QUIZ

Start

Sensory feedback for Cortical Neuroprosthetics

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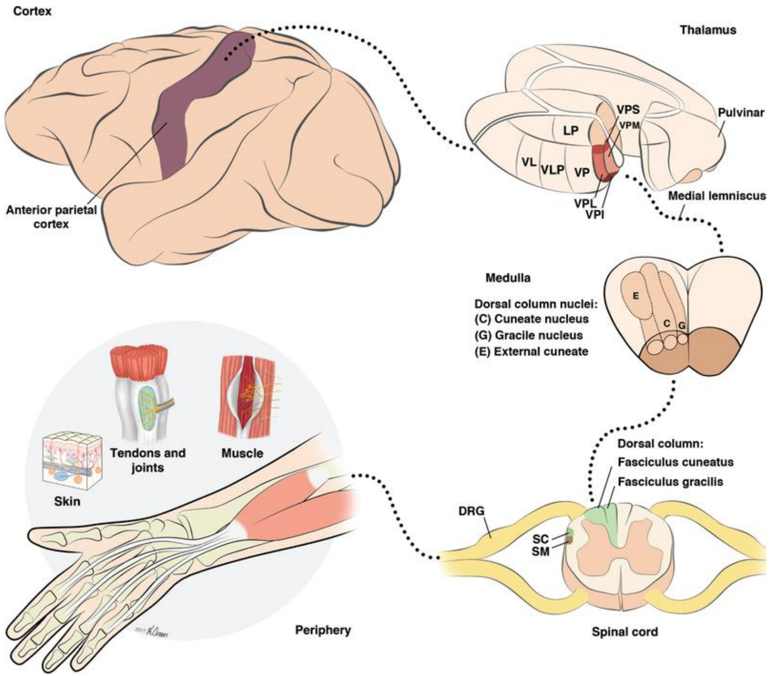
HHRI 2024

Margot Herbelin

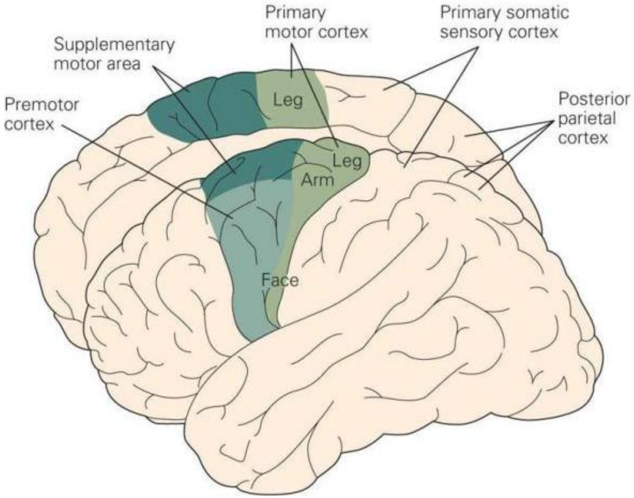
Summary

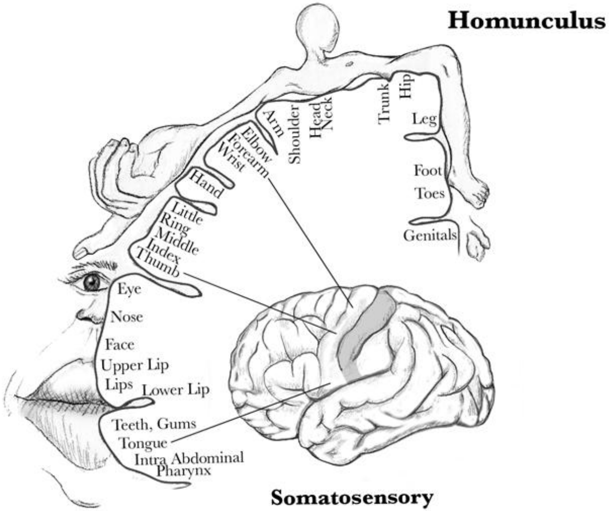
- Anatomical organization
- Intracortical microstimulation
  - Psychometric experiments
  - Bidirectional BMI
  - Functional experiments
  - Clinical tests
- Subdural stimulation
- Conclusion and take-home message

Cortical anatomical organization for Primary Somatosensory Cortex (NHP)



Basic organization of the somatosensory and motor cortex





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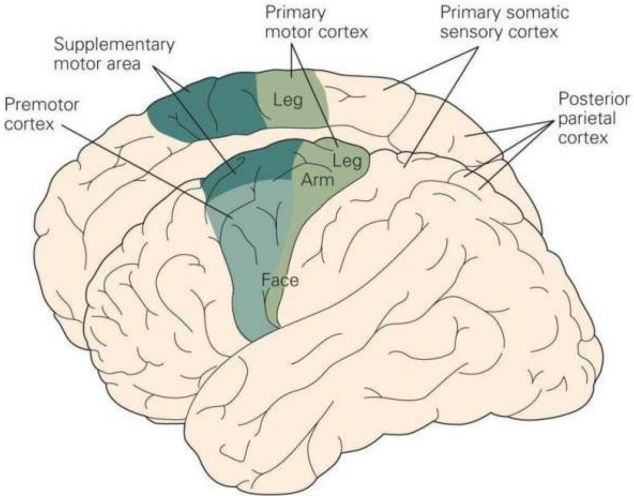
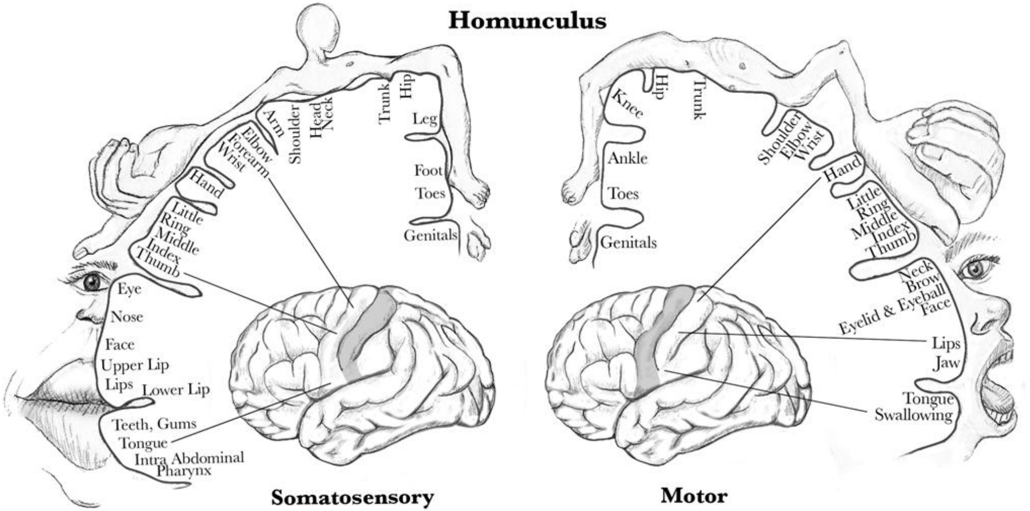
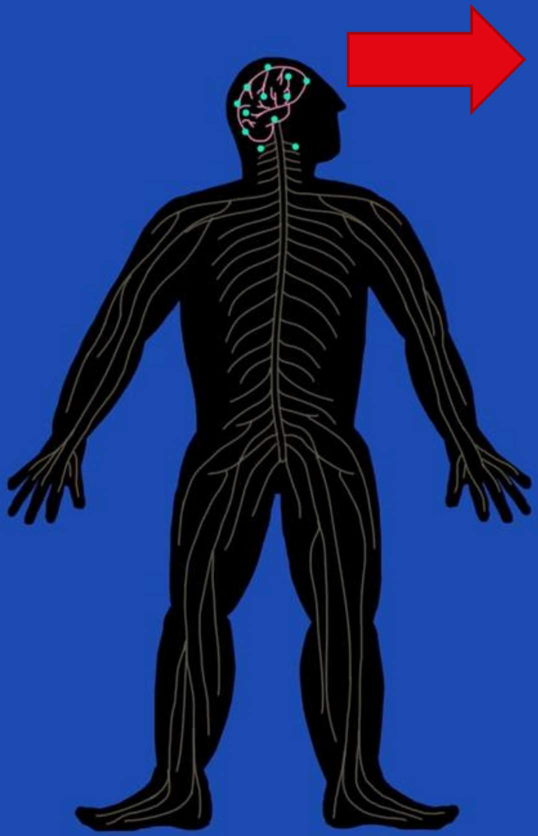




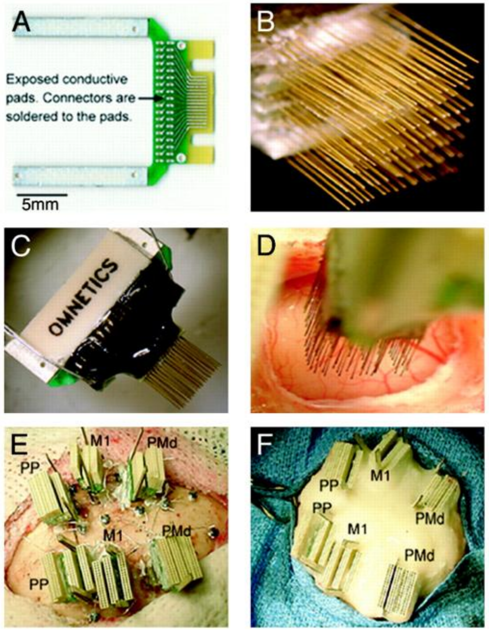


Brain-machine interfaces

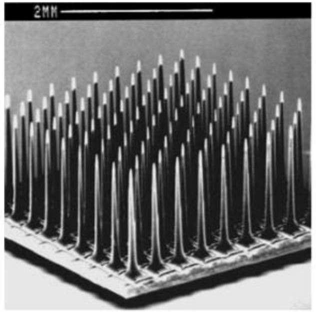
Decoding motor intentions

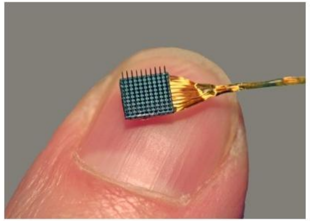
Brain implants

microwire arrays



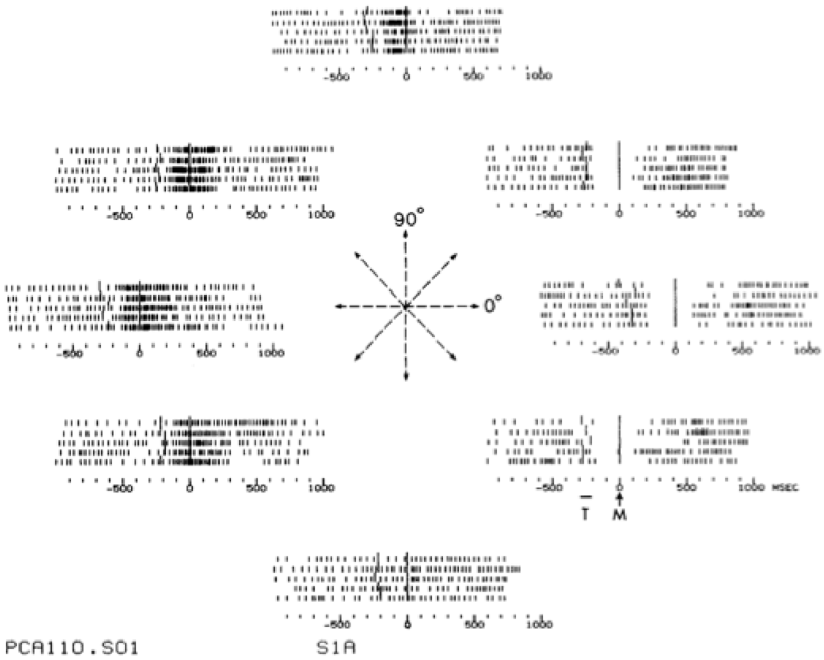
UTAH arrays





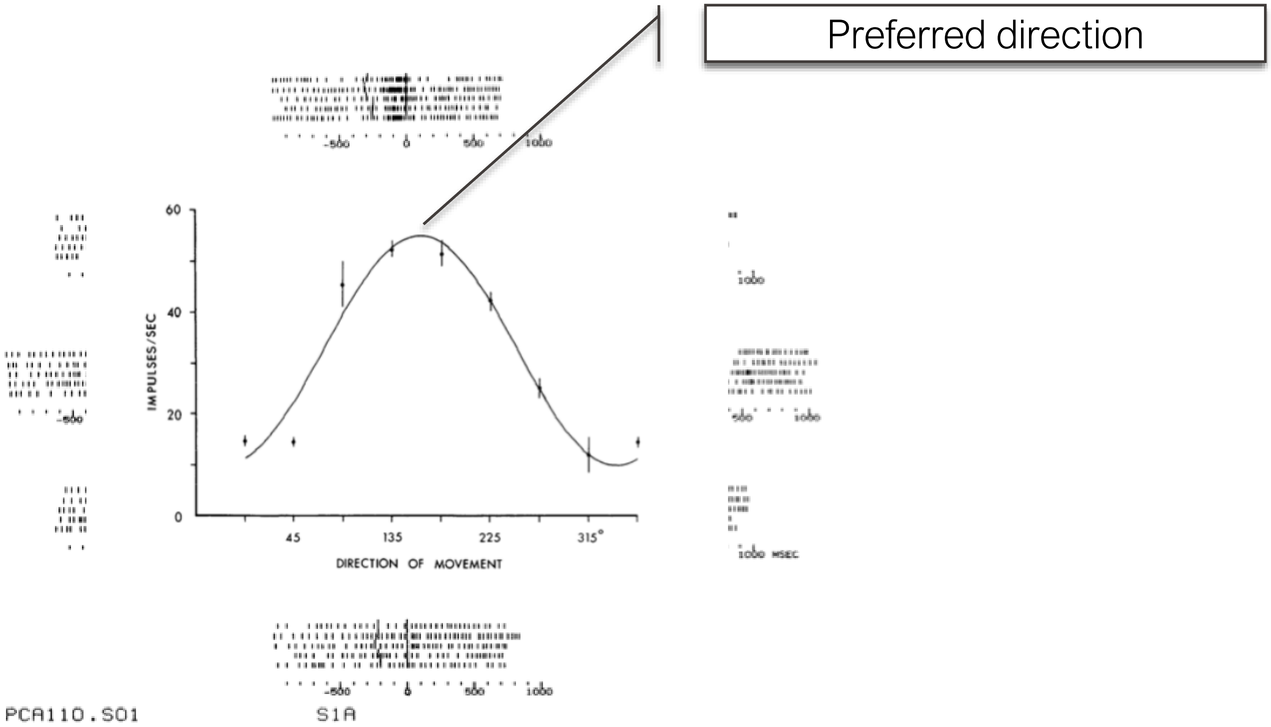
https://www.blackrockmicro.com/electrode-types/utah-array/
Nicolelis, M. A., Dimitrov, D., Carmena, J. M., Crist, R., Lehew, G., Kralik, J. D., & Wise, S. P. (2003). Chronic, multisite, multielectrode recordings in macaque monkeys. Proceedings of the National Academy of Sciences, 100(19), 11041-11046.

Motor decoding



Georgopoulos, A. P., Schwartz, A. B., & Kettner, R. E. (1986). Neuronal population coding of movement direction. Science, 233(4771), 1416-1419.

Motor decoding



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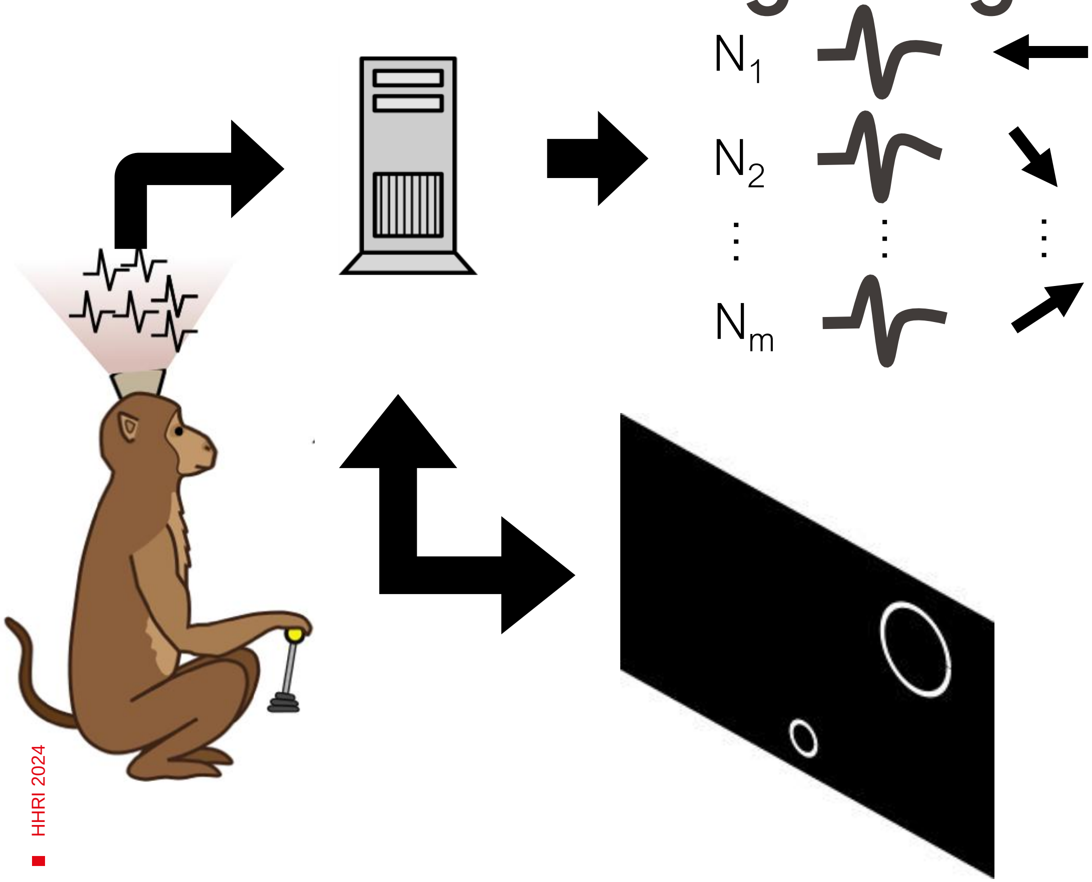
BMI for reaching and grasping



Carmena, Jose M., et al. "Learning to control a brain–machine interface for reaching and grasping by primates." PLoS biol 1.2 (2003): e42.
Velliste, Meel, et al. "Cortical control of a prosthetic arm for self-feeding." Nature 453.7198 (2008): 1098-1101.

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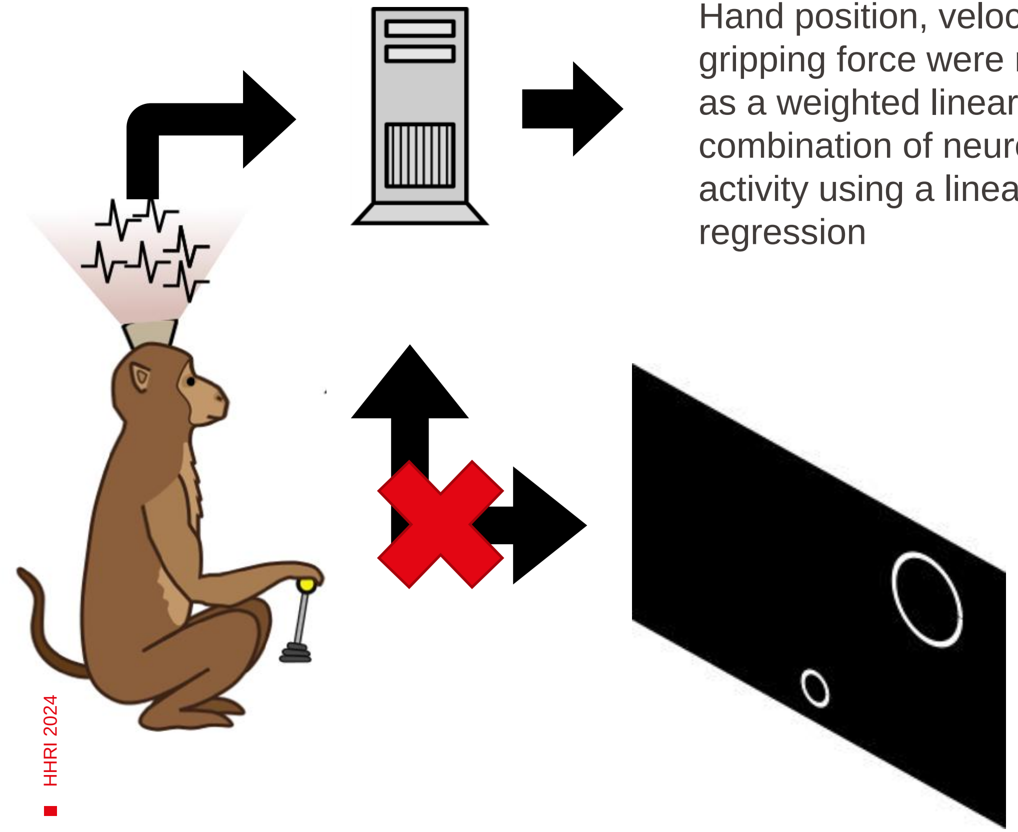

Hand position, velocity, and gripping force were modeled as a weighted linear combination of neuronal activity using a linear regression

$$\mathbf{y}(t) = \mathbf{b} + \sum_{u=-m}^{n} \mathbf{a}(u)\mathbf{x}(t-u) + \boldsymbol{\varepsilon}(t)$$

- $\mathbf{y}(t)$: Param to Predict at t
- $\mathbf{x}(t-u)$: Vector of neuronal firing rates
- $\mathbf{a}(u)$: Vector of weights
- u: Time lag (past data)

Brain areas

Primary motor cortex (M1),
Dorsal premotor cortex (PMd),
supplementary motor area (SMA),
Posterior parietal cortex (PP),
Primary somatosensory cortex (S1)

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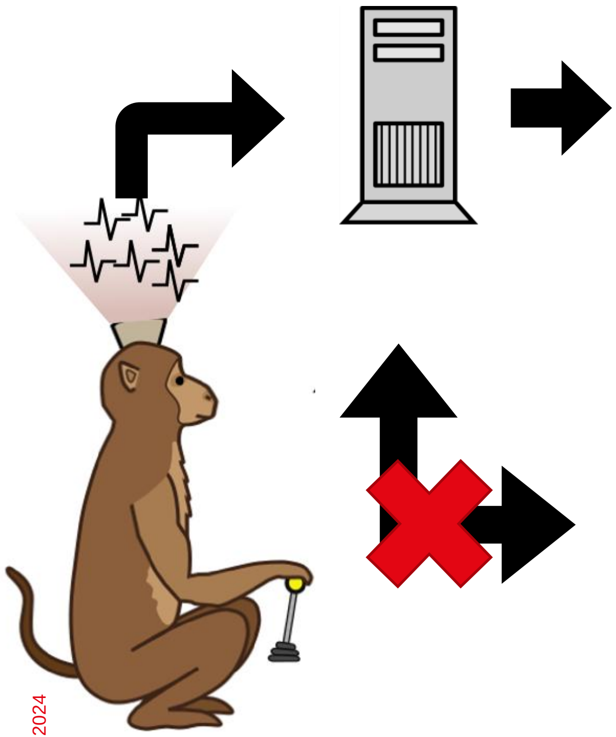

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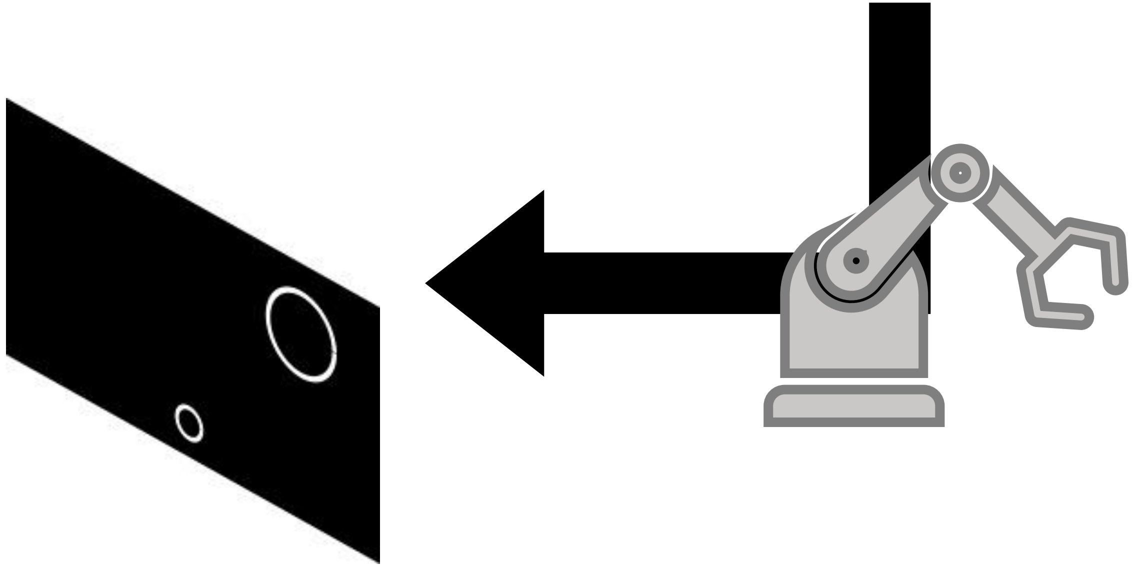

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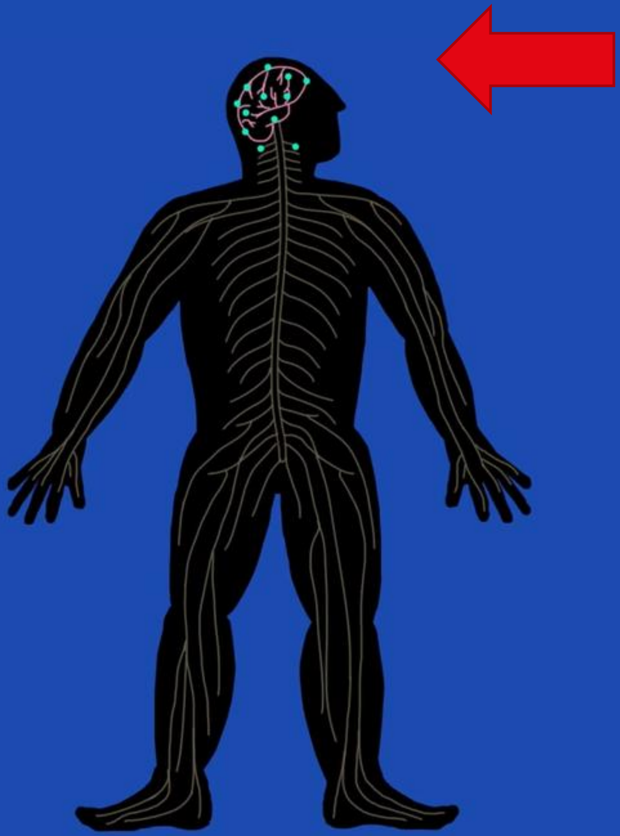
Velliste, Meel, et al. "Cortical control of a prosthetic arm for self-feeding." Nature 453.7198 (2008): 1098-1101.

Brain-machine interfaces

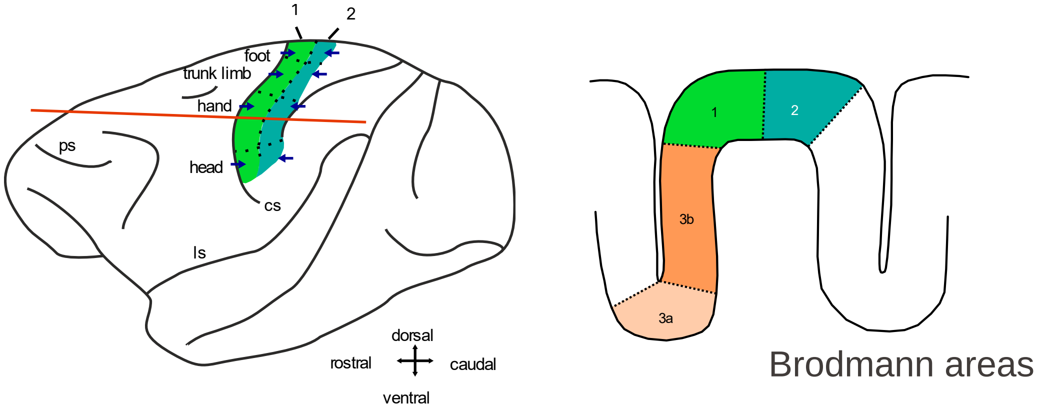
Collinger, Jennifer L., et al. "High-performance neuroprosthetic control by an individual with tetraplegia." *The Lancet* 381.9866 (2013): 557-564.



Intracortical microstimulation

Encoding sensory feedback

Cortical anatomical organization for Primary Somatosensory Cortex (NHP)



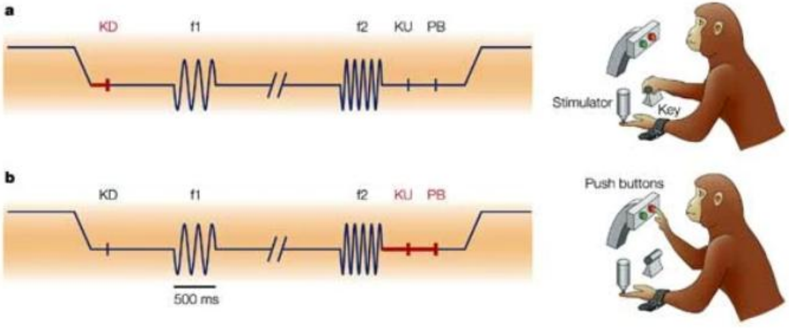
- Neurons in area 3a respond primarily to joint movements. Proprioceptive afferents are multimodally processed in this region.
- Neurons in areas 3b and 1 respond to light touch. Phase-locked responses to vibrations are primarily seen in area 3b, they gradually disappear in area 1 and area 2.
- Neurons in area 2 exhibit both response properties.

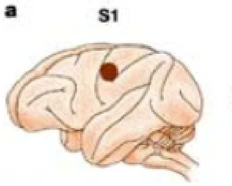
cs: central sulcus; ips: intraparietal sulcus; pcd: precentral dimple; asu: arcuate sulcus; ps: principal sulcus; ls: lateral sulcus; BA: Brodmann area. Modified from (James et al., 2007; Pons et al., 1985, 1987).

EPFL

Sensory feedback cortical mechanisms

- Test with nonhuman primates (NHP) showed that the sensation of flutter is produced with mechanical vibrations in the range of 5–50 Hz
- The stimulus activates neurons in S1 that somatotopically map to the site of stimulation.
- A subset of neurons in area 3b— those with quickly adapting properties— are strongly entrained by periodic flutter vibrations, firing with a probability related to the input frequency
- Hence, quickly adapting neurons provide a dynamic representation of such flutter stimuli.

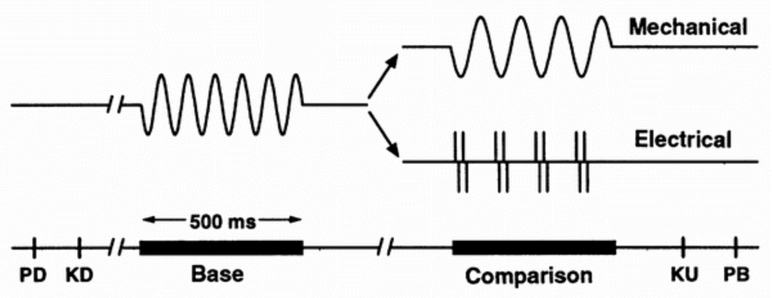




Romo, R., Hernández, A., Zainos, A., & Salinas, E. (1998). Somatosensory discrimination based on cortical microstimulation. Nature, 392(6674), 387–390. https://doi.org/10.1038/32891

Intracortical micro stimulation

- **Method**:
  - Microelectrodes implanted into area 3b of S1
  - Biphasic current pulses (lasted 0.2 ms, with 0.05 ms between phases), amplitude 65 µA and 100 µA
- **Results:** Animals reliably indicated whether electrical signal was higher or lower than that the mechanical signal
- **Conlcusion:** the neural code underlying the sensation of flutter can be manipulated.



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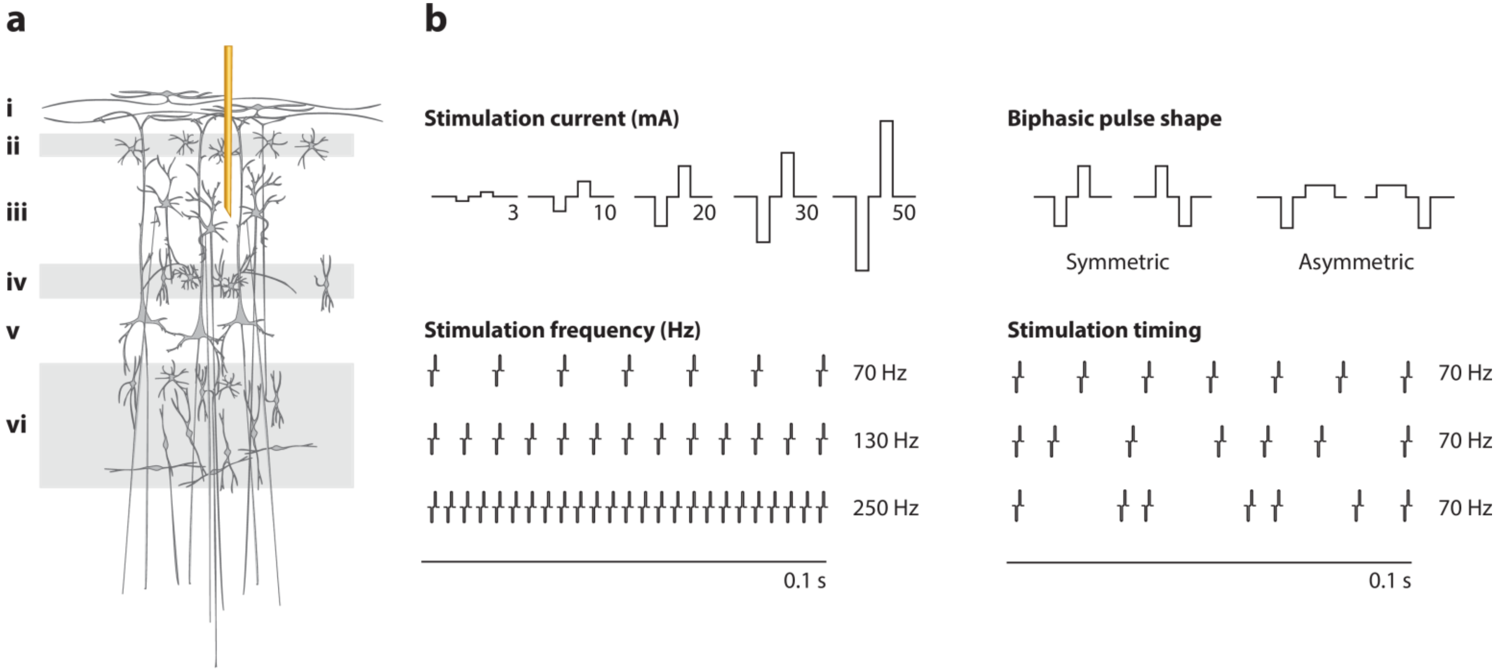
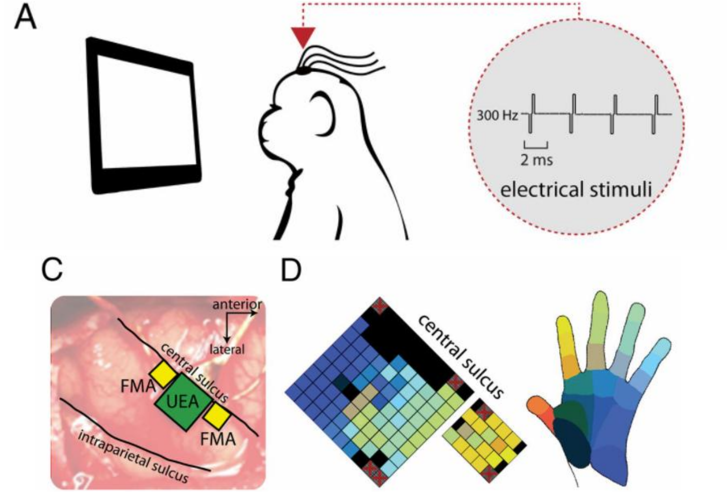
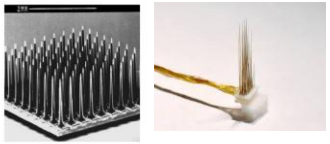
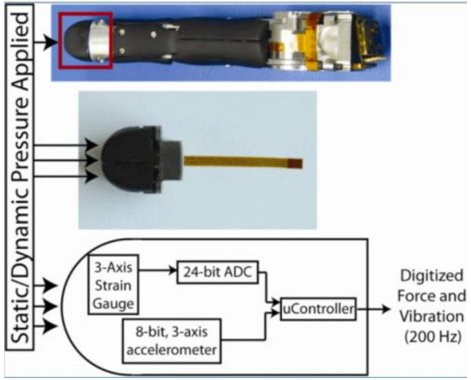


Dadarlat MC, et al. 2023
Annu. Rev. Biomed. Eng. 25:51–76

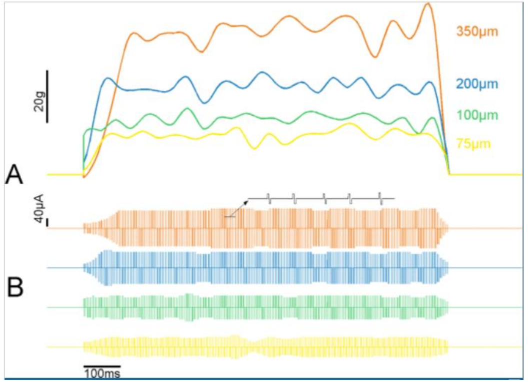
Encoding via ICMS







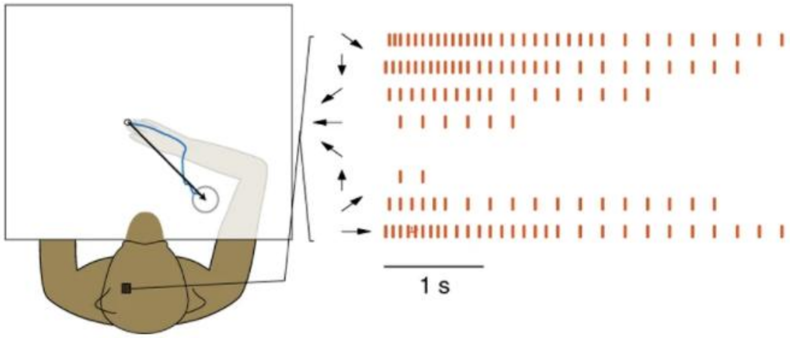
Pressure sensors on the finger-tip of a prosthetic hand

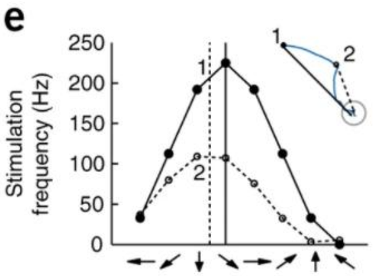


Conversion from time-varying force to ICMS pulse trains of varying amplitude. (A) Time-varying force output of the prosthetic finger on four detection trials with four different amplitudes. (B) Resulting electrical stimulation pulse trains

Kim, Sungshin, et al. "Behavioral assessment of sensitivity to intracortical microstimulation of primate somatosensory cortex." Proceedings of the National Academy of Sciences 112.49 (2015): 15202-15207.

Sensory encoding using a learning-based ICMS approach

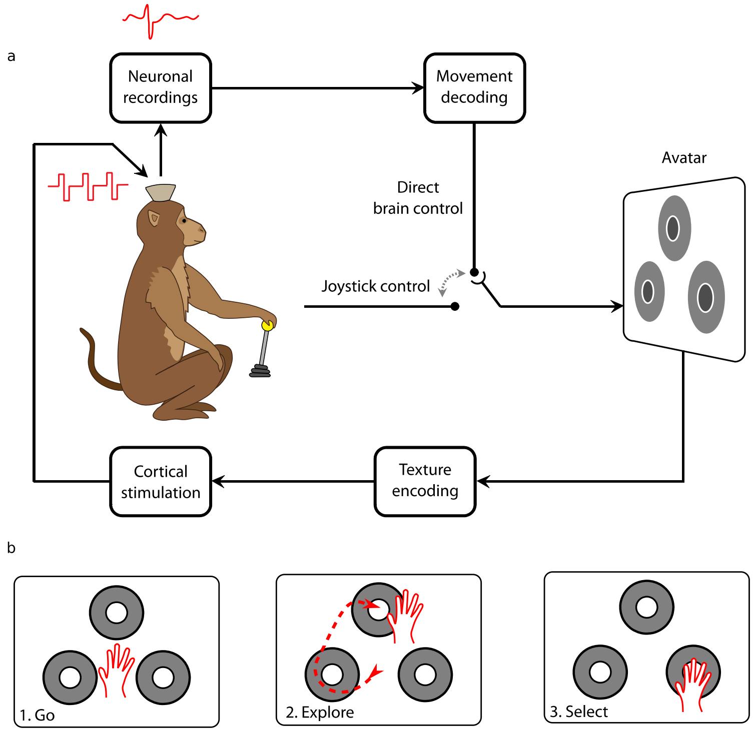


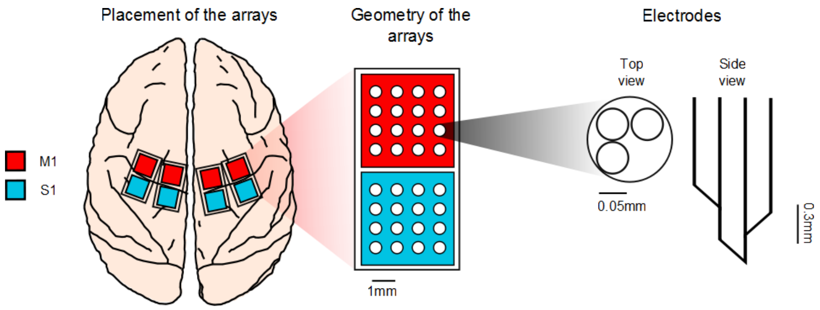


- Stimulation on 8 electrodes.
- Non-biomimetic approach, but rather a learning-based approach
  - Spatiotemporal correlations between a visual signal and novel artificial signal in a behavioral context would be sufficient for a monkey to learn to integrate the new modality.
- Provide continuous information about the hand state during reaching via ICMS
- **Result**: artificial kinesthetic feedback can be efficiently learned by the monkey and can provide rich insights for directing movements.

Dadarlat, M. C., O'doherty, J. E., & Sabes, P. N. (2015). A learning-based approach to artificial sensory feedback leads to optimal integration. Nature neuroscience, 18(1), 138-144.

Bidirectional brain machine interface

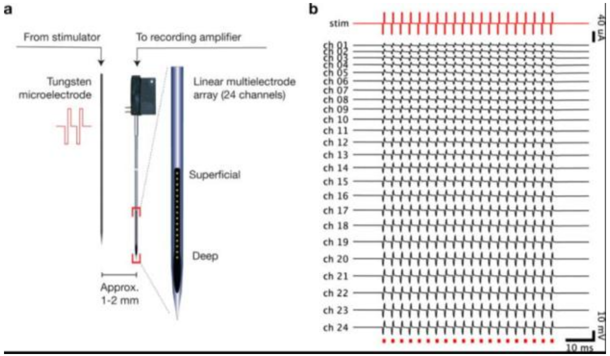




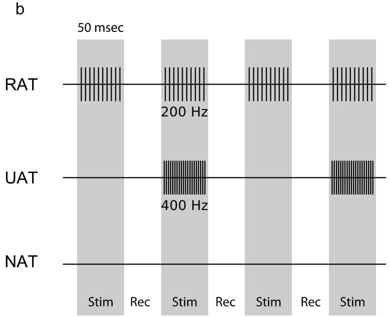
O’Doherty, J. E., Lebedev, M. A., Ifft, P. J., Zhuang, K. Z., Shokur, S., Bleuler, H., & Nicolelis, M. A. (2011). Active tactile exploration using a brain–machine–brain interface. *Nature*, *479*(7372), 228-231.

Stimulation paradigm

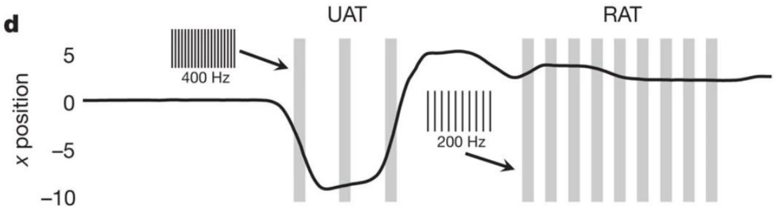
Problem
Complex signal artifact during the stimulation periods -> corrupts the signals recorded in the motor cortex



Solution (for this study):
Multiplexing of sensory encoding and motor decoding periods

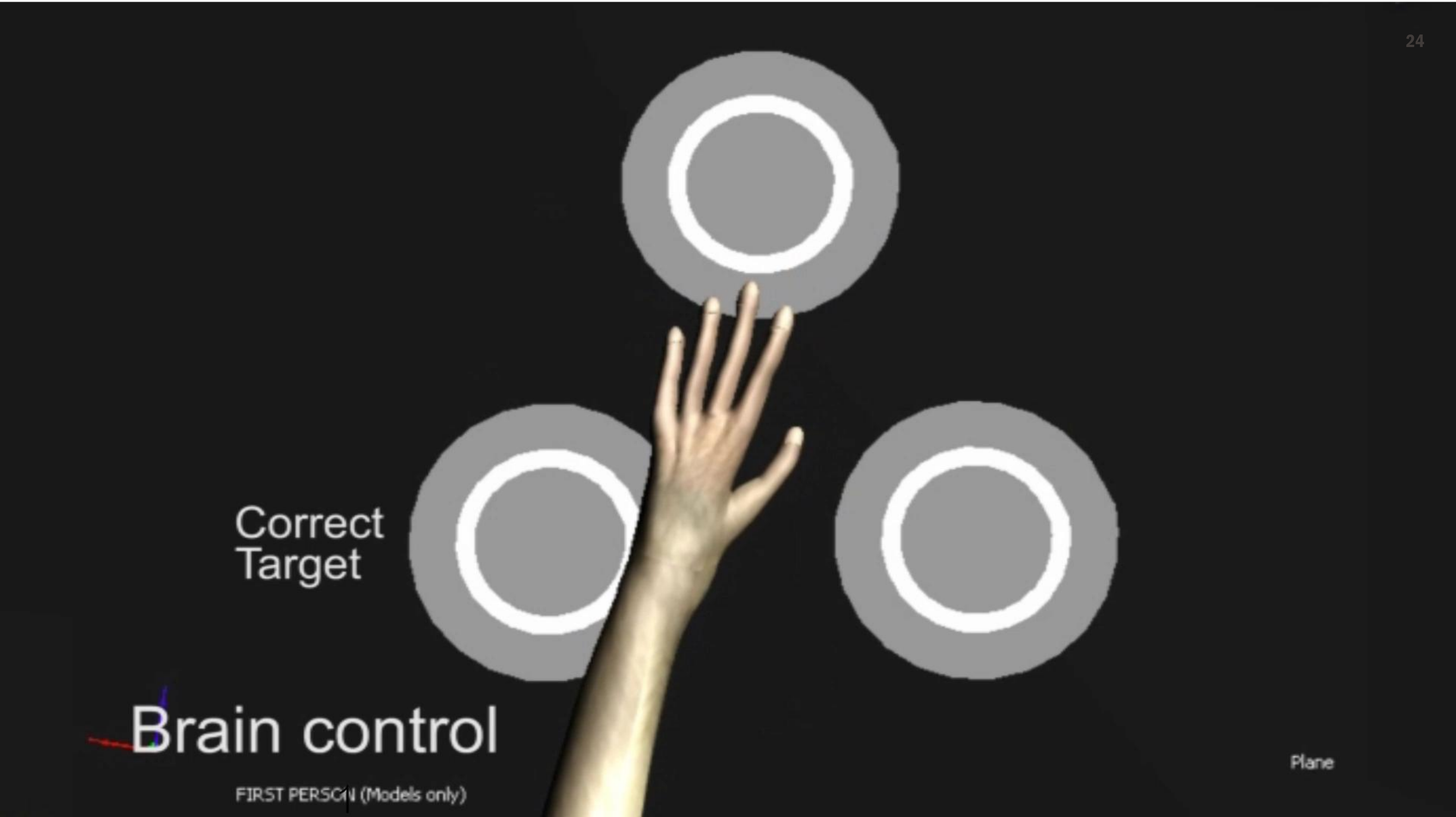


Encoding of the rewarded the unrewarded and null artificial textures

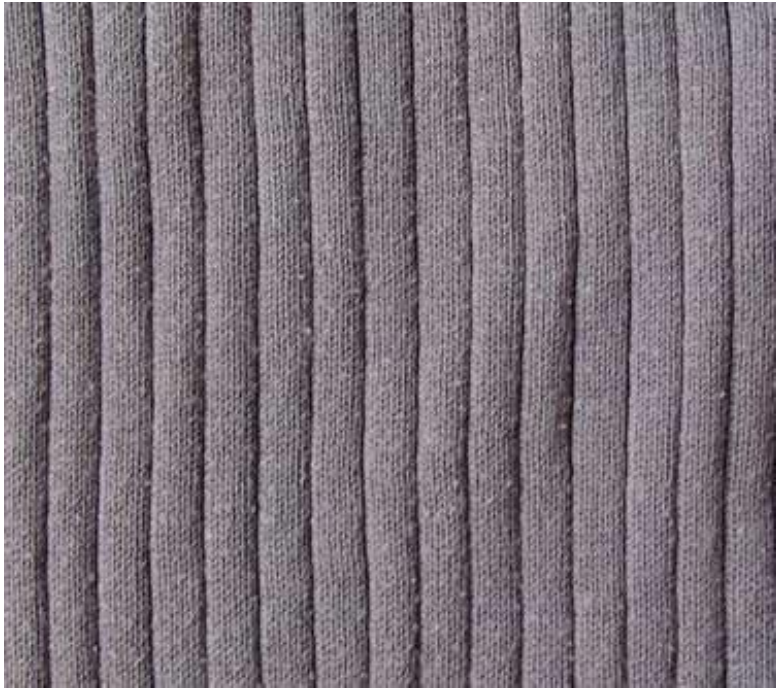


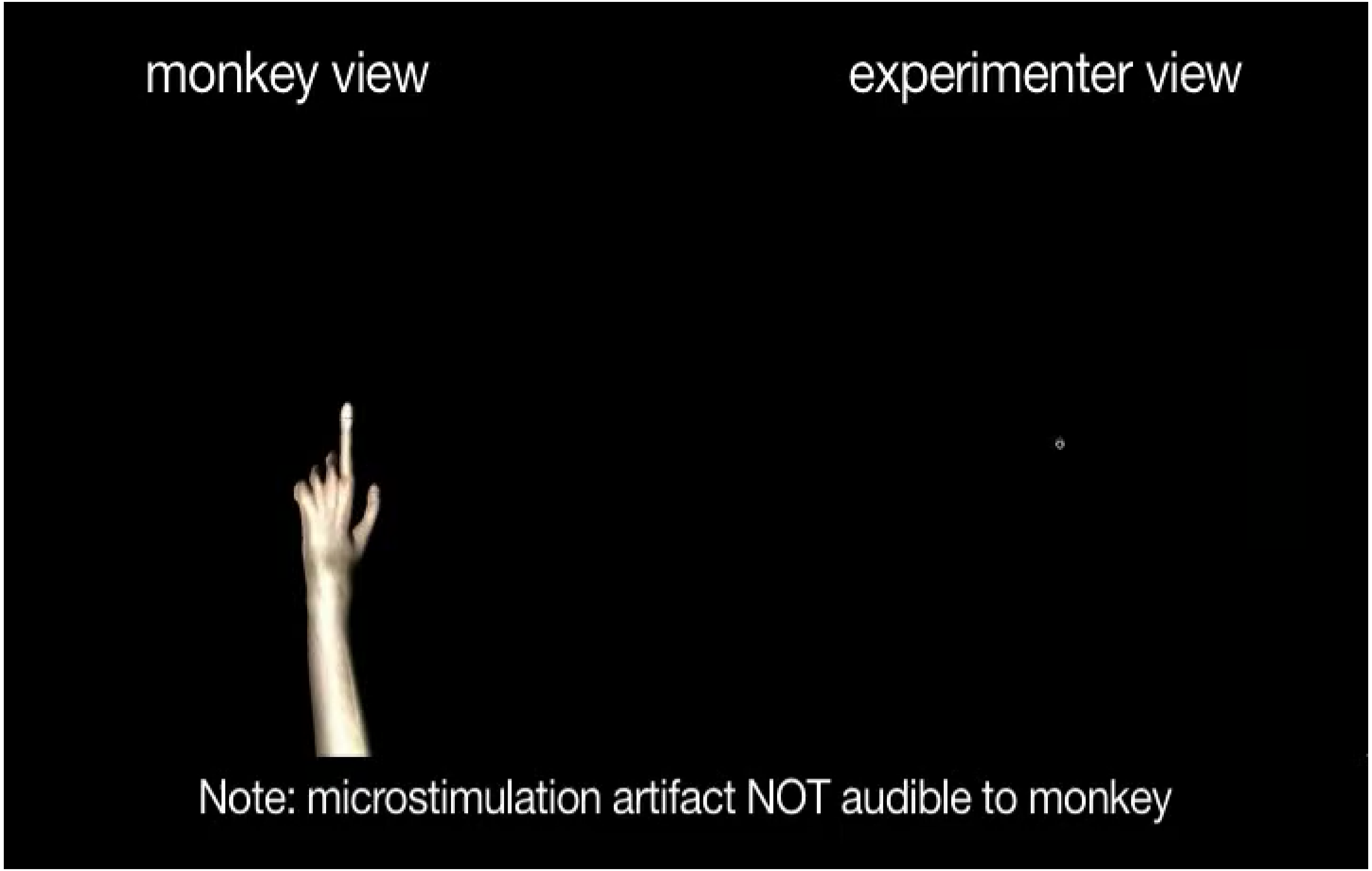
O’Shea, D. J., & Shenoy, K. V. (2018). ERAASR: an algorithm for removing electrical stimulation artifacts from multielectrode array recordings. Journal of neural engineering, 15(2), 026020.

O’Doherty, J. E., Lebedev, M. A., Ifft, P. J., Zhuang, K. Z., Shokur, S., Bleuler, H., & Nicolelis, M. A. (2011). Active tactile exploration using a brain–machine–brain interface. *Nature*, *479*(7372), 228-231.


Correct Target
Brain control
FIRST PERSON (Models only)
Plane

Texture perception

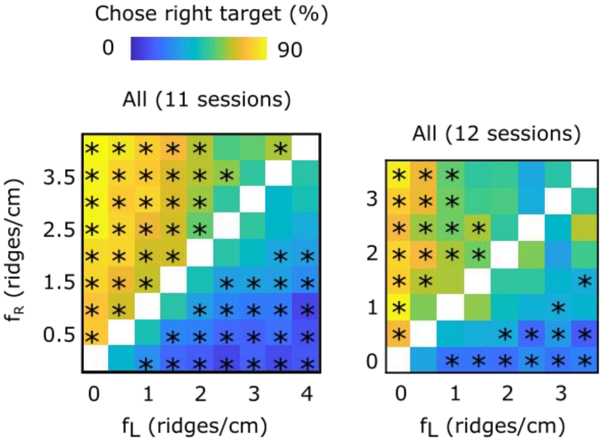




J. E. O'Doherty*, S. Shokur *, L. E. Medina, M. A. Lebedev, M. A. L. Nicolelis. Creating a neuroprosthesis for active tactile exploration of textures (2019). Proceedings of the National Academy of Sciences.

Active tactile exploration of textures: results

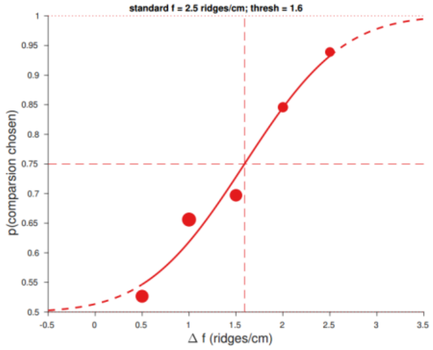
Monkeys discriminated spatial gratings based on self-generated temporal ICMS



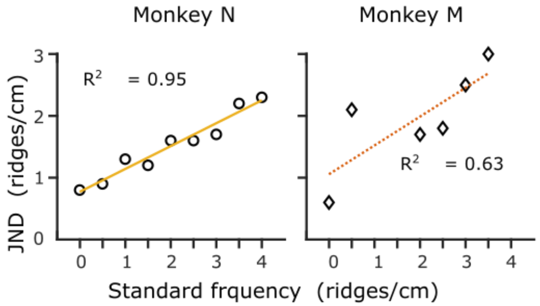
Monkey N

Monkey M

Psychometrics analysis of Just noticeable difference (JND)



JND increases proportionally to f, consistent with the Weber–Fechner/Steven's law



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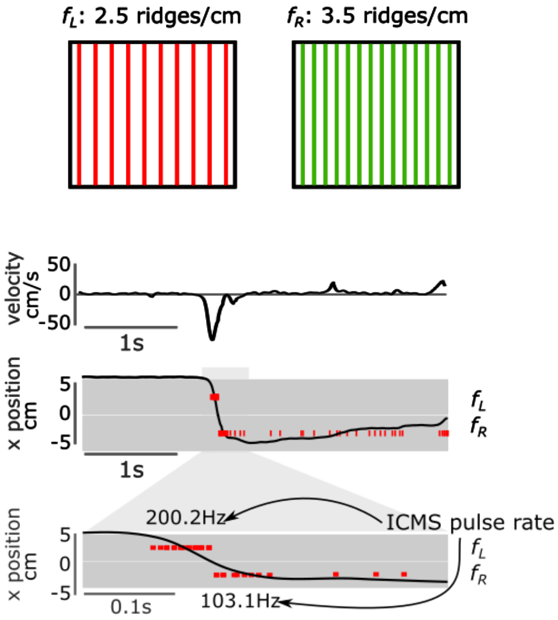
Active tactile exploration of textures: paradoxal trials



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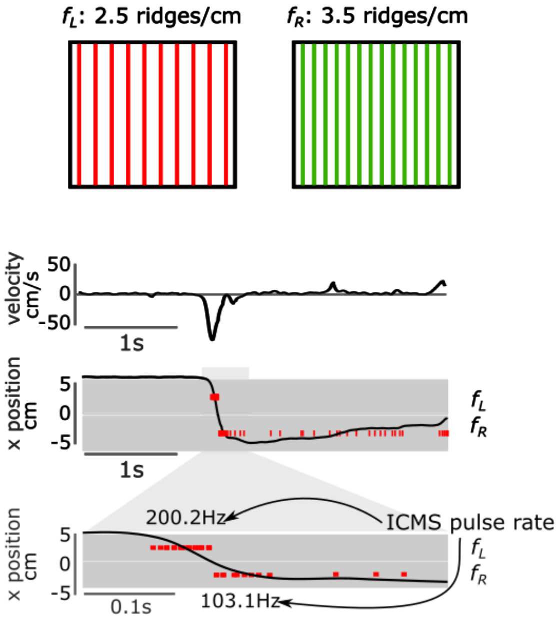

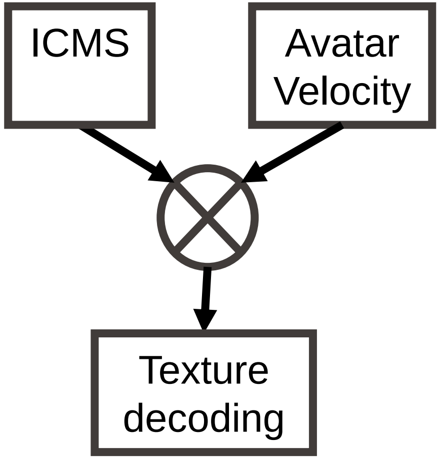

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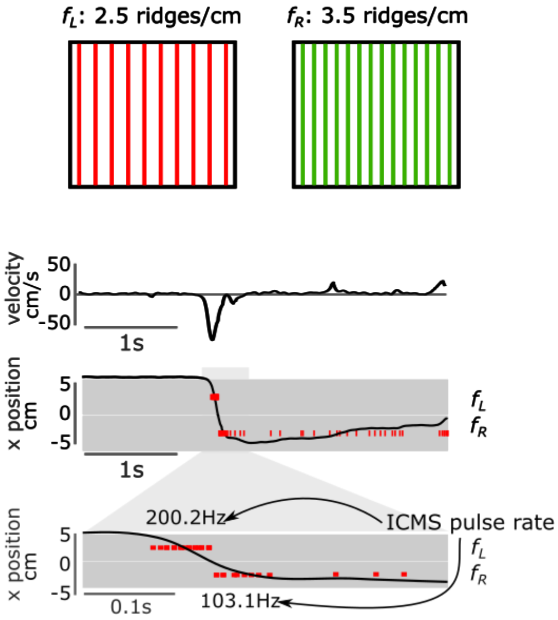

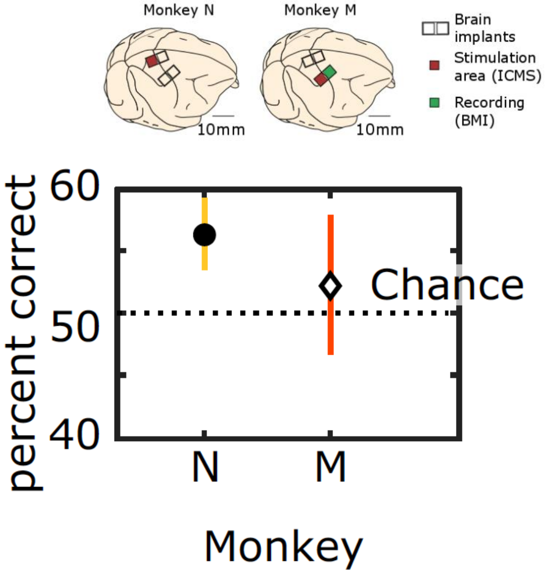

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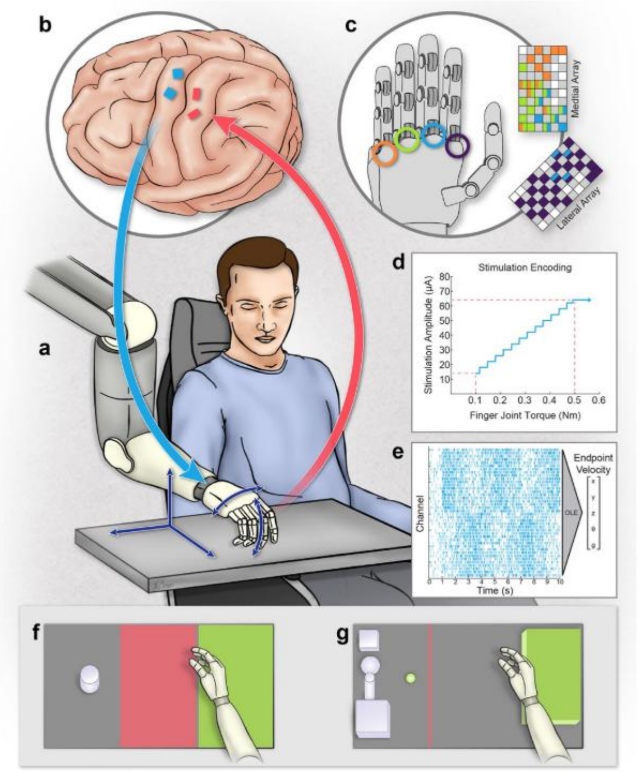
Clinical test with implanted electrodes in Tetraplegic patients

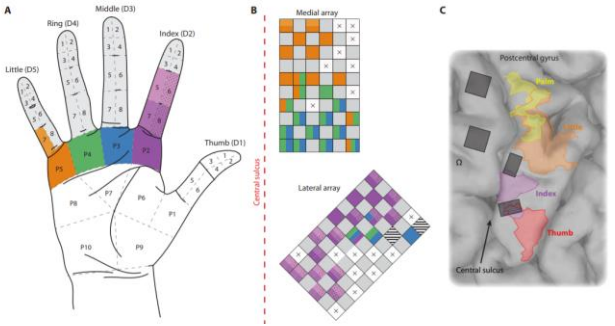


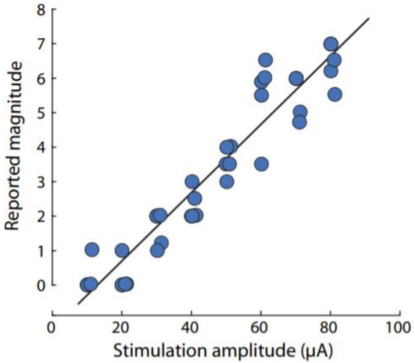
University of Pittsburgh

Patient:

- A 28-year-old male participant with tetraplegia
- Two microelectrode arrays implanted in area 1 of S1
- Electrode implanted in M1 as part of a larger protocol

How does it feel ?





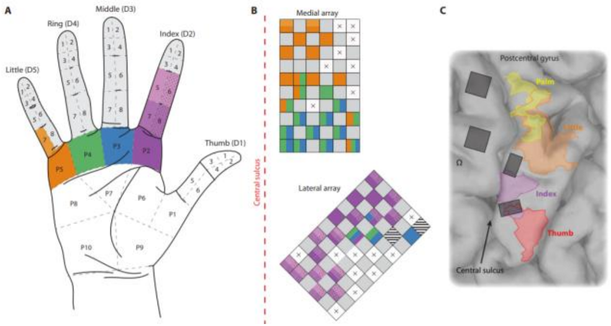
There is a linear relation between perceived intensity of tactile feedback and the amplitude of stimulation

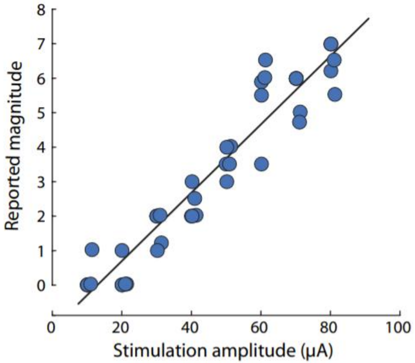
Table 1. Percept qualities evoked by intracortical microstimulation. The number of trials evoking each response type is shown. The totals in each category (naturalness, depth, etc.) differ because the participant did not always provide a complete response for every case where he could detect a stimulus. In 79 cases, a sensation of "tingle" was described without being further described by one of the subcategories.

Naturalness (250)	Depth (247)	Pain (280)	Somatosensory quality (190)
..	...	....	
..	...	....	
..	...	....	
..	...	....	

Flesher, Sharlene N., et al. "Intracortical microstimulation of human somatosensory cortex." Science translational medicine 8.361 (2016): 361ra141-361ra141.

How does it feel ?





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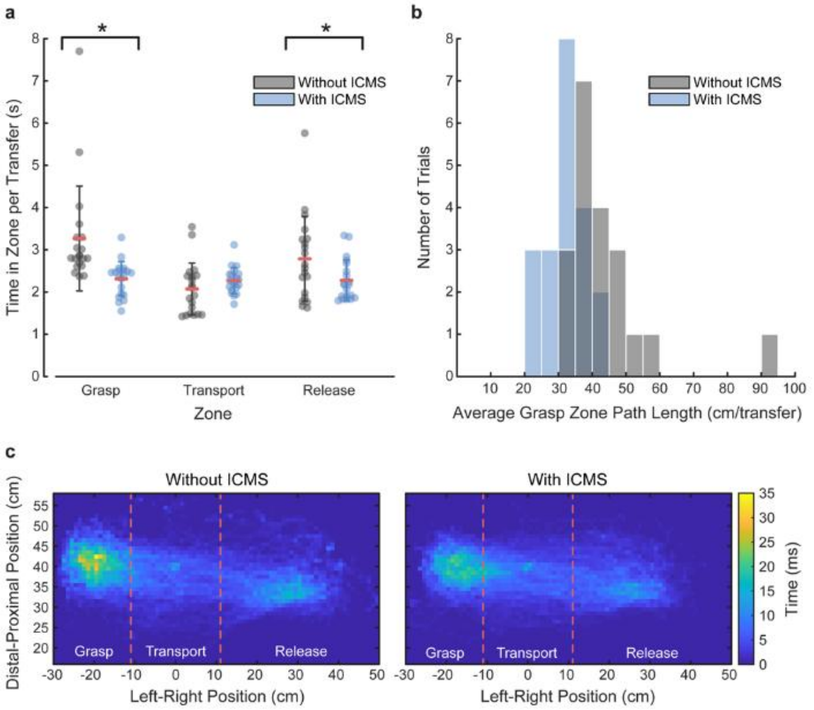
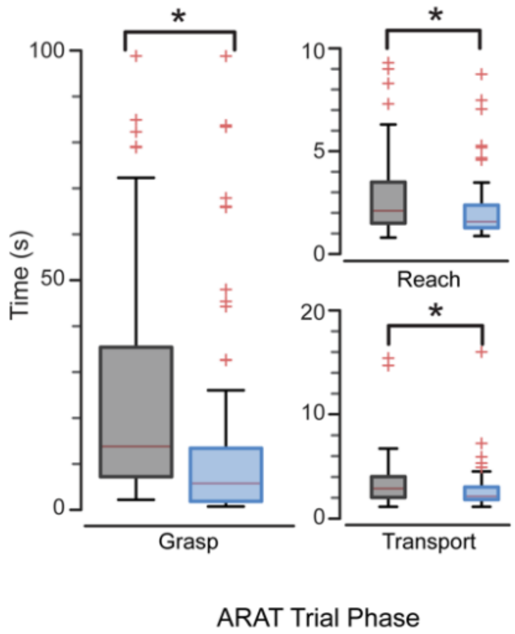
Naturalness (250)		Depth (247)		Pain (280)		Somatosensory quality (190)	
Totally natural	0	Skin surface	9	0 (no pain)	280	Mechanical	Touch (2), pressure (128), sharp (0)
Almost natural	12	Below skin	5	1, 2, 3	0	Movement	Vibration (1), movement (0)
Possibly natural	233	Both	233	4, 5, 6	0	Temperature	Warm (30), cool (0)
Rather unnatural	5			7, 8, 9	0	Tingle (79)	Electrical (29), tickle (0), itch (0)
Totally unnatural	0			10 (most pain)	0		

Flesher, Sharlene N., et al. "Intracortical microstimulation of human somatosensory cortex." Science translational medicine 8.361 (2016): 361ra141-361ra141.

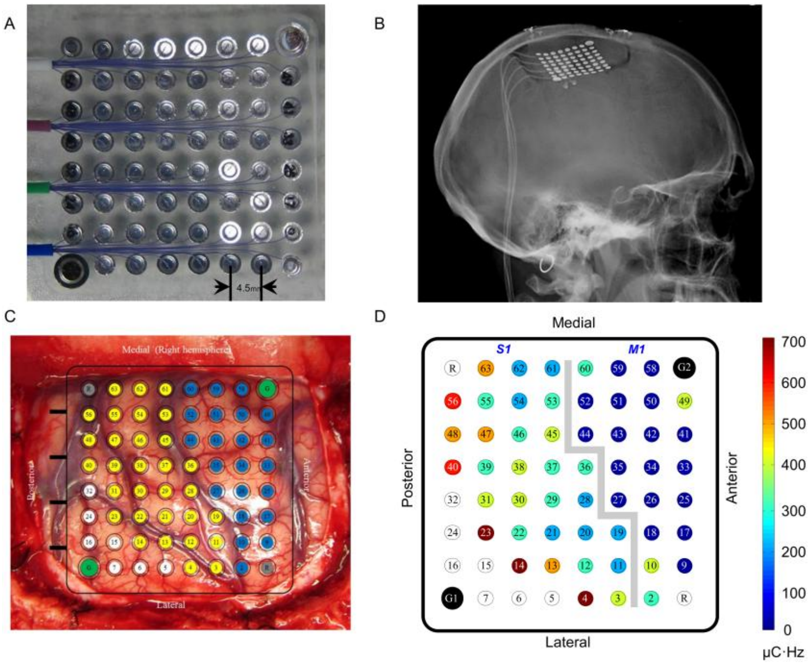
Functional improvement using a bidirectional BMI

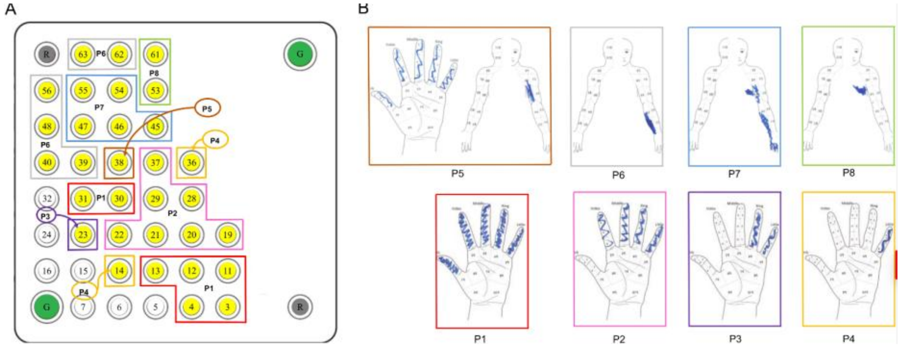




Flesher, S. N., Downey, J. E., Weiss, J. M., Hughes, C. L., Herrera, A. J., Tyler-Kabara, E. C., ... & Gaunt, R. A. (2021). A brain-computer interface that evokes tactile sensations improves robotic arm control. Science, 372(6544), 831-836.

Stimulation via subdural ECoG





Results:

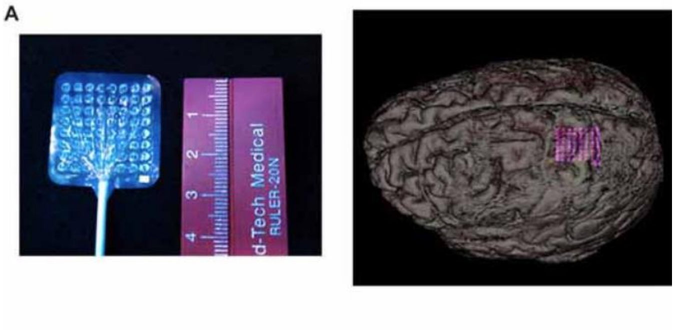
- Intensity of perceived sensation increased monotonically with both pulse amplitude and pulse frequency.

ECoG grid (PMT Corp, Chanhassen, MN USA) with 64 platinum disc electrodes

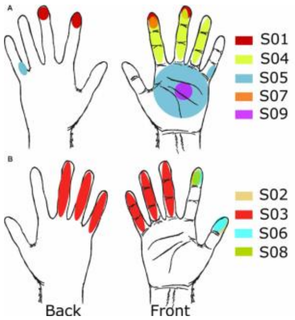
Hiremath, Shivayogi V., et al. "Human perception of electrical stimulation on the surface of somatosensory cortex." PloS one 12.5 (2017): e0176020.

Stimulation via subdural ECoG: sensory perception

64 Chan mini-ECoG



Receptive fields from grid mapping



Subject ID	Non-overlapping locations (%)*	Unique discriminable locations (%)	Receptive fields	Area of hand stimulated	Description
01	25.0	25.0	All fingers	Ventral and dorsal surface of tips of digits 2–3	"Tinging", "tickling"
02	27.3	27.3	Digits 2, 3 and 4, and palm	Ventral surface of digits 1–2	"Buzzing"
03	33.3	83.3	All fingers and palm	Ventral and dorsal surface of tips of digits 3–5	"Electricity"
04	16.7	66.7	All fingers and palm	Ventral surface of digits 2–5	"Soft", "trembling", "like it's moving"
05	100.0	100.0	Digit 5	Lateral/proximal surface of digit 5 and palm	"Itching", "tickling", "pulsing"
06	46.2	76.9	All fingers	Ventral surface of tip of digits 1–2	"Shock"
07	37.5	100	Digits 1, 2, 4 and 5, and palm	Ventral surface of tip of digit 2	"Electricity"
08	41.7	58.3	All fingers	Ventral surface of tip of digit 2	"Light tapping"
09	50.0	100.0	Digits 2, 3 and 4, and palm	Center of palm	"Tingling"

Sensation was rather non-natural

Lee, Brian, et al. "Engineering artificial somatosensation through cortical stimulation in humans." Frontiers in systems neuroscience 12 (2018): 24.

Take home message

- It is possible to encode sensory feedback via subdural or intracortical stimulation.
- Adding sensory feedback improves patients' ability to perform functional tasks.
- Encoding strategies that induce natural sensation is a challenge.

Open Projects at TNE

Researcher	Project Availability	Email
Dr. Carmiña Galvez Solano	Can be discussed if someone is interested in non-invasive spinal cord stimulation	carmina.galvezsolano@epfl.ch
Dr Daniel Leal	1 project on human augmentation	daniel.leal@epfl.ch
Dr Vincent Mendez & Dr- Daniel Leal	1 project on data analysis & ML for freezing of gait biomarkers in Parkinson’s disease and healthy controls	daniel.leal@epfl.ch / Vincent (email TBD)
Bas (Johannes Nieuwenhuis)	Project on modulation of the sense of agency using closed-loop EEG—includes experiment design, data collection, and analysis (candidate may be identified)	johannes.nieuwenhuis@epfl.ch
Jonathan Muheim	No available projects	jonathan.muheim@epfl.ch
Elena Vicari	No available projects	elena.vicari@epfl.ch
Leonardo Pollina	1 available semester project (not thesis) on cortico-muscular coherence in ECoG during single- and dual-task paradigms	leonardo.pollina@epfl.ch