Tracking the time course of structural plasticity in motor learning using DWI: skill learning vs adaptation

Florencia Jacobacci[a,b], Gonzalo Lerner[a], Abraham Yeffal[a], Arnaud Boré[c], Marcia Renata Hidalgo-Marques[d], Edson Amaro[d], Jorge Armony[e], Jorge Jovicich[f], Julien Doyon[c,g], Valeria Della-Maggiore[a,b]

a IFIBIO-Houssay, School of Medicine, University of Buenos Aires, Buenos Aires, Argentina; *b* National Council for Scientific and Technological Research (CONICET), Buenos Aires, Argentina; *c* Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal - University of Montreal, Montreal, Quebec, Canada; *d* PISA, Faculdade de Medicina FMUSP, Univ. de Sao Paulo, Sao Paulo, Brazil; *e* McGill Univ., Montreal, Quebec, Canada; *f* Center for Mind/Brain Science (CIMEC), Univ. of Trento, Rovereto, Italy; *g* BIC, MNI, McGill Univ., Montreal, Quebec, Canada

florenciajacobacci@gmail.com

Background

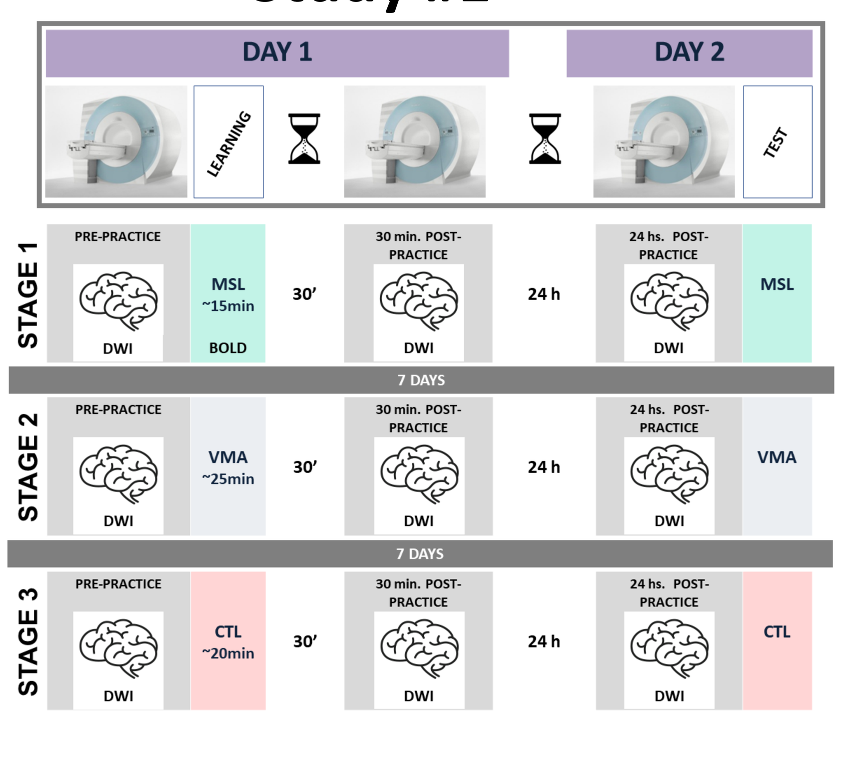
- Changes in grey and white matter structure occur in the healthy human brain following motor training (>1 week)[1-4].
- Learning-related plasticity can be detected in short time-scales using diffusion-weighted imaging (DWI) through a reduction in mean diffusivity (MD) in task-relevant regions. This MD reduction has been associated with a NMDA-dependent astrocyte hypertrophy, which may be indicative of sites of LTP induction[5,6].
- Motor learning but not mere motor activity is associated with synaptogenesis and with an increase in astrocytic volume[7].

In this study, we used MD maps to investigate the emergence of early cortical plasticity elicited by a short session of learning in two well-characterized motor learning tasks: sequence learning and adaptation. We also explored the evolution of cortical plasticity after motor memory consolidation.

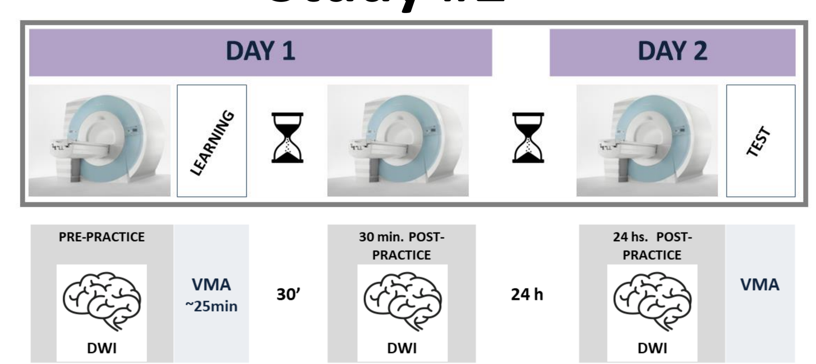
Motor sequence learning involves the acquisition a new motor skill with repeated practice of sequential movements. Motor adaptation requires us to adjust our actions by recalibrating motor commands to compensate the error introduced by perturbations.

Methods

Study #1



Study #2



DWI Acquisition

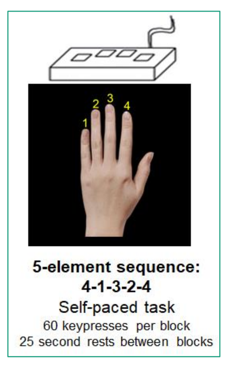
3T Siemens TIM TRIO Scanner with 12 channel head coil

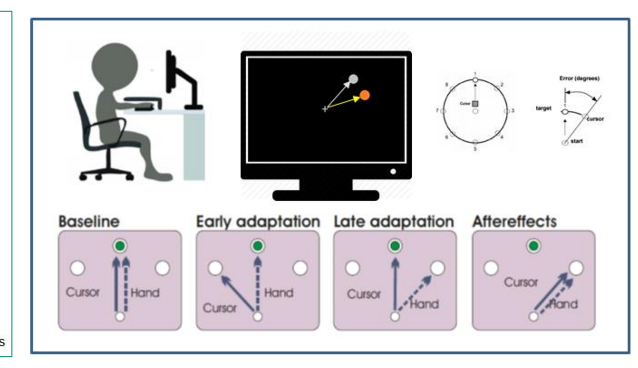
Multiband-accelerated sequence[8,9] (MB factor 2), Voxel size=2×2×2 mm^3, FOV=240x240 $mm^2$30 directions, b-value = 1000 s/mm^2, 70 axial slices, TR=5208 ms, TE=89 ms

STUDY 1:
1 acquisition with A-P phase-encoding direction
Duration 3 min 34 sec

STUDY 2:
2 acquisitions with A-P direction + 1 acquisition with P-A direction
Duration 10 min 42 sec

Motor tasks



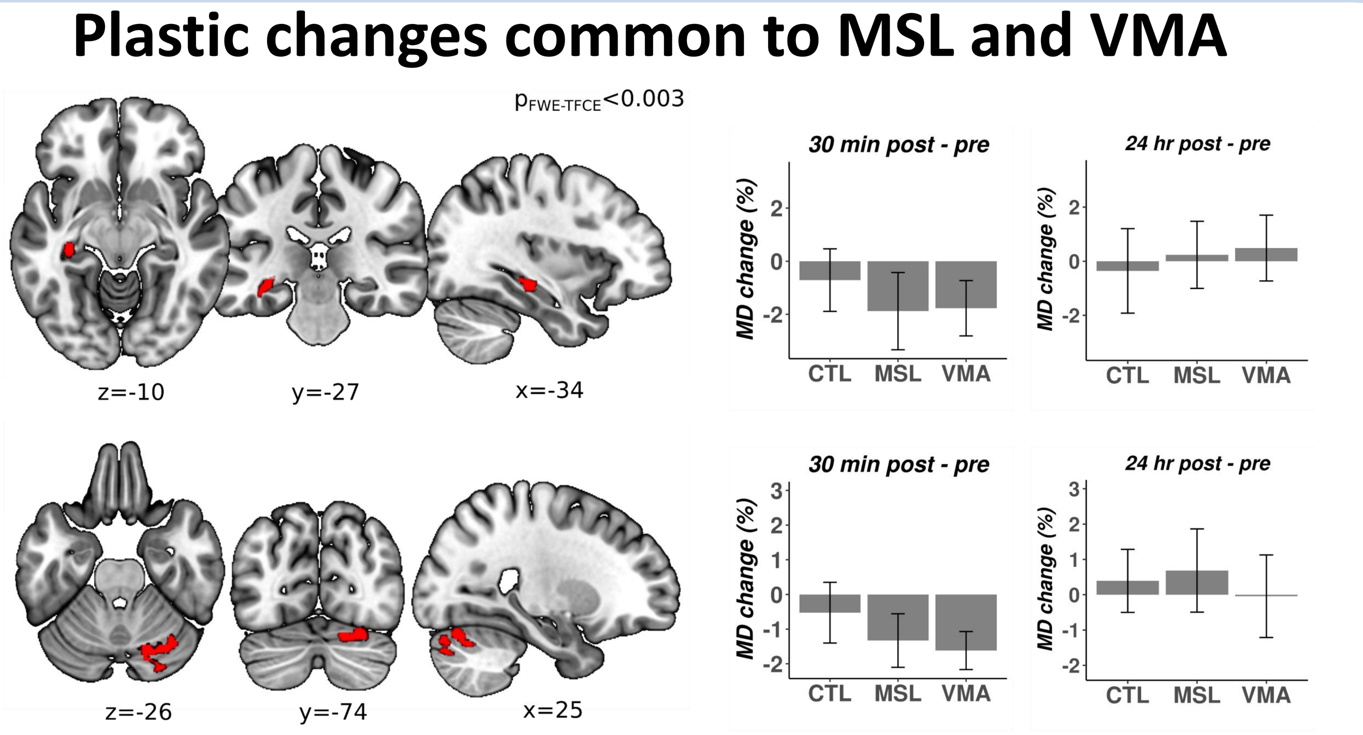


Processing and Stats

- Conversion of DW-images from DICOM to Nifti (dcm2nii)
- Distortion correction of images (FSL's topup + eddy)
- Diffusion Tensor model fit (FSL's DTIfit)
- MD Normalization to MNI152 using a non-linear pipeline based on ANTs that minimized reproducibility errors[10]
- Smoothing 4 mm FWHM
- Longitudinal MD changes associated with motor learning were statistically assessed using the Sandwich Estimator (SwE) toolbox for accurate modeling of longitudinal and repeated measures neuroimaging data[11].

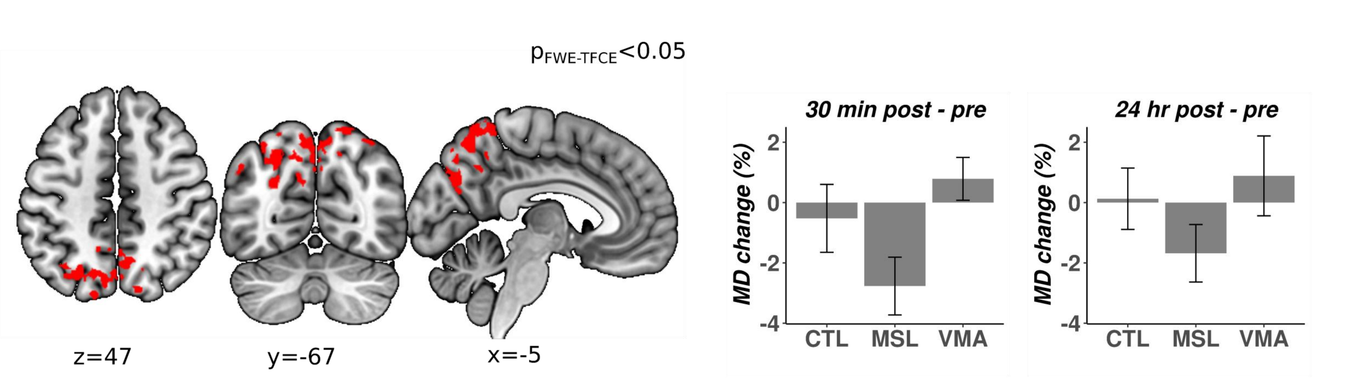
Results

1 Plastic changes common to MSL and VMA



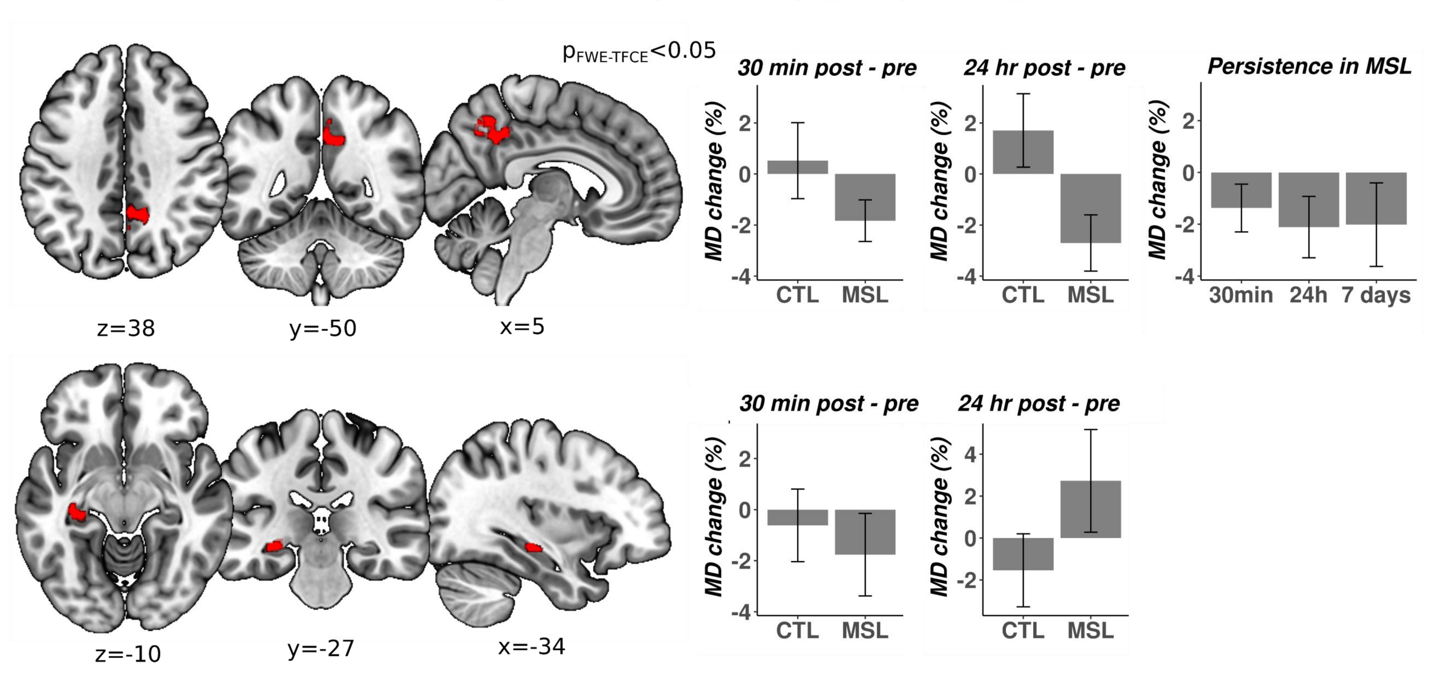
Time course of longitudinal changes in MD that are common to visuomotor adaptation (VMA) and motor sequence learning (MSL). MSL and VMA showed a reduction of MD in the right lateral cerebellum and the left hippocampus 30 min post-learning that returned to baseline at 24 hours. This temporal pattern was specific to motor learning, since it was not present in a control condition (CTL; go-nogo task). P-values<0.003 are FWE corrected using TFCE and shown in -log10 scale. Error bars represent the confidence interval of the mean. Orientation is neurological.

2 Interaction MSL vs VMA



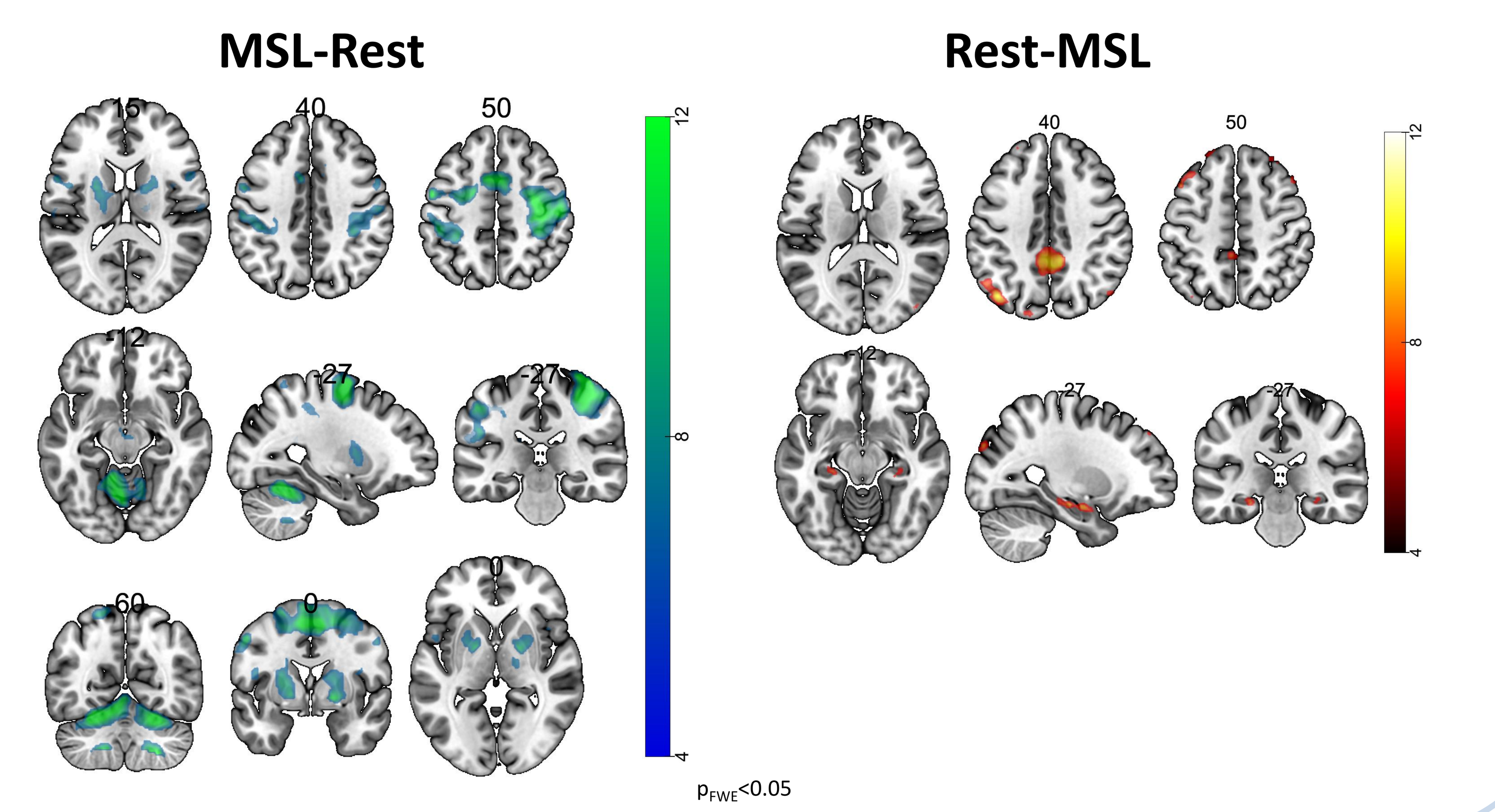
Time course of longitudinal changes in MD that distinguish MSL from VMA. A marked reduction in MD over the lateral posterior parietal cortex 30 min post-training, that persisted at 24 hours, distinguished MSL from VMA. P-values<0.05 are FWE corrected using TFCE and shown in -log10 scale. Error bars represent the confidence interval of the mean. Orientation is neurological.

3 Interaction MSL vs CTL

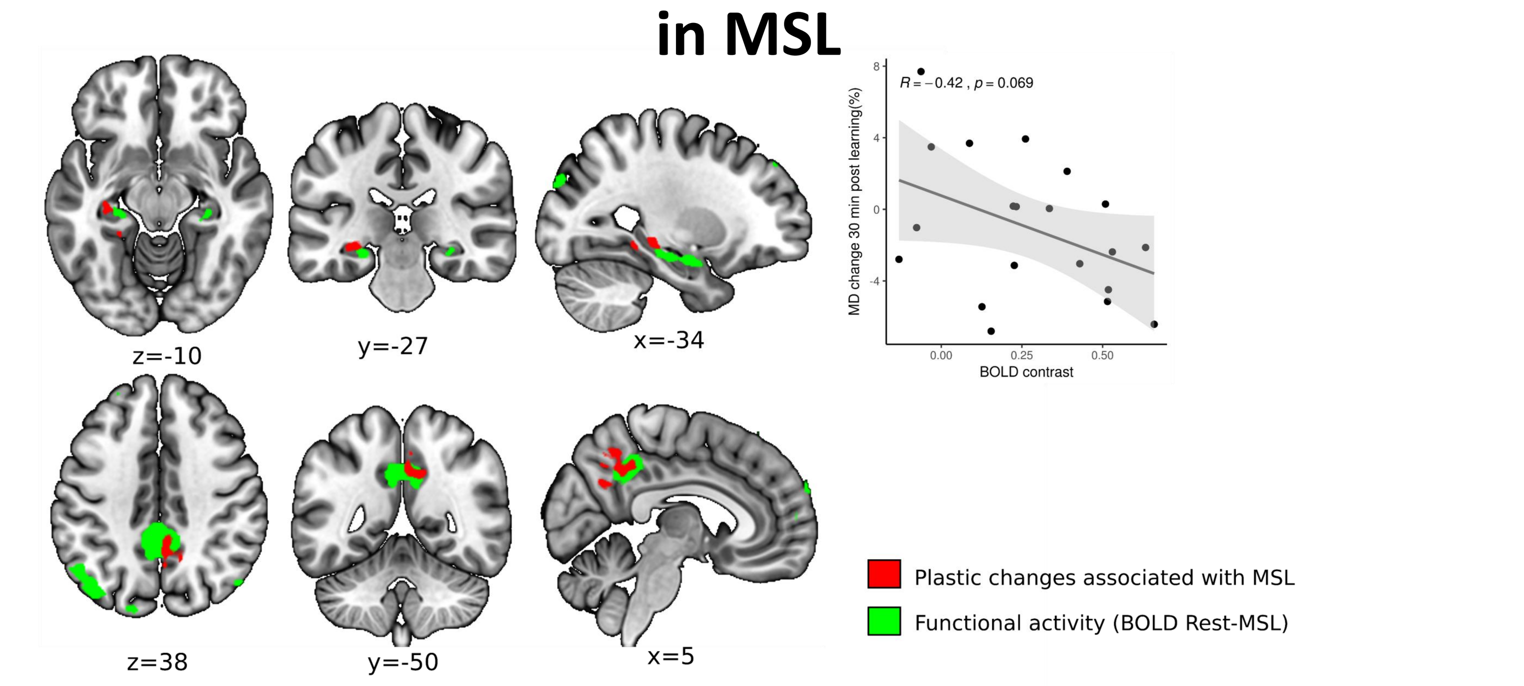


Time course of longitudinal changes in MD that are associated exclusively with motor sequence learning (MSL). MSL showed a reduction of MD in the precuneus 30 min post-learning, which persisted after 24 hs. MD remained below baseline levels even after 7 days for this brain region. In contrast, the reduction in the left hippocampus 30 min post-learning reverted at 24 hours. This temporal pattern was specific to motor learning, since it was not present in a control condition (CTL; go-nogo task). P-values<0.05 are FWE corrected using TFCE and shown in -log10 scale. Error bars represent the confidence interval of the mean. Orientation is neurological.

4 Functional activity during MSL

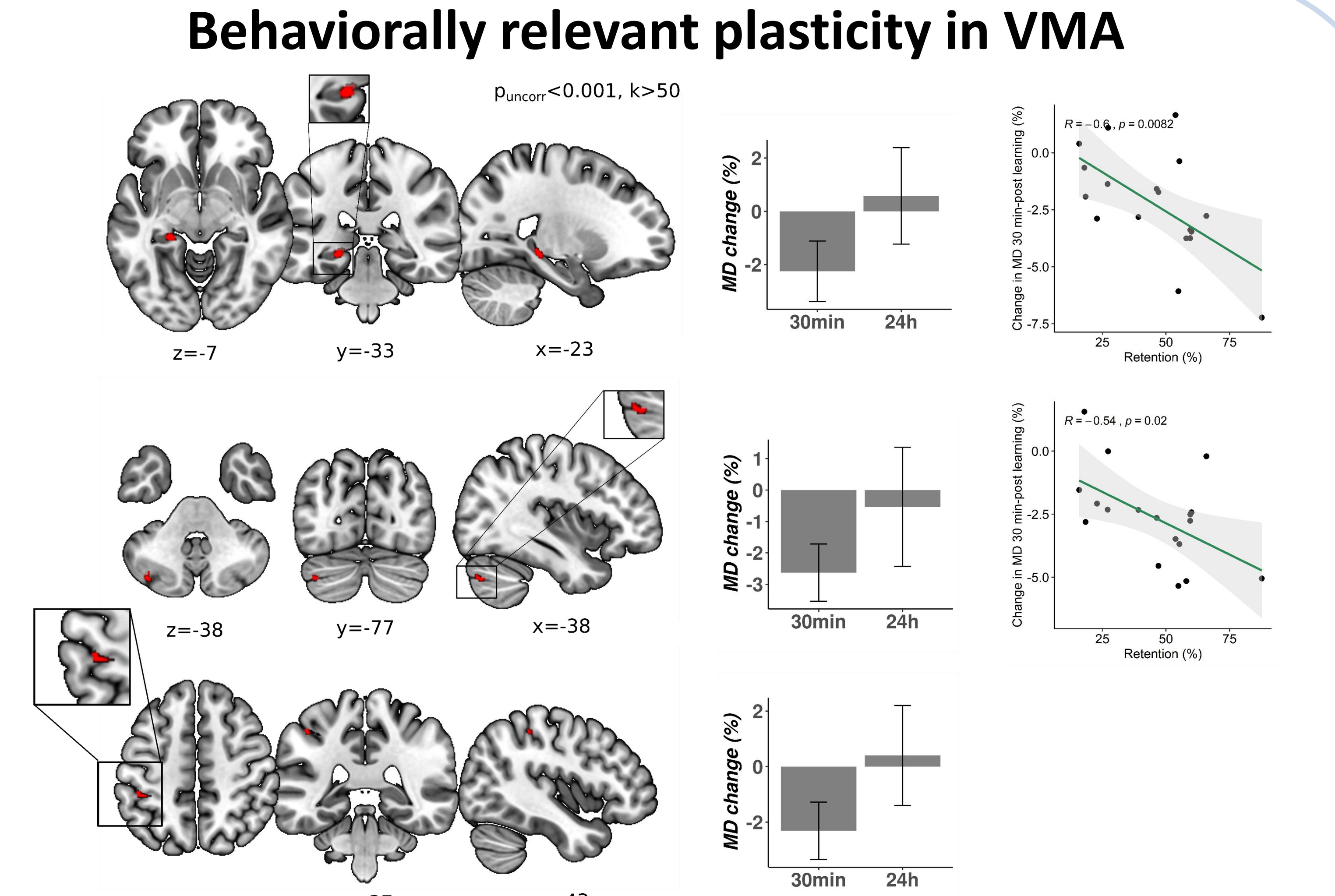


5 Relation between functional activity and plasticity in MSL



Plastic changes ocurring after motor sequence learning (MSL) are associated with functional activity.
Brain regions showing a functional deactivation overlap with areas showing MD changes after MSL. Futhermore, in the hippocampus a greater functional deactivation is associated with greater changes in MD 30 minutes post-training.

6 Behaviorally relevant plasticity in VMA



Time course of longitudinal changes in MD that are associated with visuomotor adaptation (VMA). VMA showed a reduction of MD in the left hippocampus, in the left cerebellum and in the parietal cortex 30 min post-learning. These alterations in MD returned to baseline levels after 24 hs. The plastic changes observed in the hippocampus and the cerebellum are behaviourally relevant since an MD reduction 30 min-post learning is negatively correlated with memory retention 24 hs later. Uncorrected p-values<0.001 are shown in -log10 scale. Error bars represent the confidence interval of the mean. Orientation is neurological.

Conclusions

- The left hippocampus is reliably modified by learning in both motor tasks (MSL and VMA) during a short time window.
- This result is consistent with previous work showing that the hippocampus is active during MSL[12,13], and with the fact that hippocampal amnesic patients show deficits in the consolidation of an MSL task[14].
- There are no previous reports directly linking the hippocampus with memory consolidation in VMA. Adaptation in HM was spared[15]. Yet, learning a hippocampal based declarative task after adaptation impairs memory retention[16].
- MD changes in MSL (precuneus and hippocampus) overlapped with areas active in the Rest-Task BOLD contrast. This may relate to the existence of micro offline gains during this task.[17]
- Changes in the precuneus area associated with MSL persisted after 24 hours after the end of training. These alterations proved to be long lasting, as they were still present after 7 days.
- The posterior cerebellum (VMA) and the precuneus (MSL) appear to distinguish the two tasks, whereas both engage the lateral anterior cerebellum

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