Supplementary Results and figure captions

LANGUAGE LEARNING UNDER WORKING MEMORY CONSTRAINTS CORRELATES WITH MICROSTRUCTURAL DIFFERENCES IN THE VENTRAL LANGUAGE PATHWAY

Diana Lopez-Barroso[2,3], Ruth de Diego-Balaguer[1,2,3,4,5], Toni Cunillera[3], Estela Camara[6], Thomas F. Münte[7], Antoni Rodriguez-Fornells[1,2,3]

Behavioral experiments

Experiment 2: Irrelevant speech (IS) vs. Baseline (BL)

Although participants from the experiment 1 were able to learn under the IS condition, we carried out a second experiment to assessed whether the saturation of the phonological store (IS condition) interfered with learning compared to the baseline (BL) condition without interference.

A new group of fifty-five healthy right-handed participants with similar characteristics to participants from the experiment 1 (mean age, 21.3 ± 2.6; 41 women) took part in the experiment 2. These participants were randomly assigned to the segmentation (n = 28) or rule learning conditions (n = 27). All participants were paid or received course credits.

No significant differences were found between both conditions (IS vs. BL), Language condition (segmentation/rule learning) or their interaction (all $P > 0.1$). Performance in both IS and BL conditions was greater than chance (segmentation condition IS: $t_{27} = 4.6$, $P < 0.0001$, and BL: $t_{27} = 4.6$, $P < 0.0001$; rule learning condition, IS: $t_{26} = 4$, $P < 0.0001$, and BL: $t_{26} = 2.8$, $P < 0.001$) (see Figure S1)). Consistent with the first experiment, these results suggest that interference with the phonological store does not prevent segmentation or rule learning and does not produce interference when compared to a BL condition. Comparing the AS and BL conditions across both experiments (1 and 2) indicated that, in contrast to the IS condition, AS interfered with learning compared to BL. Although performance in the BL and AS conditions was greater than chance (one sample *t*-test: AS: $t_{51} = 3.2$, $P < 0.01$; BL: $t_{54} = 5.3$, $P < 0.0001$), performance was improved in the BL compared to the AS condition ($t_{105} = -2$, $P < 0.05$, $d = 0.40$). This difference could not be explained by group differences because the IS performance of the two groups did not differ ($t_{105} = -55$, $P > 0.5$, $d = 0.003$).

Experiment 3: Articulatory suppression (AS) vs. Baseline (BL): a between-subjects design

A third behavioral experiment was developed with the aim to evaluate whether the articulatory rehearsal blockade causes a specific impairment in rule learning and speech segmentation when compared to a baseline condition. In addition, the present study used a between-subjects design in order to confirm interference effects of the AS condition, but without any possible confound due to strategic effects that may arise in intra-subject experiments.

Seventy-seven new right-handed participants took part in this experiment (mean age 22.1 ± 4.2; 56 women). Participants had similar characteristics to participants in experiments 1 and 2 and they were paid for their participation. Each participant was randomly assigned to one of the four possible conditions (AS condition in a rule learning task: n = 19; AS condition in a segmentation task: n = 19; BL condition in a rule learning task: n = 19; BL condition in a segmentation task: n = 20). The materials and procedures were the same as those used in previous experiments except that, in this case, the two working memory conditions compared were an AS condition (as in the first experiment in this article) and a BL condition without constraints. As in experiments 1 and 2, statistical effects were significant when an arcsine transformation was applied to the data.

Univariate ANOVA analysis revealed a main effect of condition (AS/BL) ($F_{1,73}$ = 8.83, $P < 0.005$, $\eta_{p^2} = 0.11$), supporting the previous effect encountered in the comparisons between Experiments 2 and 1. Thus, although again both conditions were above chance (AS: 54.7 ± 14 %, $t_{37} = 2$, $P < 0.05$; BL: 65 ± 15 %, $t_{38} = 5.9$, $P < 0.0001$, see Figure S1), performance under the AS condition was impaired as compared to the BL condition ($t_{75} = 3.01$, $P < 0.005$, d = 0.65). No differences between segmentation and rule learning were found ($P > 0.1$).

Further DTI-behavioral performance correlations:

Although we found no evidence of a different pattern of WM support to segmentation and rule-learning processes, correlation patterns between individual differences in learning and white matter microstructure were partially task-specific. In the AS condition, the separate analysis of segmentation (n = 21) and rule learning (n = 23) conditions revealed no significant correlation even at more liberal thresholds ($P < 0.05$, uncorrected). However, the rule learning level under the IS condition correlated with the FA values in the right middle cerebellar peduncle [whole-brain analysis ($P < 0.001$, uncorrected); MNI peak coordinates (X, Y, Z): 31 -48 -33, *t*-value = 5.07, $P < 0.005$, corrected at cluster level, 60-voxel spatial extent (see Figure S2)]. No significant correlation was found at this threshold for the segmentation group, but again a different pattern of correlations was found at a lower threshold ($P < 0.01$ uncorrected) in the anterior cingulum [MNI peak coordinates (X, Y, Z): -18 30 -5, *t*-value = 2.54, $P < 0.01$ corrected at cluster level, 60-voxel spatial extent (see Figure S2)]. Although the relevance and function of this path related to our task is still unclear, we highlight this pattern is different from the one obtained in the AS condition.

Figure captions

<u>Figure S1</u>

Distributions of the percentages of correct responses (for segmentation and rule learning together) in the two alternatives forced-choice test for experiment 2 and 3. The test was administered after each language exposure in the irrelevant speech (IS), articulatory suppression (AS) and baseline (BL) conditions. * $P < 0.01$; ** $P < 0.005$. Each point corresponds to an individual participant score, and pentagons denote the group mean for each condition.

<u>Figure S2</u>

Individual differences in the learning conditions correlated with fractional anisotropy (FA) of major white matter tracts. **A**. **Left:** for the segmentation condition, significant white matter-correlated clusters rendered on the FA mean image ($P < 0.01$, n = 60 voxels). **Right**. Relationship between mean FA value for each participant at the peak of the correlated ROI and performance in the IS condition [left anterior cingulum, peak MNI coordinates x = -18, y = 30, z = -5]. **B. Left:** for rule learning condition, significant white matter-correlated clusters are rendered on the FA mean image ($P < 0.001$, n = 60 voxels). **Right:** The relationship between mean FA value for each participant at the peak of the correlated ROI and performance in the IS condition [right middle cerebellar fascicle, peak MNI coordinates x = 31, y = -48, z = -33]. All the results are shown with a more liberal statistical threshold to visualize the white matter pathways ($P < 0.001$; $P < 0.005$; $P < 0.05$; n = 60). Color bar indicates the *P* values.

References

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