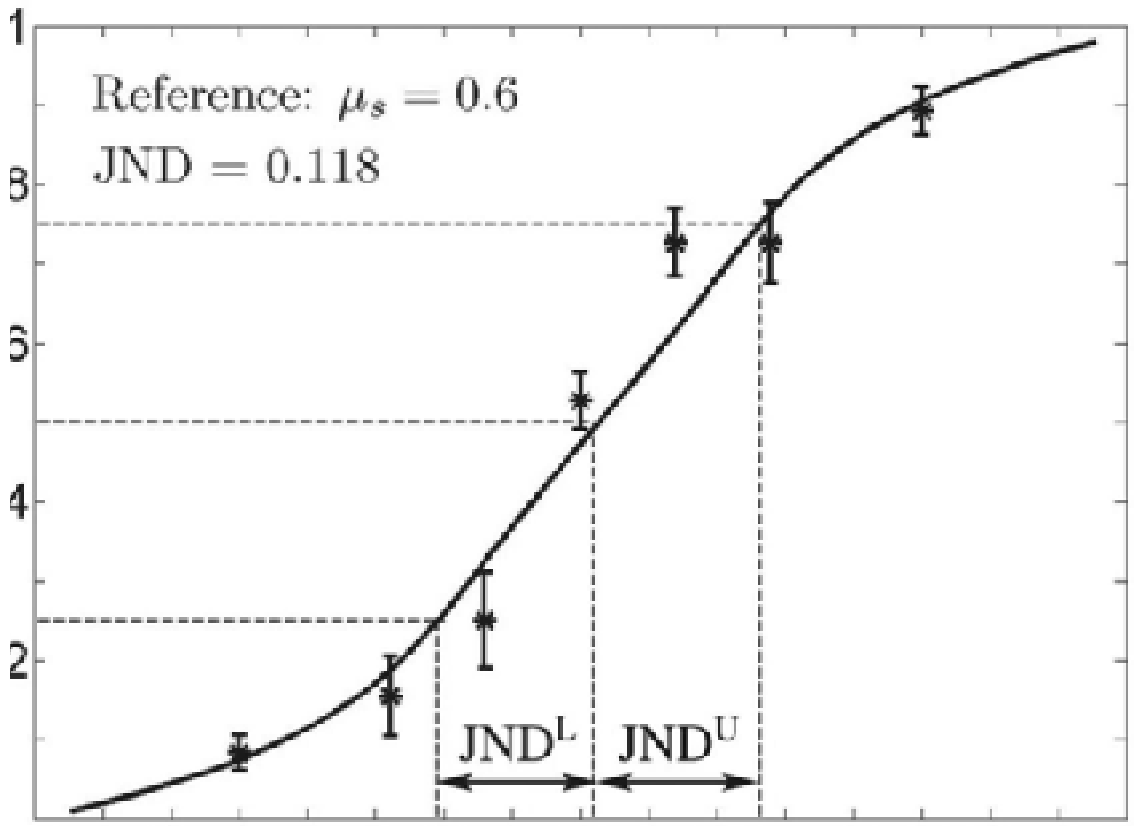
- A pre-defined set of stimuli
- Prior estimate of the sensory threshold
- Proportion of correct answers for each comparison with the reference
- Large number of repetitions per comparison (min. 10)

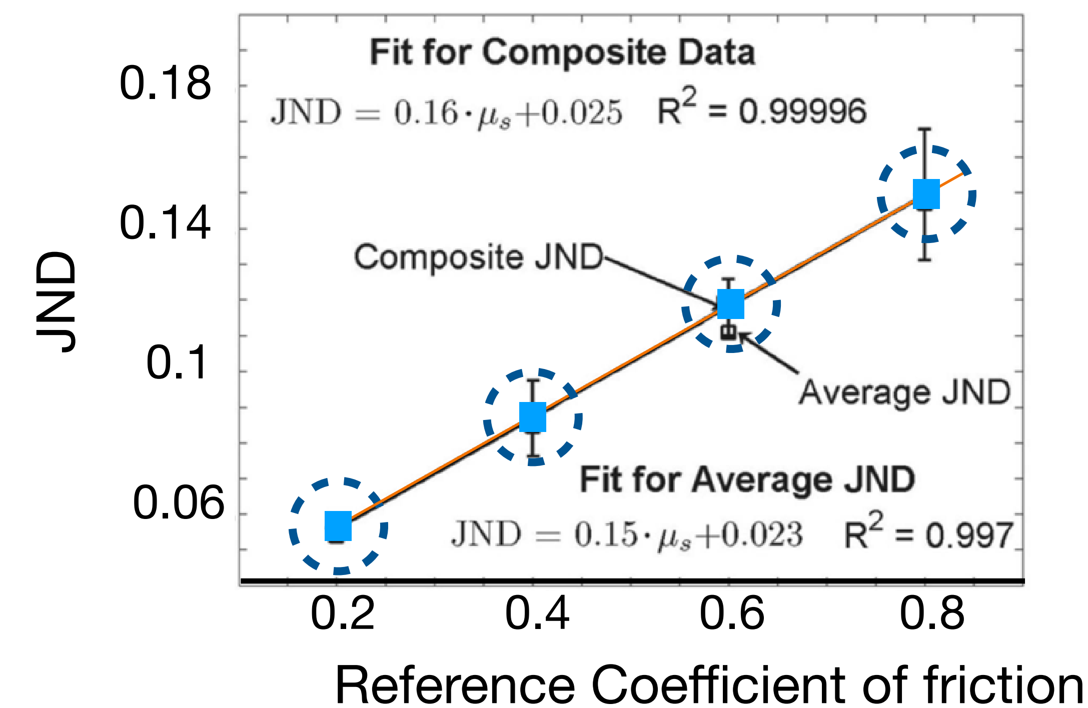
Constant stimulus in our example

TABLE 1
Experiment 1 Comparison Stimuli for Friction Levels, $\mu_s = 0.2, 0.4, 0.6, 0.8$

Reference Friction	Comparison Stimuli (μ_s)					
$\mu_s = 0.2$	0.02	0.08	0.14	0.26	0.32	0.38
$\mu_s = 0.4$	0.20	0.27	0.33	0.47	0.53	0.60
$\mu_s = 0.6$	0.35	0.46	0.53	0.67	0.74	0.85
$\mu_s = 0.8$	0.49	0.65	0.72	0.88	0.95	1.11

Results





Estimation of the probability to detect correctly the greater friction -> psychometric curve

Scientific example of an constant method

With the same method, many key parameters for GFF devices were estimated such as the minimum force resolution

Perception & Psychophysics
1991, 49 (6), 531-540

Manual discrimination of force using active finger motion

X. D. PANG, H. Z. TAN, and N. I. DURLACH
Massachusetts Institute of Technology, Cambridge, Massachusetts

In these experiments, two plates were grasped between the thumb and forefinger and squeezed together along a linear track. An electromechanical system presented a constant resistance force during the squeeze up to a predetermined location on the track, whereupon the force effectively went to infinity (simulating a wall) or to zero (simulating a cliff). The task of the subject was to discriminate between two alternative levels of the constant resistance force (a reference level and a reference-plus-increment level). Results of these experiments indicate a just noticeable difference of roughly 7% of the reference force using a one-interval paradigm with trial-by-trial feedback over the ranges $2.5 \leq F_o \leq 10.0$ newtons, $5 \leq D \leq 30$ mm, $45 \leq S \leq 125$ mm, and $25 \leq V \leq 160$ mm/sec, where F_o is the reference force, D is the distance squeezed, S is the initial finger-span, and V is the mean velocity of the squeeze. These results, based on tests with 5 subjects, are consistent with a wide range of previous results, some of which are associated with other body surfaces and muscle systems and many of which were obtained with different psychophysical methods.

Example for the 7% force detection

Adaptive methods

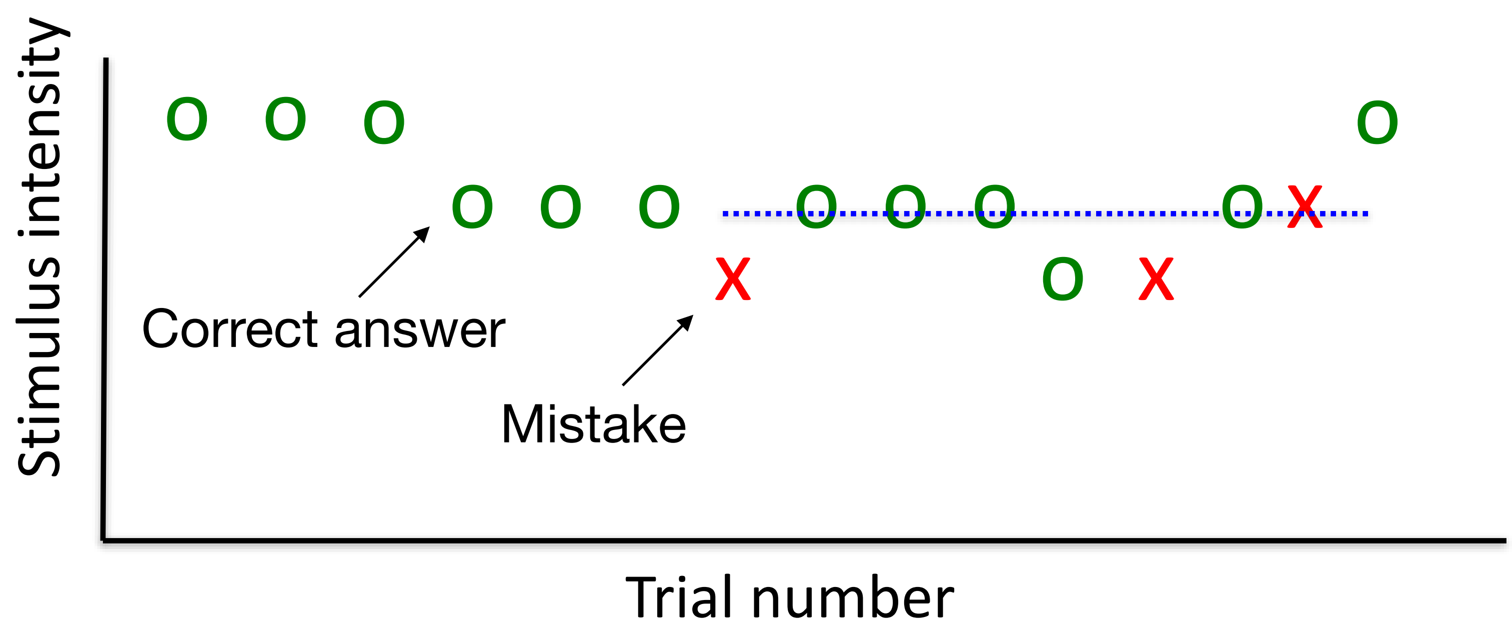
The intensity of the stimulus is changed by succesive steps depending on the previous trials in order to decrease the length of the experiment and participant’s fatigue.

Simple adaptive methods

Staircase methods that are converging toward a specific JND, which is not always 75%!.

Many examples such as Levitt one-up three-down staircase (Levitt 1971).

The difference between the reference and the comparison stimulus is increased by a predefined step after each mistake (x) and decreased after three consecutive correct answers (o). The step is commonly reduced after the first mistake in order to fine tune the sensory threshold estmation.



79,4% JND

The threshold is usually estimated by taking the mean of the ‘peaks'and 'valleys' that occur after the first mistake.

Levitt HC. Transformed up-down methods in psychoacoustics. The Journal of the Acoustical society of America. 1971 Feb;49(2B):467-77.

Drawbacks of the staircase method:

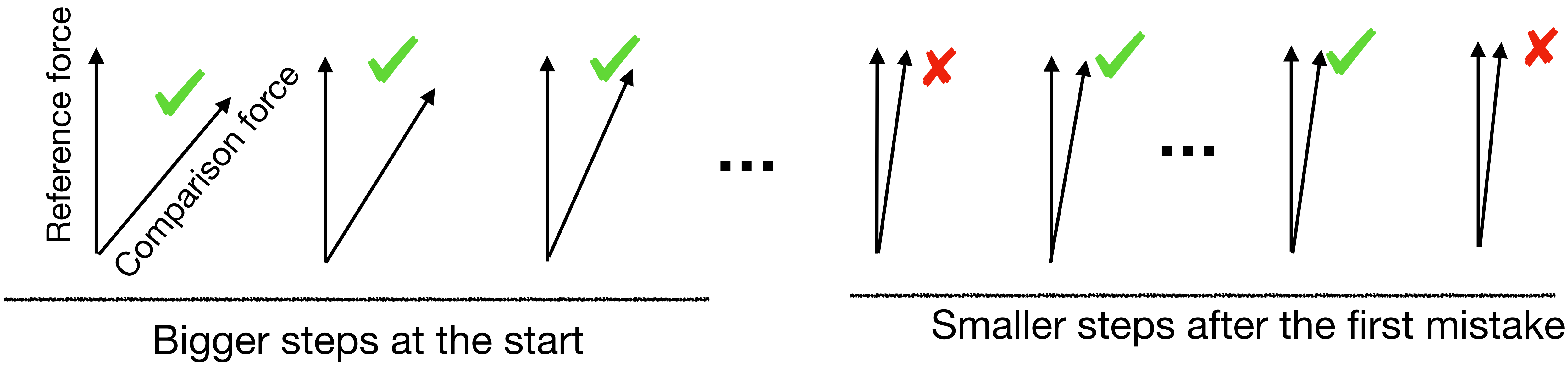
- No estimation of the full psychometric function
- Not always possible to have a constant step
- Participant can guess the staircase logic or exceed its boundaries.

Haptic Discrimination of Force Direction and the Influence of Visual Information

FEDERICO BARBAGLI and KEN SALISBURY
Stanford University
CRISTY HO and CHARLES SPENCE
Oxford University
and
HONG Z. TAN
Purdue University

Example of adaptive method

Task: discrimination of the force direction



If the step size difference is not clear enough during the animation, you can make it bigger

Two references and one comparison stimulus were displayed in each trial. Participants had to report which stimulus was different from the other two.

Others: Adjustment method

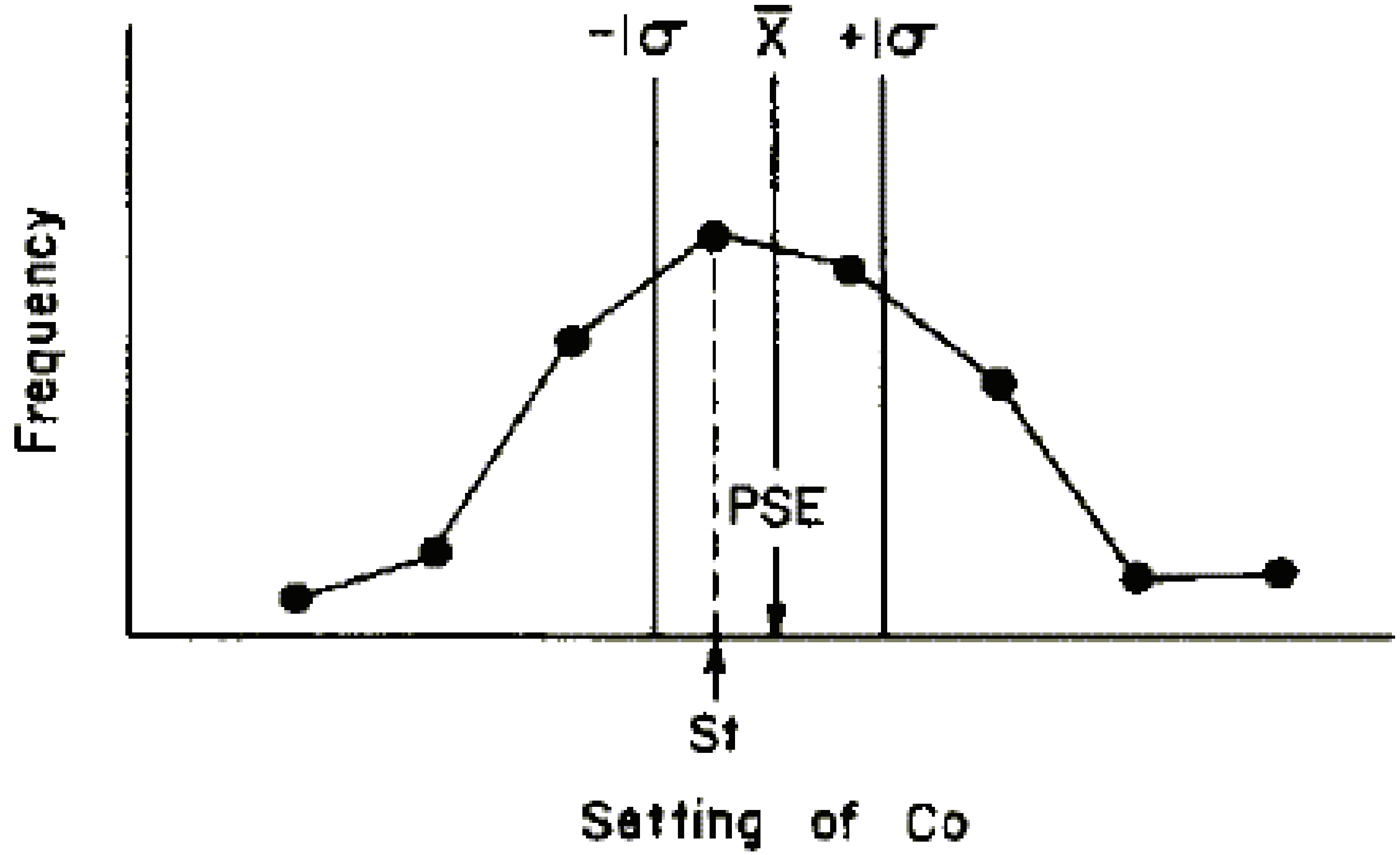


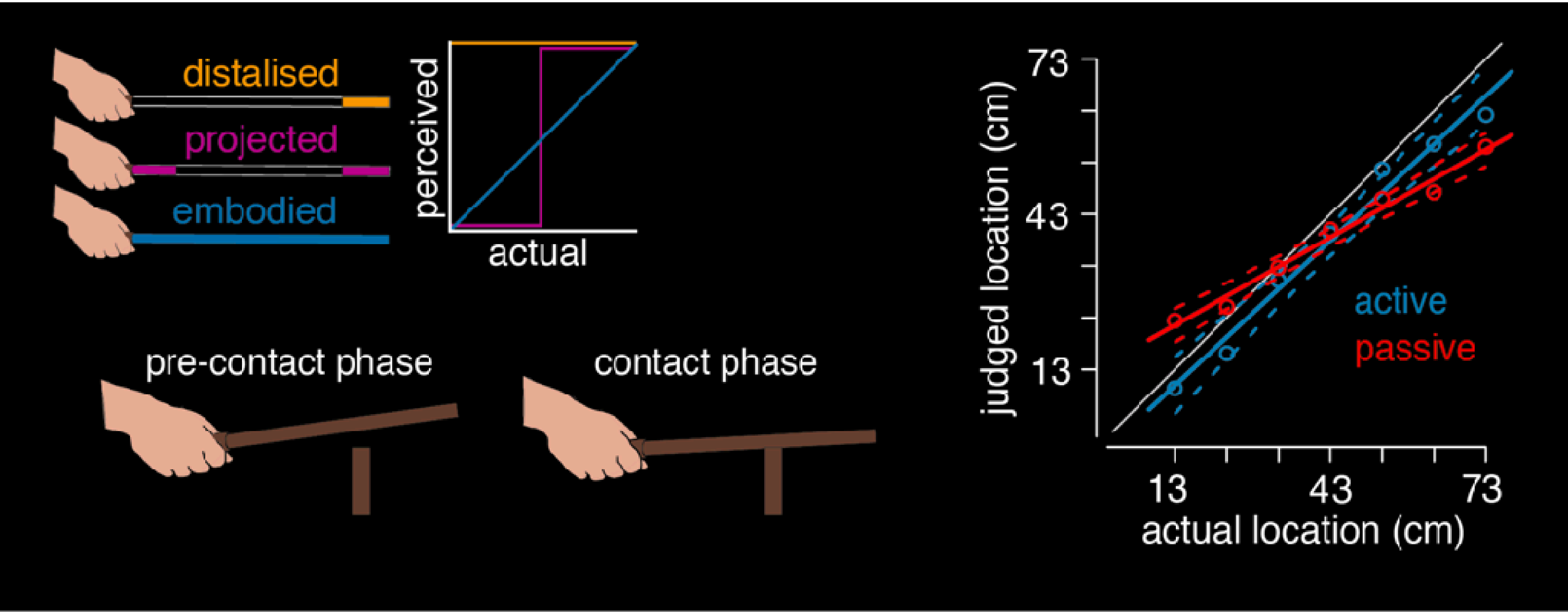
FIG. 2.8. Frequency distribution of setting of the comparison stimulus when the method of adjustment is used to measure the difference threshold. The mean of the distribution is the point of subjective equality, and the standard deviation is used as the difference threshold.

Designing haptic technology and sensations that meet human haptic sensing and output thresholds is extremely challenging.

Moreover, our haptic perception is influenced by the presence of stimuli from other senses or perceptual illusions.

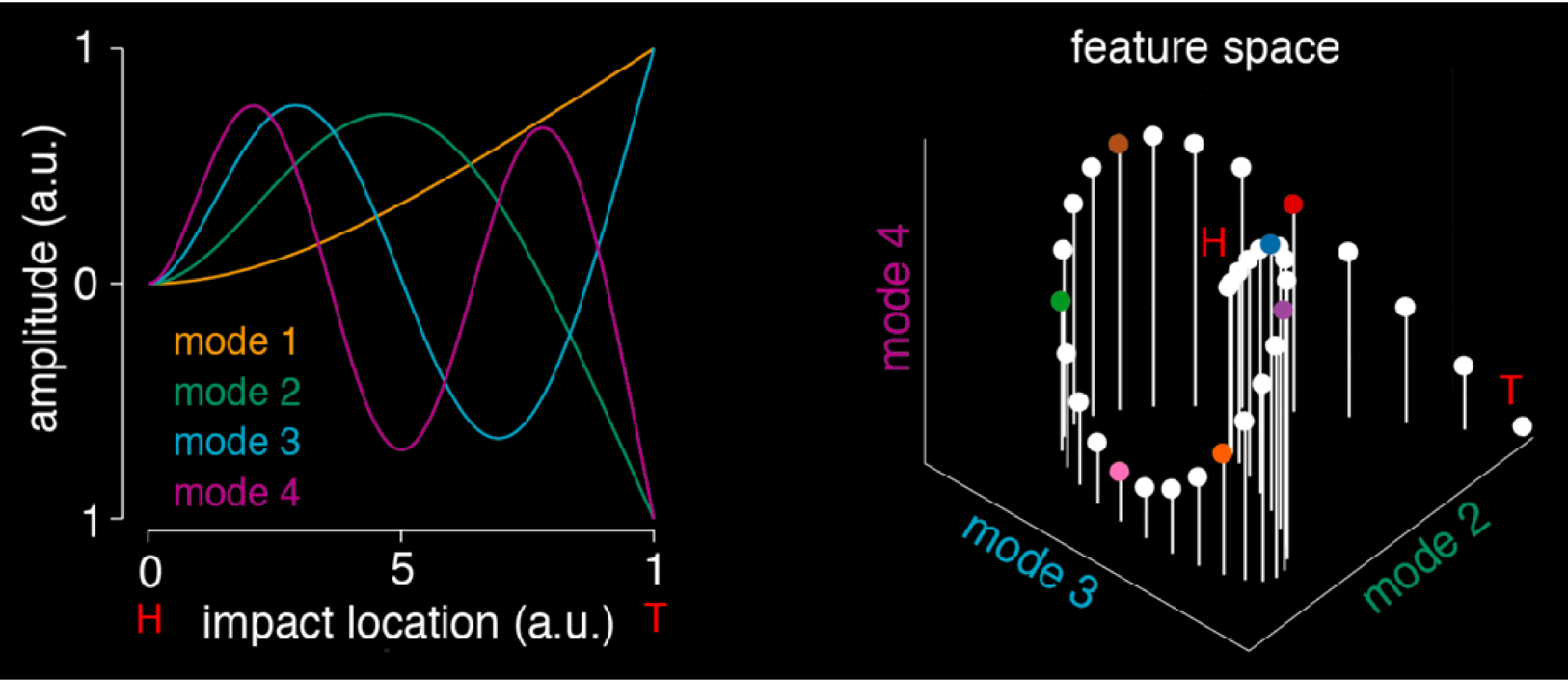
Tactile sensitivity

Sensing contact location through the vibration modes



Tactile sensitivity

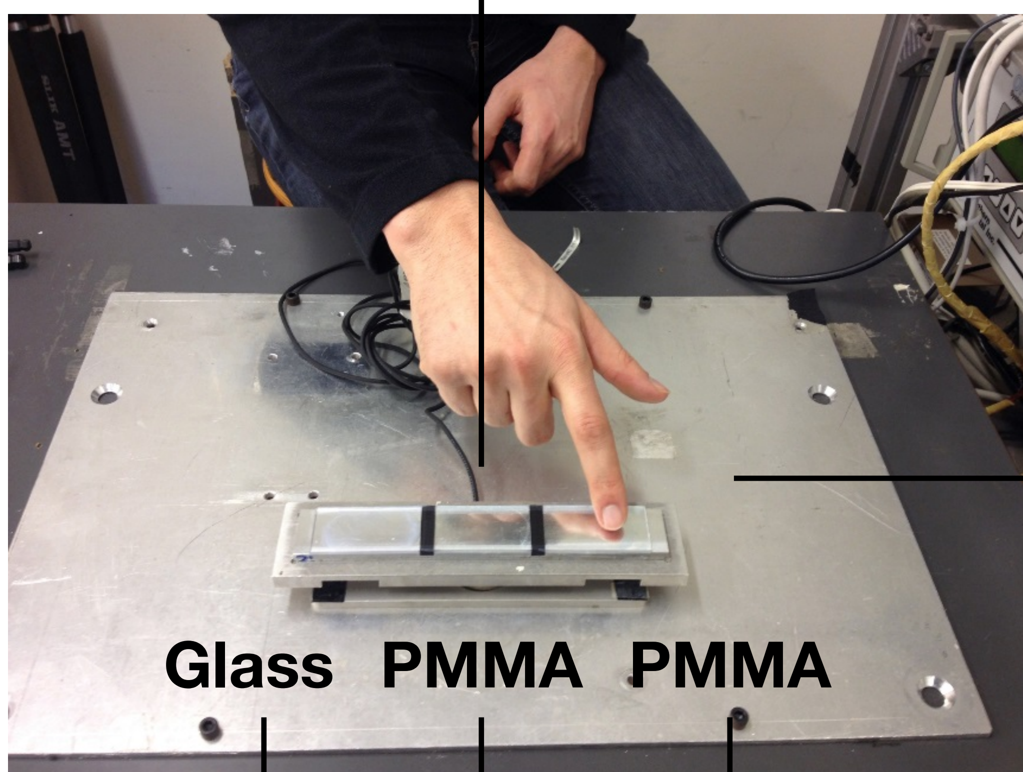
Sensing contact location through the vibration modes



Tactile sensitivity to molecular properties

The tactile perception of materials with identical topography and coefficient of dynamic friction but different molecular properties

Surface topography was identical

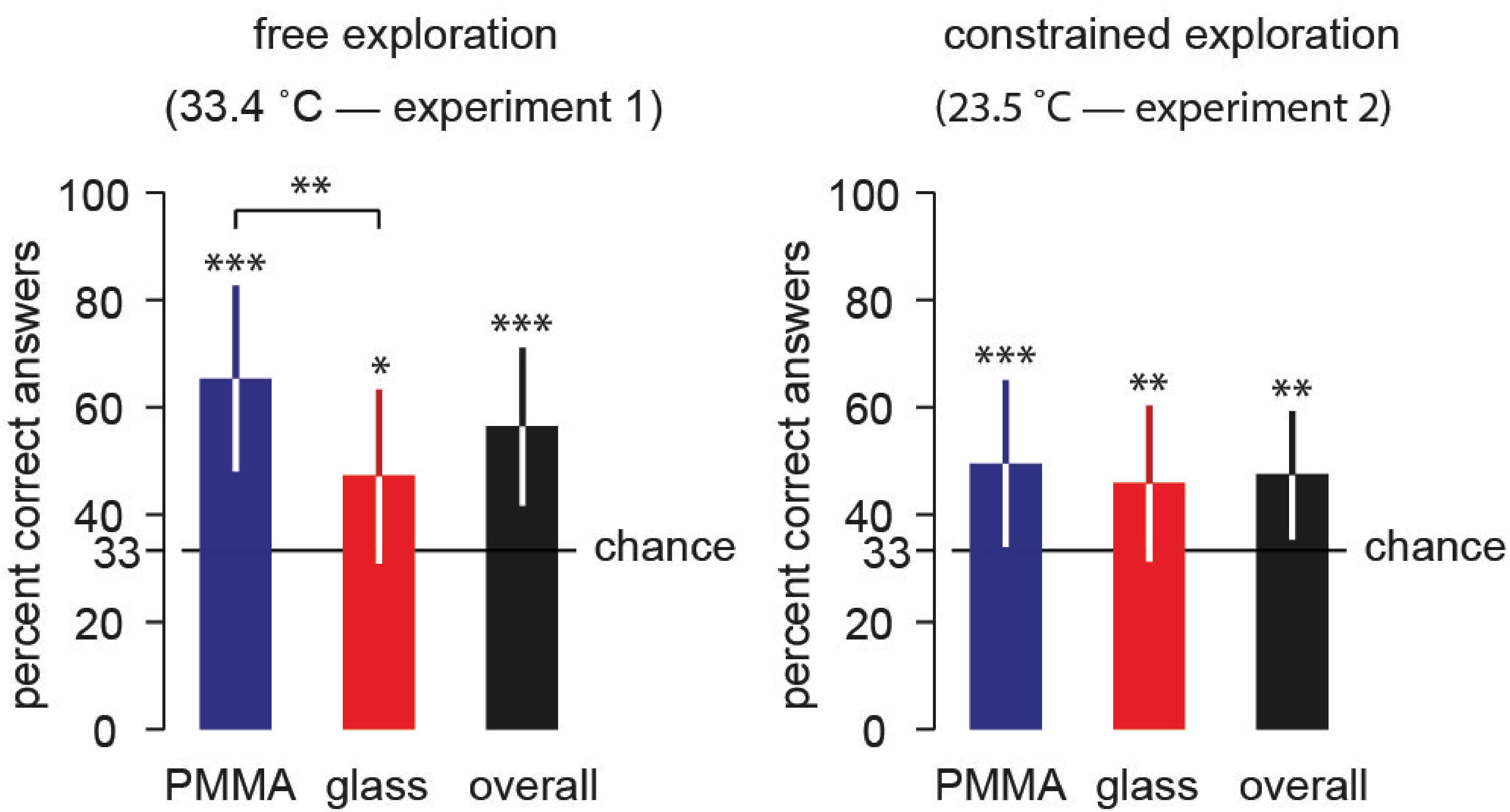


Heat sink to equalize temperature

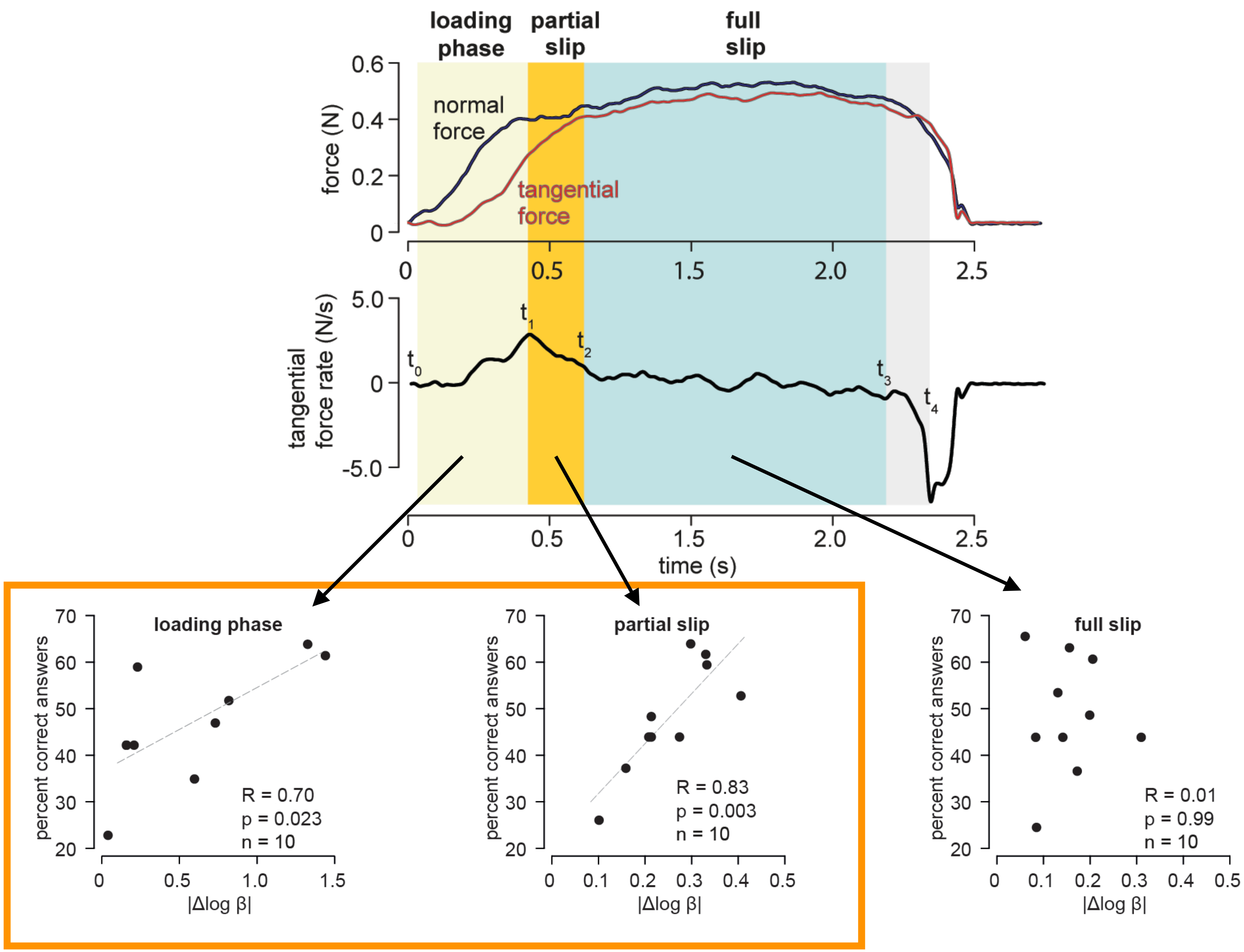
Hydrophobic

Hydrophilic

Tactile sensitivity to molecular properties



Tactile sensitivity to molecular properties

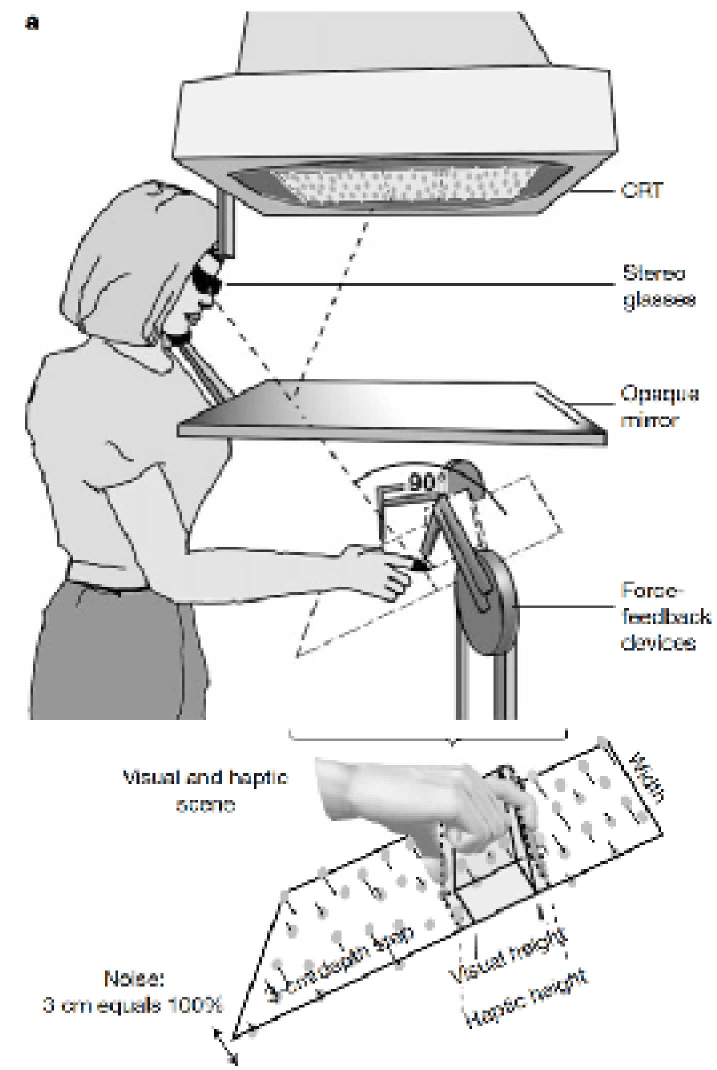


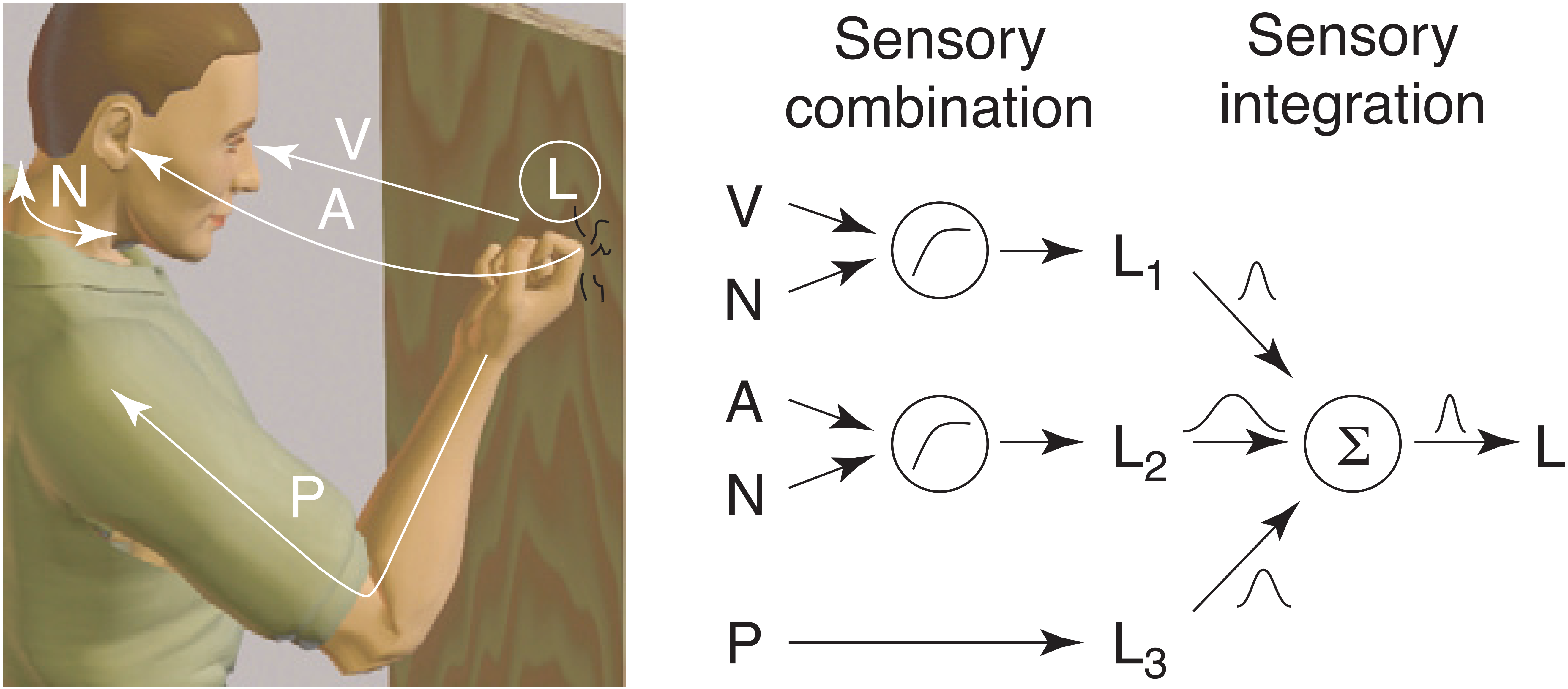
Multisensory perception

Ernst and Banks showed that we integrate information from visual and haptic in a manner that is optimal for reducing perceptual noise.

When the visual channel is noisy, humans rely on haptic information for size estimation and vice versa.

So if the haptic device is not perfect according to our sensing thresholds, vision can become the dominant source of perceptual information.




V
N
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Sensory combination
Sensory integration
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L_1
L_2
L_3
Σ
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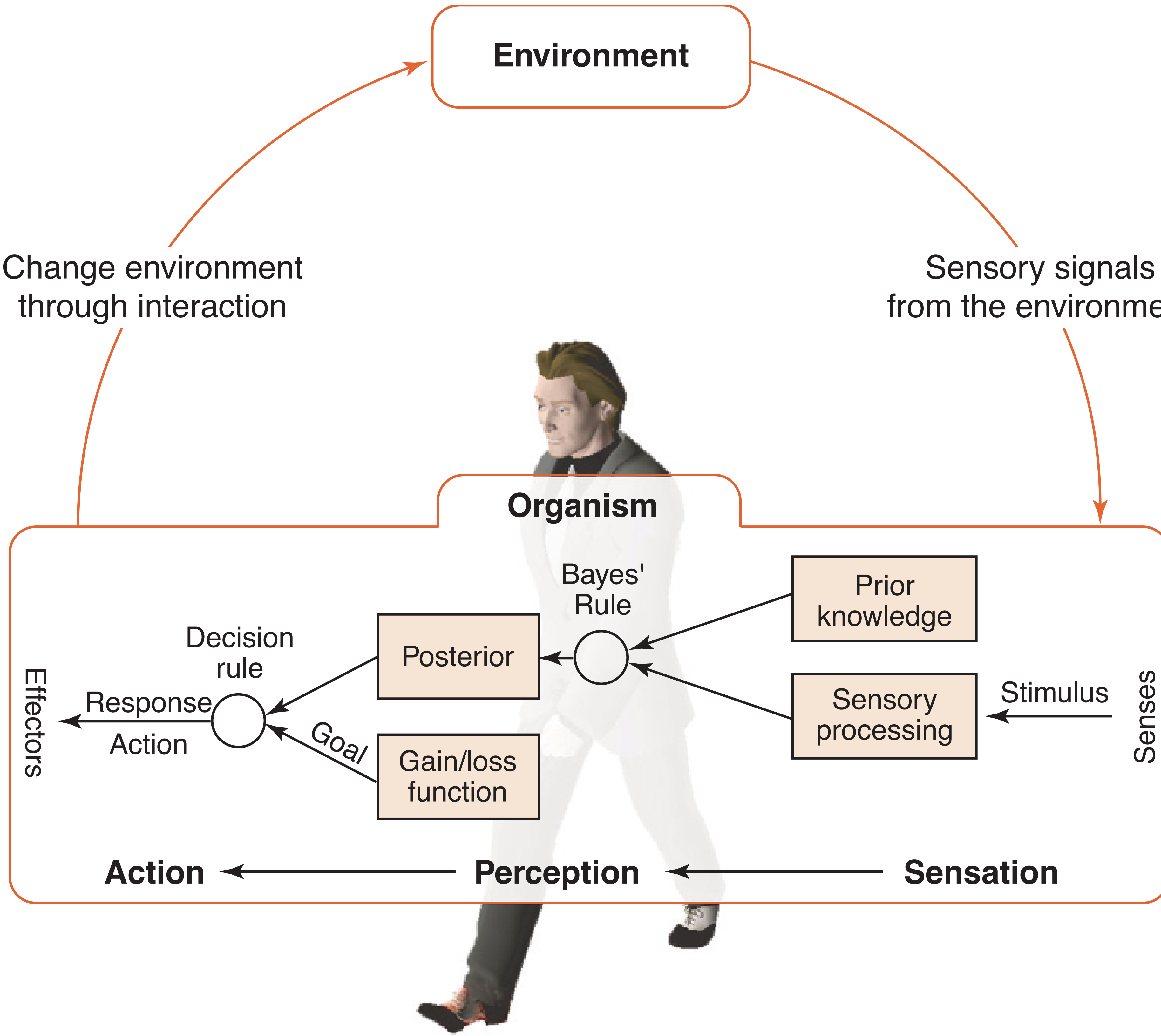


Marc O. Ernst and Heinrich H. Bulthoff. Merging the senses into a robust percept. TRENDS in Cognitive Sciences. Vol.8 No.4 April 2004

Three Approaches to Creating Haptic Content

1. Model-based Rendering

Uses physical and mathematical models of real-world object interaction.

2. Data-driven Rendering:

Captures data from real-world interactions, and recreates similar data while interacting in a virtual world.

3. Rendering Predesigned Sensations

Replays (typically) hand-tuned signals when an event occurs.

3. Rendering Pre-designed Sensations (Haptic Icons)

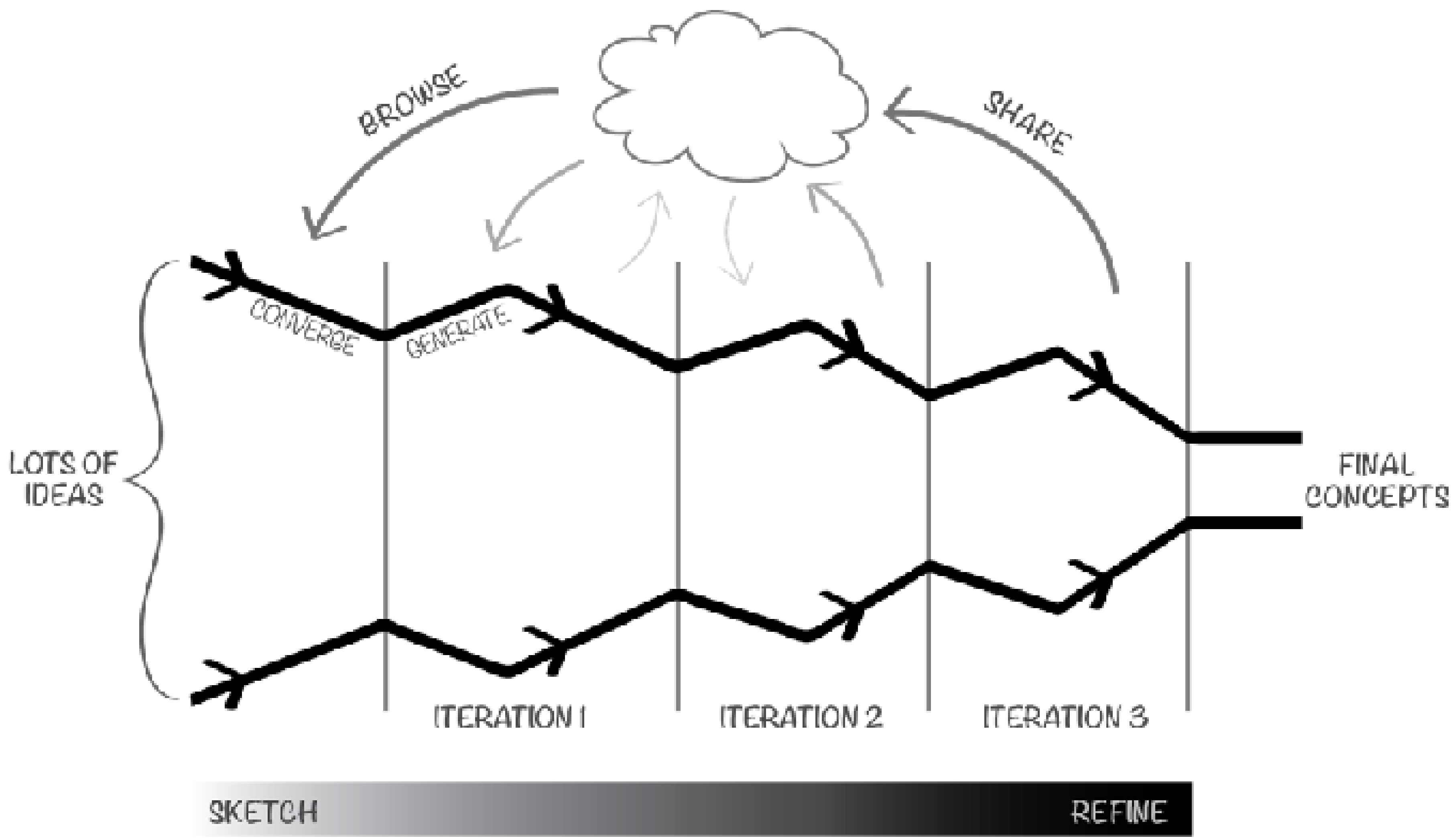
Very common approach for vibrotactile technology

Android Effect Preview App

The haptic content is created in an iterative process that considers the application goals and other modalities.

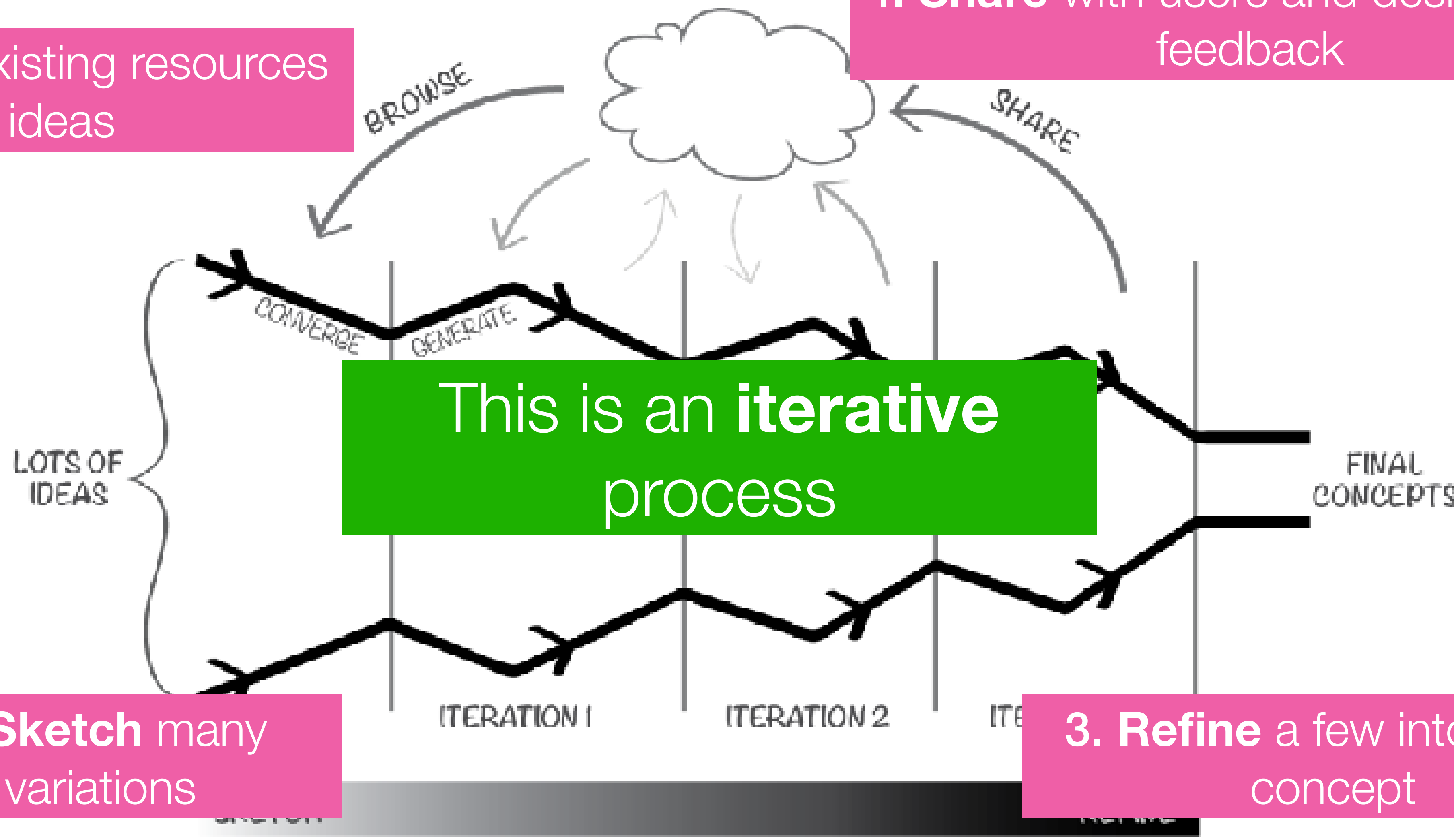
This practice is known as **haptic interaction design or HaxD** as coined by Schneider and MacLean in 2017.

HaxD is a subfield of interaction design.



From MacLean et al. 2015,
Design process defined by Bill Buxton

Four important components of any design process



1. Browse existing resources for ideas

2. Sketch many variations

3. Refine a few into a final concept

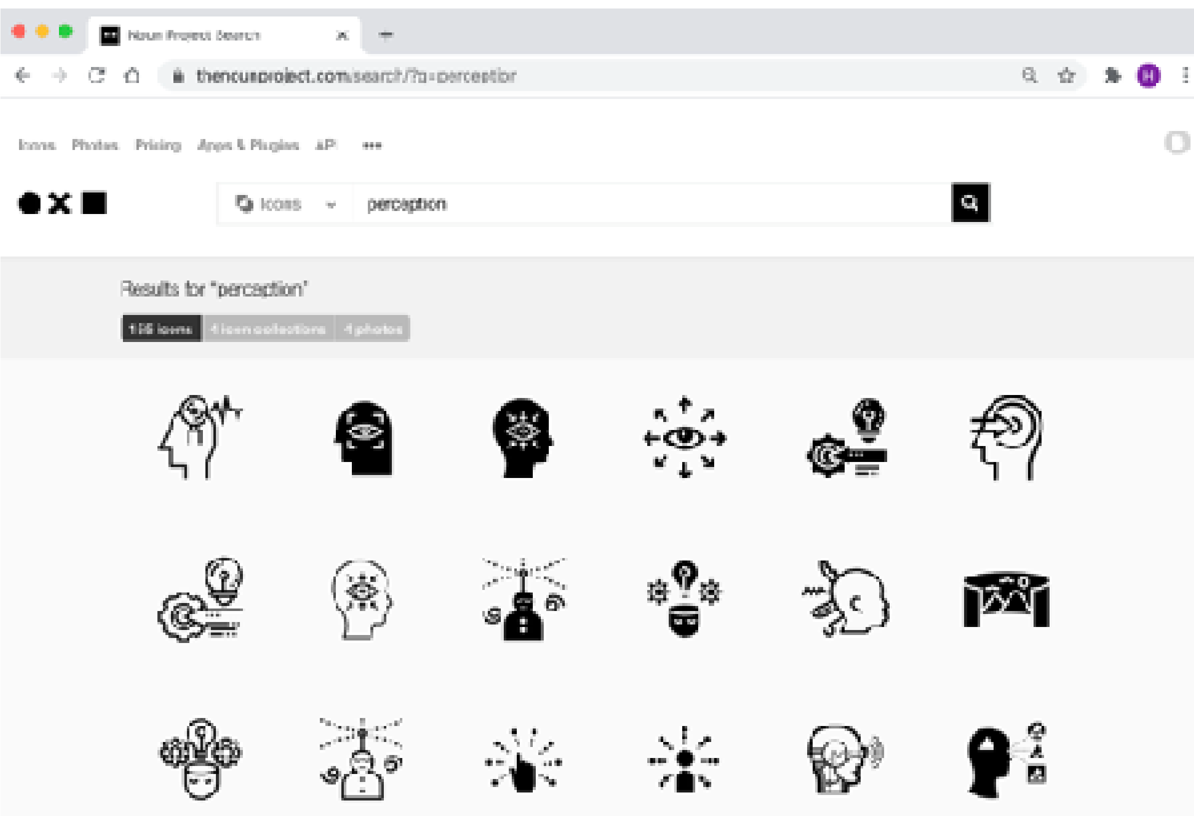
4. Share with users and designers for feedback

This is an **iterative** process

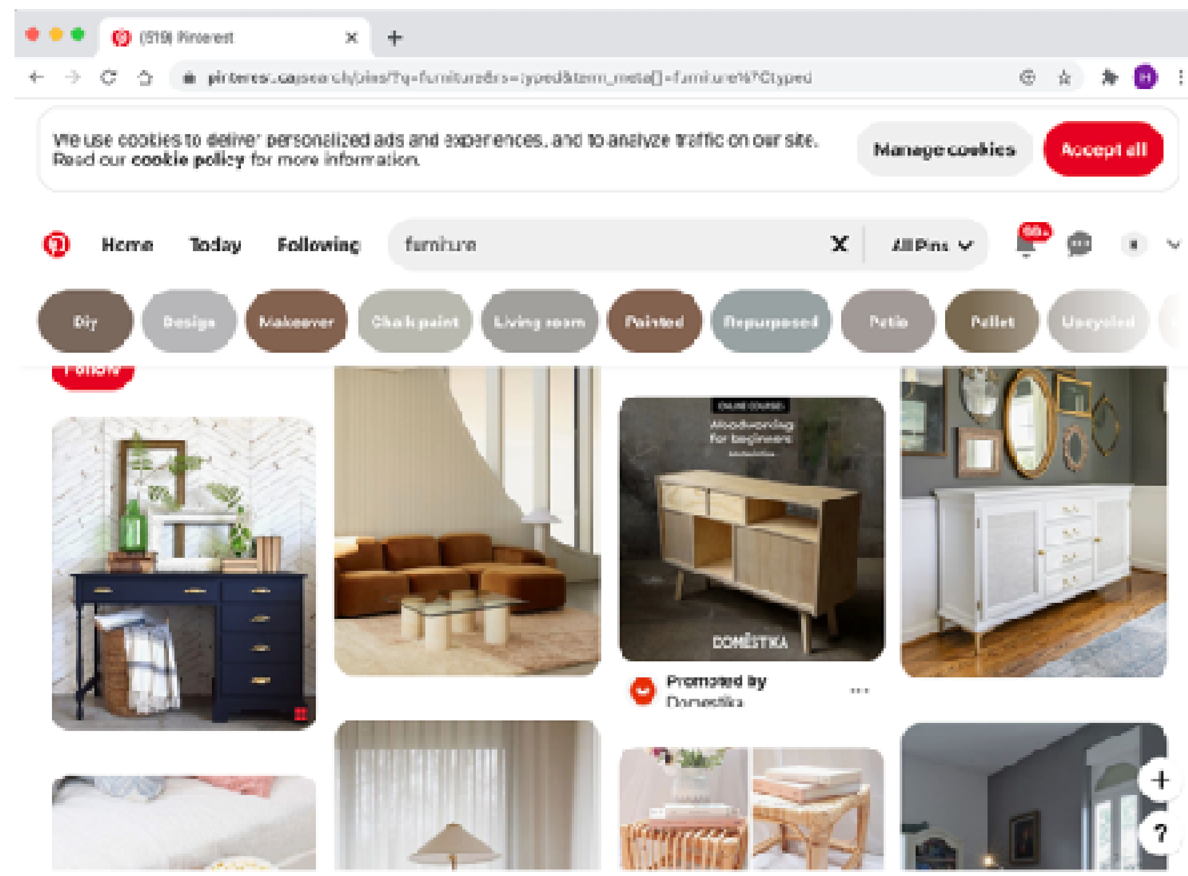
From MacLean et al. 2015,
Design process defined by Bill Buxton

Visual collections

Noun project

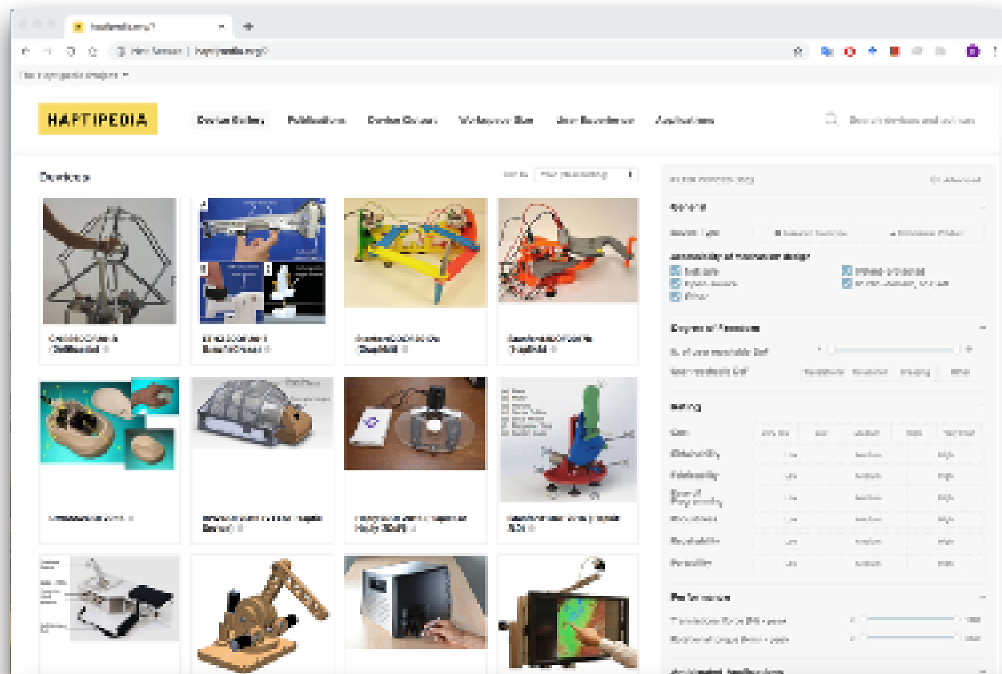


Pinterest



Example public haptic resources for browsing

Haptipedia (haptipedia.org)
A visual database of over 100 GFF devices



Seifi et al. 2019

CHAI3D (chai3d.org)
A powerful cross-platform C++ simulation framework for creating applications with GFF devices