Visual cortex recruitment during language processing in blind individuals is explained by Hebbian learning

SCIENTIFIC REPORTS
Article | OPEN | Published: 05 March 2019

Brain Language Laboratory

Rosario Tomasello [1 2], Thomas Wennekers [3], Max Garagnani [4 1] & Friedemann Pulvermüller [1 2 5]
Tomasello.r@fu-berlin.de
[1]Brain Language Laboratory, Freie Universität Berlin, [2]Berlin School of Mind and Brain, Humboldt Universität,
[3]CRNS, Plymouth University, [4]Departement of Computing, Goldsmiths, University of London, [5]Einstein Center for Neurosciences,

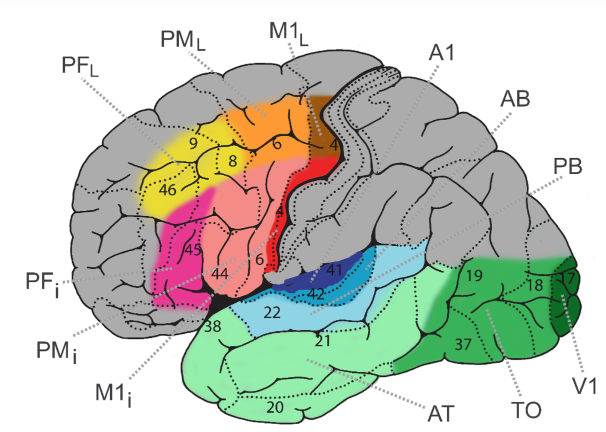
Background

People who are blind use parts of the visual cortex, typically associated with perceptual processing, for language and semantic processing. Compared with sighted individuals, blind people in the so-called verb generation, single words and sentence processing tasks showed relatively stronger activation of primary visual areas (V1) in the occipital cortex [1-3].

'Why' and *'how'* this functional reorganisation following sensory deprivation mechanistically emerges at the neuronal circuit level is not fully understood.

Here, we applied a biologically constrained cortex model [4-5] implementing features of anatomical structure, neurophysiological function and connectivity of fronto-temporal-occipital areas to simulate plastic changes in normal-sighted and congenitally blind humans during early stages of word learning.

Model Specification

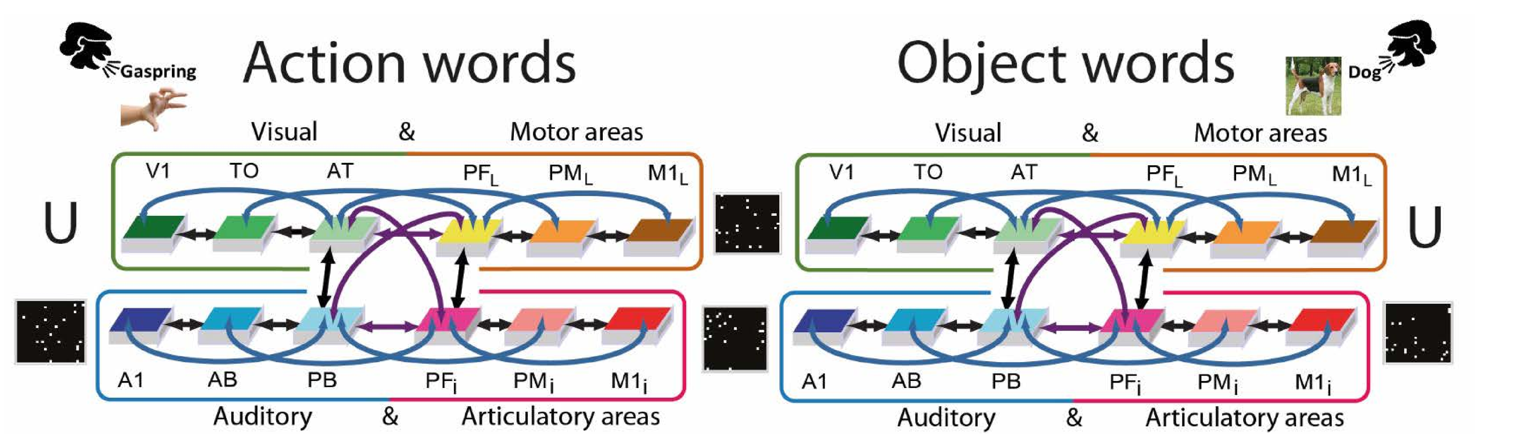


The architecture mimics 6 perisylvian **'language'** areas involved in processing **spoken word-forms**, linking the acoustic signals (A1, AB, PB – areas in blue) to articulatory movement (PFi, PMi, M1i - red colors) and 6 extrasylvian **'semantic'** areas, involved in **object perception** (V1, TO, AT – green colours) and the execution of **actions** (PFL, PML, M1L - yellow to brown).

Model architecture, connectivity

- Sparse, random and topographic **between- and within-connectivity**, based on neuroanatomical data;
- Local lateral inhibition and area-specific global regulation mechanisms **(local and global inhibition)**;
- Synaptic modification by way of Hebbian learning, including both long-term potentiation **(LTP)** and depression **(LTD)**;

Simulated 'word learning' in sighted and congenitally blind humans

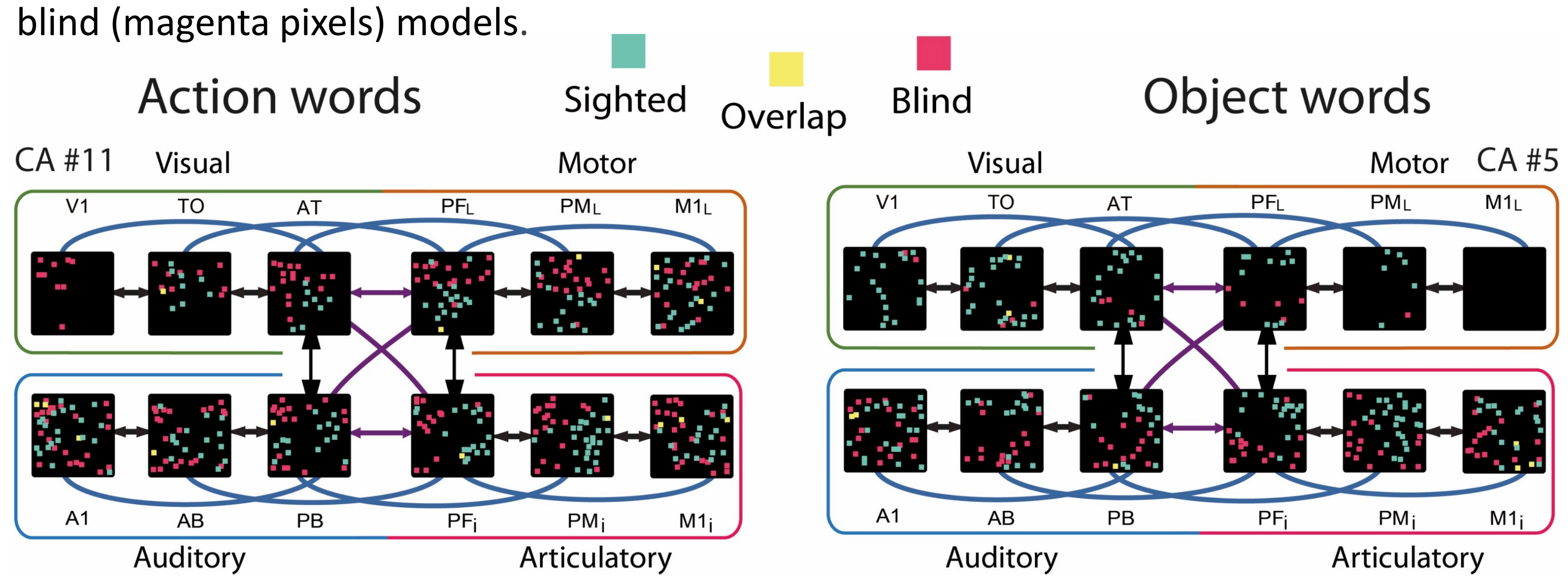


- In the sighted models, **action-** and **object** word learning were **grounded** in **sensorimotor information** presented to the primary cortices of the model.
- The symbol 'U' indicates the **uncorrelated pattern** presentation, simulating **variable sensory or motor input** typically occurring during word learning.
- Congenitally blind models were trained with the same parameters but **without any visual experience** during the learning phase (i.e. no correlated or uncorrelated neural input to V1 area).

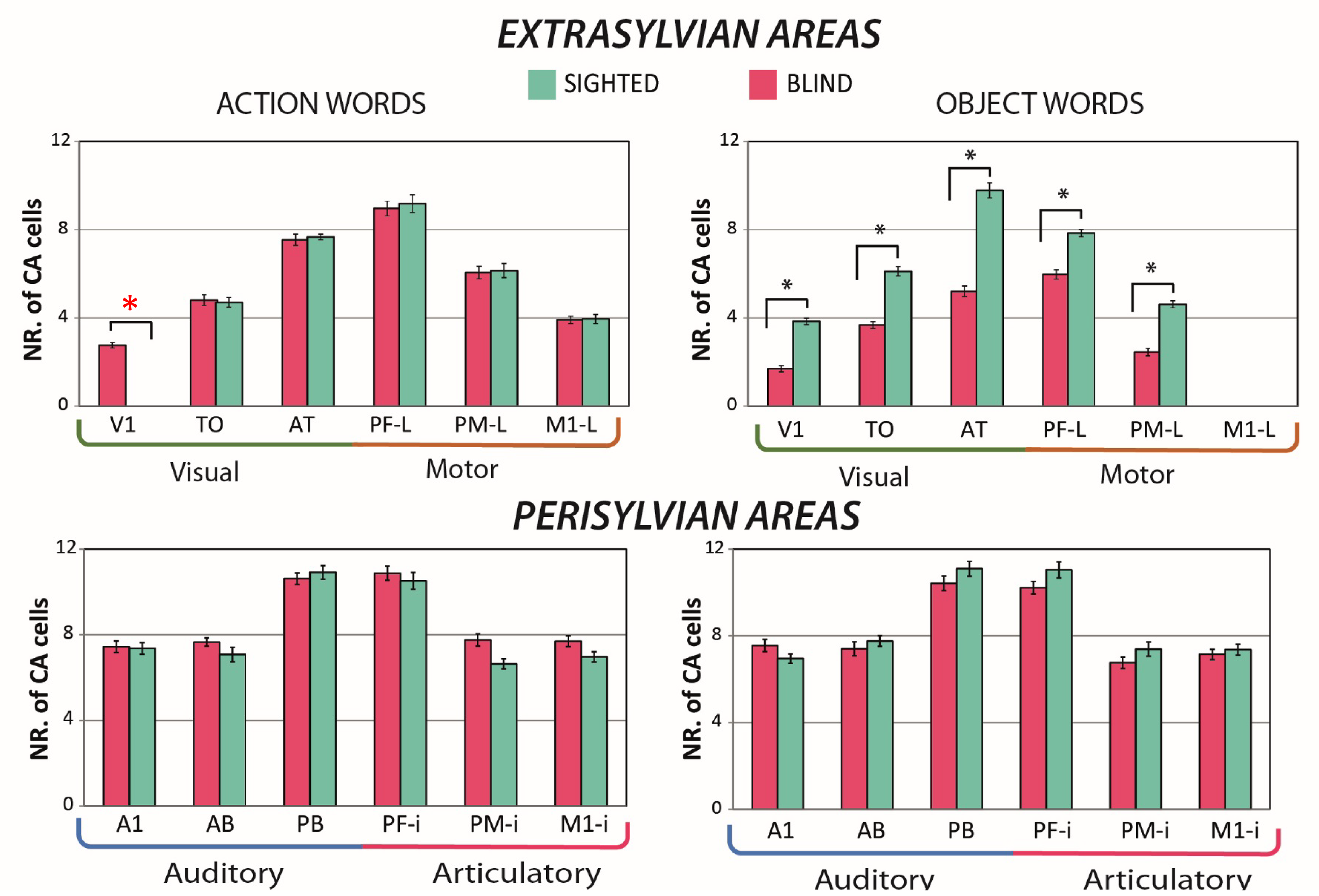
Research supported by: UK EPRSC & BBRSC (Grant no. EP/J004561/1, BABEL project)
Freie Universität Berlin and Berlin School of Mind and Brain

Word Learning Results

Learning the **association of word forms** in perisylvian language areas with the related **referential semantic information** led to the **formation of cell assemblies** (CA) across primary, secondary, and multimodal areas in both sighted (turquoise pixel) and congenitally blind (magenta pixels) models.

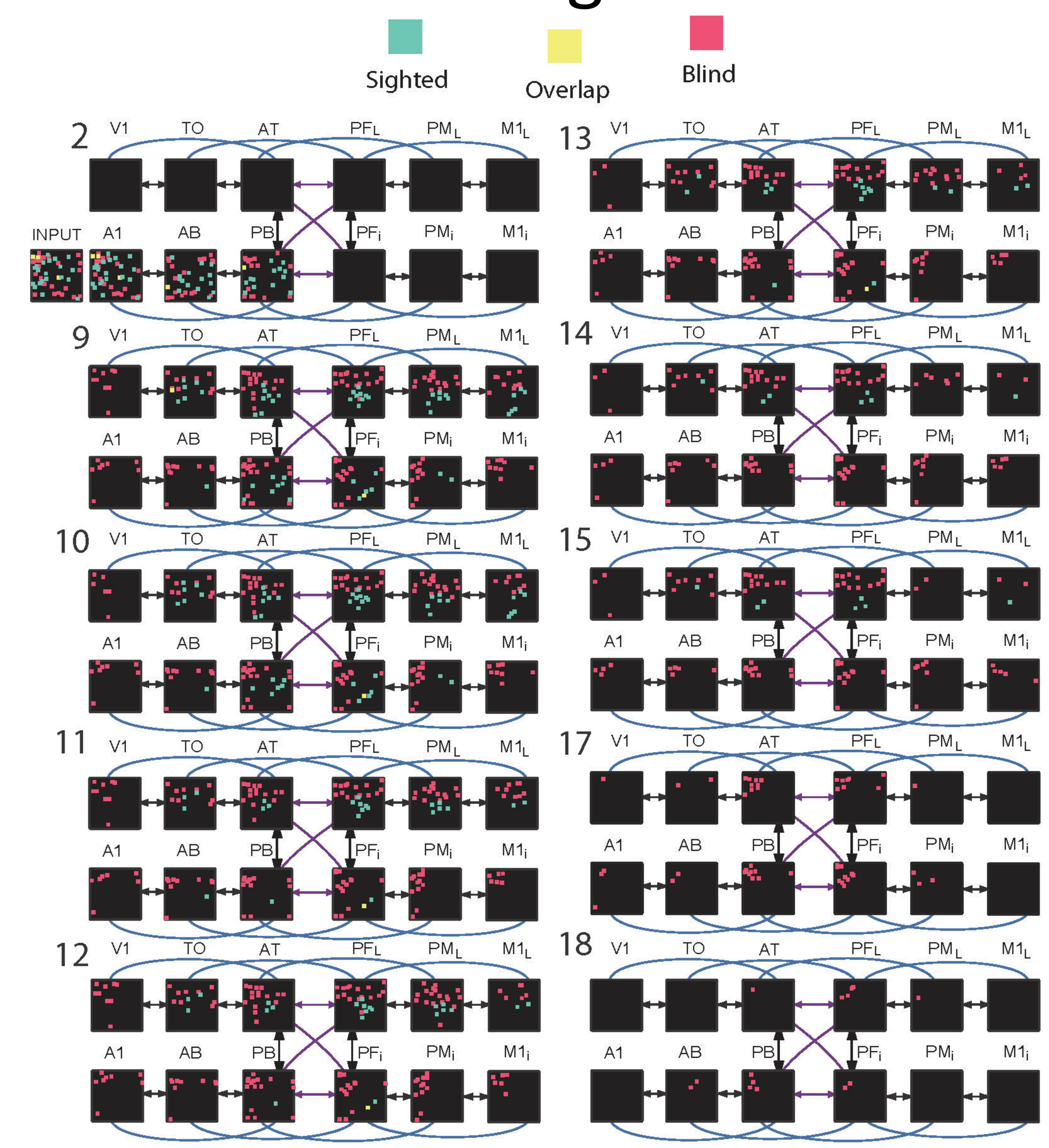


Only under visual deprivation (magenta pixels), distributed word-related **neural circuits 'grew into' the deprived visual areas** adopting a linguistic-semantic role.



- higher CA circuit density for action words in the primary visual area (V1) under visual deprivation; *Bonferroni-corrected planned comparison tests, corrected $p < 0.0083$ (V1 $p < 0.0001$)
- object-related CA circuits also extended in the deprived visual areas, however, with reduced neuron densities under deprived conditions ($p < 0.0001$);
- similar action- and object CA distribution in the perisylvian language areas for both models ($p = 0.68$);
- sighted models showed a category-specific semantic circuits with action circuits reaching into motor areas, but not into visual regions, and vice versa for object words [4-5];

Action Word Recognition



The blind model revealed **long-lasting spiking neural activity** compared to the sighted model during word recognition, which is a neural correlate of **enhanced verbal working memory**, in line with previous studies [2,6].

Conclusion

Three factors are crucial for explaining the visual cortex recruitment in blind people and the semantic category specificity in sighted individuals:

(i) Hebbian correlation learning and the 'Doursat-Bienenstock' expansion, which gives rise to the formation of strongly connected CA extending into adjacent/connected areas;
(ii) the absence of uncorrelated input to the visual cortex, which under normal conditions is critical for preventing the excessive CA extension and the formation of category-specific topographical distributions;
(iii) the connectivity structure modeled between the different cortical areas of the network, based on neuroanatomical evidence;

The present spiking neural network constrained by well-established neuroscience principles of cortical anatomy and Hebbian learning offers a neurobiological account of visual cortex reorganization following sensory loss from birth and its functional recruitment for language and semantic processing.

References:
[1] Bavelier, D., & Neville, H. J. (2002). *Nat. Rev. Neur.*, *3*(6).
[2] Amedi, A. et al. (2003) *Nat. Neurosci.* **6,** 758–766.
[3] Bedny, M. et al. (2011) *Proc. Natl. Acad. Sci.* **108,** 4429
[4] Tomasello, R. et al. (2018) *Fron . Comput. Neur.,* 12, 88
[5] Tomasello, R. et al. (2017) *Neuropsychologia* 98, 111
[6] Occelli, V., et al. (2017) *Exp. Brain Res.* **235,** 1709–1718
Reference of the present study: Tomasello, R., et al. (2019). Visual cortex recruitment during language processing in blind individuals is explained by Hebbian learning. *Scientific reports*, *9*(1), 3579. DOI https://doi.org/10.1038/s41598-019-39864-1