

“Role of the working memory phonological loop subcomponents in rule-based learning and segmentation of language: a behavioural and DTI neuroimaging study”

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Abstract

To learn a new language, we need the capacity to identify the words which compose it, and to extract the structural information which govern it and guide grammatical acquisition. These two processes may be supported by phonological loop subcomponents of working memory: the phonological store and the articulatory rehearsal. The specific contribution of each subcomponent in segmentation and in rule extraction and the possibility of a differential weight in these two learning processes remains still a matter of controversy and represents the major issue of the present study. Moreover, since the last decade, neuroimaging studies have tried to attribute a neural place of each subcomponent as well to define the brain networks associated with the language learning process. By blocking the rehearsal mechanism and the phonological store while learning an artificial language we studied whether the two subcomponents of the phonological loop contribute in a different way to both segmentation and rule learning in language. In addition, the neural pathways related to successful learning in each condition were studied using Diffusion tensor imaging (DTI). Results showed that although the phonological store seems to optimize language acquisition, the rehearsal seems to represent the crucial component to successfully perform the word segmentation and rule extraction processes. DTI analyses stand out the role of subcortical structures connecting with prefrontal and parietal cortical areas in language acquisition probably coordinating the articulatory and attentional functions they handle.

Introduction

Language as a communication skill is known as the human capacity *par excellence*. The actual mechanisms that allow humans to learn and produce the complexity of language remain a key question in actual neuroscience. In order to learn a new language, the *word segmentation* process supposes a first step necessary to isolate the words embedded in a continuous sound stream (1). Word segmentation could be carried out even when no semantic or prosodic information are available by computing the higher transitional probabilities of adjacent syllables within words (2) and using it to establish the word boundaries. Since this point, children facing their first language or adults facing a second language learning are in the position to store the isolated words (word learning) as well as to extract the non-adjacent dependencies which are structuring the language and will be the source of grammatical acquisition (3).

The way in which the different cognitive functions orchestrate to support these distinct steps in language acquisition is still largely unclear. Nevertheless, there is extensive evidence about the crucial role of working memory in children acquisition of new vocabulary (4, 5) and in second language learning (6). The phonological loop is the working memory subcomponent involved in the temporary maintenance and manipulation of the acoustic and verbal information while more fixed memory representations are being constructed (7). Its characterisation has been developed from evidence from a range of different views as cognitive psychology or neuropsychology, and more recently this disciplines have been able to take benefit from new neuroimaging techniques (8, 8-11). It is further divided into two subcomponents, one of them is the limited-capacity passive *phonological store*, which retains verbal and acoustic information. Due to its passive nature and its limited capacity this component is sensitive, among other factors, to the concurrent presentation of irrelevant speech while performing a verbal task (5, 12). In addition, this information tends to decay over a period of about two seconds, unless refreshed by the second subcomponent, the *articulatory rehearsal*. Through a subvocalization mechanism it enables to maintain the

information active in the store for a longer period of time to allow eventual manipulation. This rehearsal mechanism can be blocked by uttering an irrelevant syllable while performing a task. Due to these characteristics it has been suggested that the phonological loop could be strongly related with acquisition and processing of language (4, 5).

Indeed, the phonological loop has been proposed as an essential mechanism in children's first language and even more prominently in adults' second language acquisition (13). In regard to first language acquisition, evidence points that during early childhood the phonological loop is basically composed by the phonological store only. The rehearsal mechanism, if present, has a much slower articulatory activity than in adulthood. The first evidence of robust rehearsal component appears around seven years of age (4, 14, 15). The appearance of rehearsal allows the child to maintain increasing amounts of verbal information in the phonological store, but until then, and even without rehearse, children's phonological store itself appears to be enough to sustain a significant short-term memory load which lets them acquire the language properties (14). These studies have used a non-word repetition task. The non-word repetition task is able to measure the general phonological loop capacity independently of lexical knowledge, however, it lacks subcomponents specificity. Nonetheless, the fact that this measure correlates with learning of phonological forms of new words (16) together with the absence of rehearsal in early childhood, has been interpreted as support for the phonological store as the essential word learning device (4), being the rehearsal just a supporting mechanism. Nevertheless, there is evidence regarding a more prominent role of the rehearsal component during adult second language learning. For example studies with adults have found a harmful effect of articulatory suppression in new word learning (17). Therefore, although in children's first language the store could play a crucial function, in second language acquisition its role could be less relevant than the rehearsal component.

On the other hand, the neuroanatomical substrates of verbal working memory has been widely studied (18-21). Most neuroimaging data principally show that the phonological store component of the phonological loop is sustained by the left supramarginal gyrus (BA 40), while the articulatory rehearsal is related to the left ventrolateral prefrontal cortex (BA 44/45), left pre-SMA (BA 6), left premotor cortex (BA 8) and right cerebellar cortex (22). From a somewhat alternative view to Baddeley's proposal, Cowan's model of working memory (23) relates supramarginal gyrus (BA40) to an attentional controller component selecting the information from the store that will be handled in the focus of attention to avoid decay. The role of subcortical structures in this topic has been less studied than the cortical participation, however, the key position of these structures as a funnel from the above mentioned brain regions speaks for its role in the coordination between the different subcomponents of working memory. Indeed, recent evidence supports the role that some subcortical structures have in working memory (11, 24) as well in second language acquisition (25) and syntactic and semantic aspects of language processing (26, 27).

In the present work, based in the classic model of working memory from Baddeley and Hitch (28), we have focused in one of its components: the phonological loop, to study the differential contribution of its two subcomponents (phonological store and rehearsal) in two essential processes of language learning (segmentation and rule-learning from speech). While the function of the phonological loop in learning new words has been documented and there is evidence pointing to its role in the segmentation process (29), to our knowledge, there are no results about the contribution of the specific phonological loop subcomponents. Related to rule-based language learning, a study has found a relation between phonological short-term memory and rule learning in language, nonetheless they did not distinguish between working memory subcomponents neither (30). Taking together the above background, we were interested to dissociate how the blockade of

either the phonological store or the articulatory rehearsal affects segmentation and rule extraction. **Experiment 1** was a behavioural study conceived to assess the role of the rehearsal process in segmentation and rule learning. **Experiment 2** was aimed to investigate the role of the phonological store upon these same processes. After this first behavioural approximation, and with the aim to correlate the performance in each condition of experiment 1 with brain pathways associated with the success in the language learning task, subjects were scanned to obtain diffusion tensor imaging (DTI) data (**experiment 3**). The study of in vivo structural connectivity between brain areas in humans has been possible thanks to the Diffusion tensor imaging (DTI) technique. Thus, the obtained information brings us the opportunity to relate behavioural performance in each condition with the neural pathways which connect critical areas for successful learning.

Experiment 1: Role of the articulatory rehearsal in word segmentation and rule learning

Material and method:

Participants:

Fifty-two subjects (mean age: 22.1; SD: 2.36) with no neurological or auditory problems participated in this experiment. All subjects were native speakers of Spanish and they were paid for their participation in the study. Subjects were randomly distributed to one of each between subject condition (word segmentation group: N = 25; rule-learning group: N = 27).

Material:

Two different language streams were created for each condition (segmentation and rule-learning) by using the text-to-speech synthesizer MBROLA with a Spanish male diphone database at 16 kHz (31). We decided to use two different language streams to control for possible arbitrary listening preferences. Each stream was made by concatenating the trisyllabic nonsense words of each language in pseudorandom order so that a word was never immediately repeated in the stream. All phonemes had equal duration (116 ms) and pitch (200 Hz; equal pitch rise and fall, with pitch maximum at 50% of the phoneme). Thus, the duration of each word was 696 ms. All the selected phonemes existed in Spanish and the words of the artificial language respected the phonotactics of that language. Words were combined so that each word in the stream was followed by each of the other words equally often. During the learning phase, participants were exposed to two minutes of each language stream. Language streams were counterbalanced between conditions (ASC / ISC) and subjects were never exposed to the same language stream twice. None of the syllables were repeated across languages.

- **Word Segmentation condition:** Language streams in this condition were built following the structure of Saffran et al. (1) 36 different CV syllables, 18 for each language stream, were combined to create 6 different trisyllabic nonsense words for each language. The language streams were already used in a previous study (32). The synthesizer did not insert any acoustic word boundary cues and produced equivalent levels of coarticulation between all syllables. Thus, the only reliable cue for word boundaries in all streams was the transitional probability of the syllables, being 1.0 for the syllables forming a word and 0.14 for syllables spanning word boundaries.

- **Rule learning condition:** Two different sets of 9 trisyllabic nonsense words for the two languages. Forty-eight different CV syllables were combined to create the two language streams, following the structure created by Peña et al (3). Words were built following a rule which established that their initial syllable determined their ending (e.g. **lekadi**, **lefidi**, **lerodi**) irrespective of the middle element forming a structure similar to some morphological rules (e.g. **unbelievable**, **untreatable**, **unbearable**) (table 1). Those language streams were already used in a previous study (33) confirming that subjects were able to learn both words and rules from this material. Words in the language had the same duration as the words from the segmentation condition, 696 ms, but in this case, they were pre-segmented by 25 ms pauses, as in Peña et al. to induce extraction of structural information and avoid measuring here again segmentation abilities. As the same three middle syllables appeared in the three frames of a given language, the transitional probability between the initial and middle syllable, or between this one and the final syllable was 0.33. The transitional probability between the first and the last syllable of every word was 1.0 and the probability between the last syllable of any word and the first syllable of the following one was 0.5.

Test stimuli:

- **Word Segmentation condition:** test items were created in order to test the participants' segmentation ability. In addition to the 6 words from the learning phase, 36 non-words were created for each language by recombining the syllables of the 6 words composing the stream. Non-words were sequences of three syllables never forming a word in the language stream. 18 of these were created by concatenating the last two syllables of a word and the first one of another, and the other 18 were concatenations of the last syllable of a word and the first two syllables of another (see table 1). During the test phase, participants had to choose between a total of 36 pairs of words and part words.

Table 1 Material used for the segmentation condition. Nonwords were formed by recombining the syllables composing the words (ABC) in two ways: BCA or CAB. Word and Non-word columns provide examples of test items.

	Words		Nonwords
Language 1	demuri	medapo	murise
	senige	rakuso	riseni
	kotusa	lirepu	
Language 2	pabela	kifobu	beladu
	lufagi	tagofu	lalufa
	dubipe	rutega	

- **Rule learning condition:** in addition to the 9 words appearing in the language, new items were created for the test phase. In order to assess the rule-learning abilities, 9 non-words and 9 rule-words were formed for each language. Non-words were created with the same three syllables of the previously exposed words but with the syllables corresponding to the structural frame in the inverted order (see table 2). In contrast, rule-words were created

with the same initial and final syllable of a word from the exposed language while a syllable corresponding to another word was inserted in the middle position. Thus, even though these new words followed the structure of words in the artificial languages, the participants had not heard these rule-words before enabling to test for the generalisation of the acquired rule. During the test phase, participants had to choose between a total of 18 trials of rule-words and non-words pairs.

Table 2 Material used for the rule-learning condition. Middle syllables could be combined with the three structures of the language. Word, Non-word and Rule-word columns provide examples of test items.

	Embedded structures	Middle syllables	Word	Non-word	Rule-word
Language 1	le__di	ka, fi, ro	lerodi	dirole	lemadi
	bo__ma				
	to__ne				
Language 2	ba__gu	fe, pi, lo	bapigu	gupiba	badogu
	do__ke				
	mo__ti				

Procedure:

The experiment consisted in learning two artificial languages under two learning conditions: the Articulatory Suppression Condition (ASC) and the Irrelevant Speech Condition (ISC). During the learning phases, subjects were told that they would hear a nonsense language and that their task was to pay attention to it because they would be asked to recognize words of this language after listening to it. Subjects were given no information about the structure or the length of the words or how many words composed the language. Before the beginning of the learning conditions, participants were required to record their own voice uttering the syllable “bla” during two minutes with equal frequency and volume by using a digital voice recorder. The ASC involved an articulatory suppression task to block the use of the rehearsal mechanism of phonological working memory. In this condition, participants were asked to continuously utter the word “bla” while they were hearing the language stream. The ISC was a condition with phonological interference obstructing the capacity of the phonological store. In this condition, participants were informed that they would hear their own previously recorded voice while they were hearing the artificial language. They were asked to pay attention to the nonsense language stream, while ignoring the irrelevant voice stream. The presentation order of each intra-subject condition (ASC and ISC) was counterbalanced across participants resulting in 24 participants who performed the articulatory suppression condition (ASC) in the first place and 28 participants who performed first the irrelevant speech condition (ISC).

Each participant was presented with either two streams where only words could be learned by segmenting the continuous stream (word segmentation condition) or with a stream where rules could be extracted from the stream composed of pre-segmented words (rule-learning condition). They were tested individually for either segmentation or rule-learning, respectively, while seated in front of a 15” screen in a sound attenuated room. Both the language and the voice streams (in

the ASC) were presented through four loudspeakers (two for the language stream and two for the ISC stream). The loudspeakers were located symmetrically with an angle of 45° and at approximately 30 mm distance at each side of the subject and were played at equal volume.

Each learning phase in both the articulatory suppression and the irrelevant speech condition was followed by a two-alternative forced choice test. For each test trial, participants heard two trisyllabic words, separated by 700 ms in the rule learning condition and 500 ms in the word segmentation condition. Subjects were requested to press either the “1” or “2” key on the keyboard to indicate if either the first or the second word of the pair was a word from the language learned. Test trials were presented in random order. The order of presentation of the test items in the pair was counterbalanced for each subject.

Results

A repeated measures ANOVA was conducted with condition (ASC/ISC) as within subject factor and with task (segmentation / rule learning) and order (ASC first/ISC first) as between subject factors. The overall mean was 58.3% (± 13) in ISC and 55.34% (± 11.9) in ASC. The mean in all conditions was significantly different than chance (50%) (segmentation group: ISC $t(24) = 3.74$, $p < .01$ and ASC $t(24) = 2.45$, $p < .01$; rule-learning group: ISC $t(26) = 2.85$, $p < .01$ and ASC $t(26) = 2.16$, $p < .05$). However, the difficulty introduced with interference in the two conditions led to results close to a floor effect (set at a chance level of 50%) (see **table 3**). The analyses showed no significant main effects of condition or task or significant interactions (all $P < .1$).

Thus, in order to improve the sensitivity of our manipulations in the context of the difficulty introduced, we decided to run a post-hoc analysis with only those subjects that were able to learn in the easier condition, the irrelevant speech condition (ISC). The rationale under this selection is that the effect of articulatory suppression can only be observed in those subjects that are able, individually, to learn at least in the easier condition, the ISC. The articulatory condition involves an introduction of background noise in the auditory stimulation by the articulated syllables as in the ISC. Therefore, the ASC condition was actually interfering both with the storing and the articulatory component of the model. Thus, only those subjects able to learn in the storing condition can show an additional effect of articulatory suppression if this component is necessary in the learning process.

We applied a binomial test to create our group of interest. Thus, this group included those subjects with an individual performance at or above 63% for a 36-items ISC test with a p value $< .05$, in the segmentation test. The cut off in the rule-learning test was 66% for a 18-items test with a p value $< .05$. After the application of these filters, 21 subjects remained, 11 in the segmentation group and 10 in the rule learning group. We carried out a repeated measures ANOVA using the same within and between subject factors as in the first whole sample analysis. These analyses showed a main effect of condition (ISC/ASC) in global performance reflecting a better performance in the ISC than in ASC ($F(1,17) = 24.7$, $p < .001$). However, no effect of task was found, neither a task by condition interaction (both $F_s < 1$). Thus, in the subsequent analyses segmentation and rule conditions were collapsed together. A substantial interference was observed in the ASC compared to the ISC (see **figure 1**) ($t(20) = 4.9$, $p < .0001$). Moreover, only the ISC differed from chance (50%) ($t(20) = 25.5$, $p < .0001$) (see **table 3**).

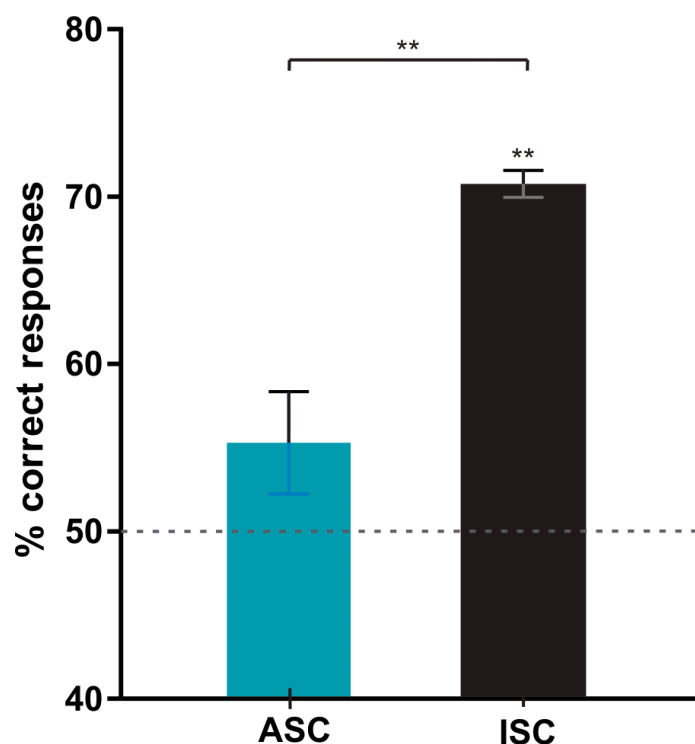


Figure 1: Percentage of correct responses in experiment 1 for segmentation and rule learning (n = 21). ASC: articulatory suppression condition; ISC: irrelevant speech condition. **p < .0001

Table 3: Means and SD in experiment 1 for the whole sample and the learner group. ASC: articulatory suppression condition; ISC: irrelevant speech condition.

	ASC (all sample)	ISC (all sample)	ASC	ISC
Segmentation	55.11 (10.41) n = 25	58.88 (11.86) n = 25	53.03 (13.11) n = 10	70.20 (3.74) n = 10
Rule learning	55.55 (13.34) n = 27	57.81 (14.22) n = 27	57.22 (15.05) n = 11	70.55 (3.74) n = 11
Segmentation & rule learning	55.34 (11.91) n = 52	58.33 (13.02) n = 52	55.02 (13.88) n = 21	70.37 (3.66) n = 21

Discussion of Experiment 1

The results obtained suggest that the articulatory rehearsal, one of the two components of the phonological loop represents an important factor to successfully perform the cognitive operations embedded in word segmentation and rule extraction.

Focusing in the analyses in people who could perform the task with success in the easier irrelevant speech condition, segmentation as well as rule learning appeared to be disrupted by articulatory suppression while participants were trying to learn a new artificial language. Interfering with the rehearsal completely blocked learning, even in good learners, because

performances dropped to chance levels. The experiment did not show evidence for a differential effect of the articulatory component for adjacent segmentation and the extraction of non-adjacent rules. Thus, according to our results, it appears that articulatory rehearsal is essential to both make the computational operations required for segmentation and to extract the non-adjacent rules embedded in the presented language.

Experiment 2: Role of the phonological store in word segmentation and rule learning

Material and method

Participants:

Fifty-five subjects (mean age: 21.3; SD: 2.6) with no neurological or auditory problems participated in this experiment. All subjects were native speakers of Spanish. The participants received extra course credit for their participation in the study. As in experiment one, subjects were randomly assigned to one of each between subject condition (word segmentation group: N = 28; rule-learning group: N = 27).

Material:

The same training and test stimuli of the experiment 1 were used to test word learning and rule learning.

Procedure:

This experiment consisted in learning two artificial languages under a baseline (BLC) and an irrelevant speech condition (ISC). BLC was a pure condition without interference and the ISC was identical to that used in the first experiment. The procedure was the same as in experiment 1. The presentation order of each intra-subject condition was also counterbalanced for each participant resulting in 29 participants who performed the baseline condition (BLC) in the first place and 26 participants who passed in the first place the irrelevant speech condition (ISC).

Results

A first general repeated measures ANOVA with the same within- and between-subject conditions as in the experiment 1 was carried out, using the whole sample. Following the results obtained in the first experiment, we found no significant effects neither for condition ($F < 1$) nor for task ($F(1, 51) = .681, p < .4$). The task by condition interaction was not significant either ($F(1, 51) = 1.32, p < .2$). However, the overall performance was 60.5 % (± 14.7) in BLC and 59.6 % (± 11.6) in ISC and mean performance was above chance both in the word segmentation group, in BLC ($t(27) = 4.69, p < .0001$) and in ISC ($t(27) = 4.69, p < .0001$), and in the rule-learning group, in BLC ($t(26) = 2.85, p < .01$) and in ISC ($t(26) = 4, p < .0001$).

Because, in this case, difficulty was decreased with the baseline condition without interference and there was enough space for interference, the results suggest that the interference with the

phonological store does not block segmentation or rule learning in this artificial language learning. However, in order to ensure this conclusion we followed the same reasoning previously applied in experiment 1 to perform a second post-hoc analysis. According to this reasoning only those subjects that individually show performances above chance in the easier condition (BLC) should be able to show interference when storing suppression is introduced. Thus, the same binomial test described in experiment 1 was applied in the segmentation and rule learning condition. After that, the group of interest was composed by 24 participants, 13 of them from the segmentation task and 11 from the rule learning task.

Participants showed better performance in BLC than in ISC ($F(1,20) = 39.0, p < .0001$) (see **figure 2**). However, the interference introduced in the irrelevant speech condition was only partial because subjects could still perform better than chance (50%) in both the conditions (ISC: $t(23) = 4.567, p < .0001$; BLC: $t(23) = 17.344, p < .001$) (see **table 4**). In contrast to the previous experiment there is a marginal effect of task ($F(1, 20) = 4.115, p < .056$), this is, the segmentation task was better performed than rule extraction. However, task and condition did not interact ($F < 1$).

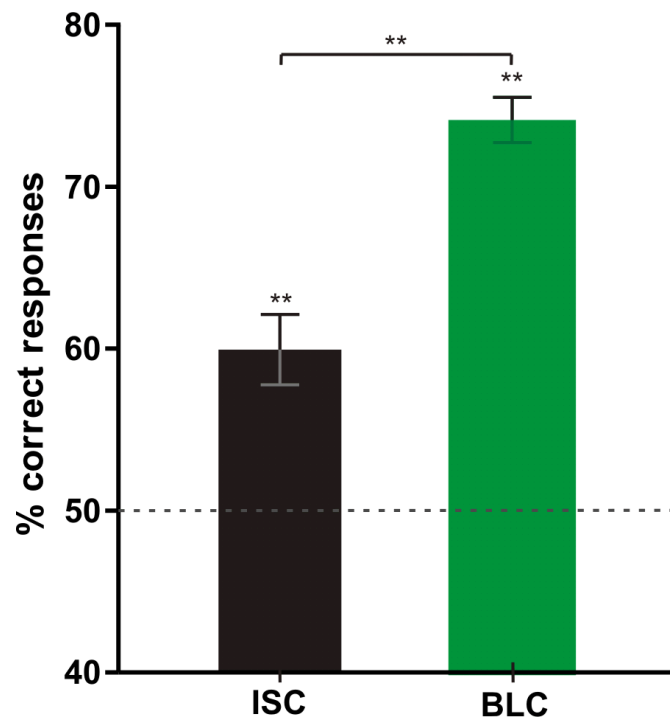


Figure 2: Percentage of correct responses in experiment 2 for segmentation and rule learning ($n = 24$). ISC: irrelevant speech condition; BLC: baseline condition $**p < .0001$

Table 4: Means and SD of experiment 2 for the whole sample and the learner group. ISC: irrelevant speech condition; BLC: baseline condition.

	ISC (all sample)	BLC (all sample)	ISC	BLC
Segmentation	59.22 (10.39) n = 28	62.79 (14.41) n = 28	62.82 (9.85) n = 13	75.64 (8.57) n = 13
Rule learning	60.08 (13.07) n = 27	58.23 (14.96) n = 27	56.56 (11.06) n = 11	72.72 (3.89) n = 11
Segmentation & rule learning	59.64 (11.68) n = 55	60.55 (14.73) n = 55	59.95 (10.68) n = 24	74.31 (6.87) n = 24

Discussion of experiment 2

This experiment was conceived to address the role of the phonological store in segmentation and rule learning, by comparing a storing interference condition with a baseline without any kind of interference. The obtained results indicate a coherent pattern to those found in experiment 1. Those subjects who were able to learn showed a better performance in the baseline condition (BLC) than in the irrelevant speech condition (ISC). Moreover, and according with experiment 1, participants performed above chance in both conditions (BLC/ISC), and not only in the baseline.

The results indicate that the phonological store is an important resource to obtain better results in the both tasks but its total availability is not necessary to successfully perform the learning tasks. Notice that although in the ISC participants can learn words and extract the non-adjacent rules, their performance was much better when they took advantage of the phonological store without saturation in the BLC (see **figure 2**). In summary, the phonological store supposes an adaptative mechanism to facilitate and optimize the cognitive operations involved in word and rule learning, operations that can still be carried out when the phonological store is limited by interference.

Experiment 3: Neural pathways associated with learning in the phonological store and articulatory rehearsal interference tasks

Material and method

Participants:

All participants of experiment 1 were scanned with diffusion tensor imaging (DTI).

MRI-DTI protocol

DTI data were collected using a 3T MRI scanner (Siemens Magnetom Trio, Erlangen, Germany) using an eight channel phased array head coil with parallel imaging (GRAPPA) and an acceleration factor of 2. Diffusion weighting was conducted using the standard TRSE (twice refocused spin echo) sequence. Images were measured using 2 mm thick slices, no gap, TR=8200

ms, TE=85 ms, 128 × 128 acquisition matrix, FOV 256mm x 256mm, 64 axial slices. To obtain diffusion tensors, diffusion was measured along 12 non-collinear directions, chosen according to the standard Siemens DTI acquisition scheme using a single b-value of 1000 s/mm². Two signal averages and three runs were acquired per slice and diffusion gradient direction. Each run was preceded by a non-diffusion-weighted volume for purposes of registration for motion correction.

Pre-processing of diffusion-weighted data

DTI data were motion corrected and eddy current-induced distortions were removed prior to the estimation of the diffusion tensors. The first non-diffusion-weighted image of each block was realigned with the first image of the first series. Then, the determined transformation parameters were applied to the remaining diffusion-weighted images of the respective block. Subsequently, all images were averaged across the 3 runs. In order to assess FA values, using the SPM2 diffusion toolbox (<http://www.fil.ion.ucl.ac.uk/spm/>), diffusion tensor elements were extracted from an over-determined set of diffusion-weighted images. Diffusion tensors were diagonalized and the eigenvectors and eigenvalues were obtained. Based on these eigenvalues, FA was calculated on a voxel-wise basis. Normalization of the FA data was performed based on the FA anisotropy images without Jacobian modulation of the signal intensities (34).

FA images were first normalized using the EPI-derived MNI template (ICBM 152, Montreal Neurological Institute) provided by SPM2. From these normalized data sets, a preliminary study template was created by signal averaging. Next, FA images were normalized again using this preliminary study template. Afterwards, a second and final study template was created by averaging these newly normalized images after the extraction of only brain parenchyma. The extraction of brain tissue was performed by a three-class brain tissue segmentation (grey matter, white matter and cerebral spinal fluid). Individual native-space brain parenchyma maps were extracted from the initial FA images and normalized to the final extracted-brain template. Finally, all individually normalized FA images were smoothed by convolving them with isotropic 8 mm FWHM (full width at half maximum) Gaussian kernels.

Statistical analysis

The voxel-wise analysis aimed on detecting the voxels in which FA values correlated with each of the two working memory conditions when learning the artificial languages. FA values range from 0 to 1 with larger values indicating that water diffusion occurs preferentially along one direction, as is the case for the structural organisation of white matter tracts (35). Previously normalized FA images were independently regressed on the proportion of ASC and ISC by applying a simple regression model in SPM2. This analysis was constrained to those voxels with FA values > 0.15 in each single participant. This cut-off allowed to reliably isolate white matter from other brain tissues (36). Correlations of FA with ASC and ISC conditions were performed independently for the two language conditions (word segmentation and rule-learning). As a function of the behavioural results correlations were also performed taking the two types of learning together. Locations and significance levels from the correlation analysis were restricted to three different uncorrected thresholds: $p < .01$, $p < .005$, and $p < .001$ (all of which with 60 voxels spatial extent) for displaying proposals (**figure 3**). The use of this gradual threshold allows the visualization of the underlying white-matter path. However, only regions significant at the cluster level (FWE-corrected for multiple comparisons $p < .01$, $n = 60$ voxels) are reported and discussed in the text.

Results

Different patterns of FA correlation were found between fractional anisotropy (FA) and ASC for segmentation and rule learning conditions altogether, and between FA and ISC for the rule learning condition. The ASC in rule learning and segmentation conditions together was significantly correlated with FA in the white matter region corresponding with the left external capsule (MNI peak coordinates: -27 9 0; $T = 4.35$ $p < .05$, corrected at cluster level, 60 voxels spatial extent) (**figure 3, left**). The external capsule is a corticostriatal fibre tract, situated between the putamen and the claustrum (37) which connects frontal (as motor cortex, premotor cortex, supplementary motor area, or dorsolateral prefrontal cortex) and parietal areas (as posterior parietal cortex) with striatum (and other areas). There was also a significant correlation between this same condition and the region coinciding with left internal capsule (MNI peak coordinates: -22 9 1; $T = 3.78$, $p < .05$, corrected at cluster level, 60 voxels spatial extent) (**figure 3, right**) near striatal regions. The internal capsule contains ascending thalamo-cortical fibers and descending fibers linking, among others areas, fronto-parietal cerebral cortex with basal ganglia (38). In contrast, the ISC was correlated with FA coinciding with right middle cerebellar peduncle (MNI peak coordinates: 31 -48 -33, $T(1.0, 21.0) = 5.07$ $p < .005$, corrected at cluster level, 60 voxels spatial extent) only in the rule learning condition. The cortico-ponto-cerebellar tract is the largest cerebellar pathway that sends inputs from the contralateral fronto-parietal cortex to the cerebellum (38).

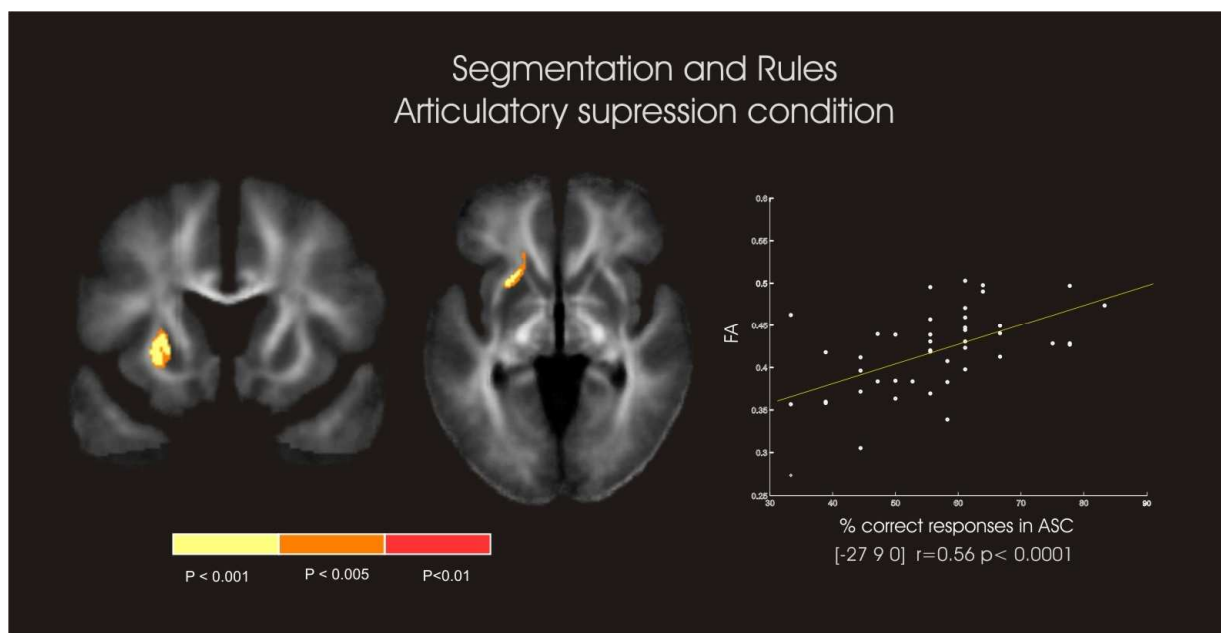


Figure 3: Correlation between FA and performance in ASC (from Experiment 1)

General discussion

Through three experiments, we have tried to elucidate whether each component of the phonological loop has the same weight, or whether each one contributes in a different way to language acquisition. Our behavioural experiments have brought us the opportunity to discover the important and essential role of the phonological rehearsal in both segmentation and rule learning in the context of second language acquisition simulated by the acquisition of a simplified artificial language. This vital involvement of the rehearsal mechanism is in clear contrast with the role of the phonological store, which supposes a strengthening mechanism to improve performance in our two language learning tasks, but it does not suppose a critical learning device to succeed as we have found the rehearsal does.

A general view of the present data supports the amply accepted hypothesis that claims the phonological loop as a second language learning facilitation device (5). Our study goes further because it is focused in segmentation and rule acquisition processes. Although a lot of studies have showed the implication of the phonological loop in learning new words (6), less is known about its specific participation in speech segmentation and in the extraction of rule-like regularities. Baddeley and colleagues (4) based their studies in tasks as non-word repetition or digit span. While the phonological store was proposed as the learning device for new vocabulary, the articulatory rehearsal was supposed to have a less important role and described as a simple promoter learning mechanism, especially in adult second language learning. Although in apparent contradiction, these studies (39, 40) may actually be compatible with our results because they were less specific in the components of language and working memory studied. They used measures of general phonological loop to correlate essentially with new word learning capacity, whereas we have made use of segmentation and rule learning measures while dissociating between phonological loop subcomponents. Here we demonstrate a priority and essential role of articulatory rehearsal in word segmentation and rule learning, while the amount of impairment induced by the phonological store saturation interferes on these processes but does not fully block learning. Taking the evidence all together, we conclude that the phonological store supposes an important mechanism to learn and to long-term memorize new words but the rehearsal represents the critical mechanism for speech segmentation and rule extraction, at least in second language learning. This is not to say that the store is not necessary. In fact, our store interference condition introduced irrelevant material. It was thus more a saturation than a completely blockage of the component. Service and Craik (41) claimed that younger individuals require less the phonological loop for acquiring new words, and they rely more on associative abilities. We believe nevertheless that a context of total store blockage could have fatal consequences in learning first or second adult language. However, a limited storage capacity can be well compensated by a good rehearsal mechanism. Thus, although a minimal phonological store availability is necessary in both child and adult second language learning, the rehearsal capacity turns out to be indispensable to the learning process.

A second important finding in this study is the absence of significant differences in word segmentation and rule extraction through the two phonological loop constraining conditions, reflecting a similar contribution of working memory in these processes. It has been proposed that the detection of adjacent relations for speech segmentation and the extraction and generalization of non-adjacent dependencies requires different mechanisms (3). One is based on statistical computations applied to the discovery of word boundaries in the speech stream, the other requires algebraic-like computations for the discovery of language structure. From an alternative view (42-44) the same statistical mechanism can be applied to adjacent and more distant dependencies to fix word boundaries and extract non-adjacent rules. Although the way in which people make the pertinent operations to segment or to extract the underlying rules from language goes beyond the scope of this

study, the unspecific role of the phonological loop to extract the two types of information is compatible with both perspectives. Nevertheless, it indicates that whatever computations are applied to the speech stream (statistical and algebraic-like computations or single statistical computation), the rehearsal mechanism is engaged for these computations to be effective. This phonological loop component may probably be necessary to be able to apply these computations to the phonological information held in working memory.

Referred to the DTI anisotropy/behavioural measures correlations, our major interesting finding has been the white matter pathway coinciding with internal and external capsule that correlates with success in the ASC in both rule learning and segmentation. The striatum interacts with cerebral cortex through bidirectional multiple loops which have been linked to motor processes as well with distinct cognitive functions engaged in different types of learning (45-48) via this white matter tracts. Although several studies relate cortical areas to different working memory subcomponent as well for multiple language functions, the subcortical implication has been less studied but seems also to play a major role (11). We were especially interested in these subcortical structures due to their pivotal position connecting with different cortical areas related with working memory. In our experiment, the head of the caudate participates in the pathway highlighted in the correlation analysis for the articulatory suppression condition. This structure belongs to the executive loop linking with the dorsolateral prefrontal cortex (DLPFC) and with the posterior parietal cortex (supramarginal gyrus). These cortical areas are relevant to executive functions (19). In the context of the models of working memory, Cowan's Embedded-processes model related these structures to the control of the attentional focus (22) and Baddeley's model (19, 49) to the central executive and the phonological store.

The Embedded-processes model (23) supposes an alternative working memory model. The most prominent difference between Cowan's and Baddeley's model is the existence of a second alternative mechanism to rehearsal refreshing, the attentional controller. The attentional controller is able to maintain information into the store in easier learning context than rehearsal and with less demand of resources (23). Moreover, neuroimaging studies place the attentional controller in the inferior parietal cortex (BA40) (for a review, (22)), the same area in which Baddeley's view places the phonological store (50). In our experiment, when rehearsal is disrupted, there is no way to successfully execute the learning tasks, all participants performed at chance. Why is it that the participants did not take advantage of the focus of attention in a context in which rehearsal was not available? Following Cowan's model, in our learning experiments, the complex tasks we used needed a powerful rehearsal, and although they could take advantage of the attentional controller this mechanism is not sufficient to succeed on its own.

It is noteworthy to mention that, in agreement with Cowan's attention component, different proposals assume a critical role of the shift of attention from the initial focus on adjacent element necessary for segmentation to more distant information for the extraction of non-adjacent regularities. Perruchet and collaborators (43, 44) claim that attention is the necessary and sufficient mechanism to chunk either adjacent or non-adjacent information by simply modifying the focus of attention (51). This shift of attention has also suggested to be vital in order to succeed rule-learning in a recent electrophysiological study with the same material used in the present study (52). A similar view has also been formulated by Ellis (53) proposing that language acquisition requires an attentional tuning to the characteristics of the language and underscores the role of an attentional filter to learn the relevant dependencies in a new language.

On the other hand, the putamen participates in the motor loop, which connects it with motor cortex, premotor cortex and supplementary motor area (54). These cortical areas has been related

with speech production as well with speech-based rehearsal of working memory (10, 11, 20). Therefore, our DTI results are consistent with the cortical view that has been typically claimed in several neuroscience studies, and contribute to the knowledge of the basal ganglia non-motor functions. Functions associated to the connections with the anterior caudate and those connecting with the putamen may be regulated and coordinated by the pathways conforming the internal and the exterior capsule. Thus, the results reinforce the integrative role of these subcortical structures between different relevant functions for the language learning process.

In the current study, although no differences between working memory contributions to segmentation and rule learning have been found, the patterns of white matter related with success in the ISC showed differences between these two learning conditions (segmentation and rule learning). FA corresponding with the middle cerebellar peduncle white matter tract correlated with performance in rule learning condition (ISC) did not correlate with segmentation or with overall performance in the two language learning tasks. Functional MRI studies claim a cerebellar role in verbal working memory (55). Although the predominant view relates cerebellum with the working memory rehearsal network (49, 50), there are some studies that also highlight its support to the phonological store component (56, 57). These later studies would be in line with the results reported in our study, because the correlation arose under the saturation of the phonological store. Further studies are required to clarify the specific interrelation between phonological loop subcomponents and white matter tracts related with successful performance in this context.

Finally, the differences in white-matter tracts between left putamen and left caudate might explain differences in the execution of cognitive tasks that require the articulatory rehearsal participation as well attentional control from working memory. The differences in white matter are related to the axonal myelination process by oligodendrocyte and Schwann cells, helping to a better axonal transmission (58). Recent studies have shown a relation between FA and behavioral patterns in some cognitive processes (59-61). The reason of this white-matter differences still been debated. Thus, the source could come from innate structural differences, but also variance in life experiences may induce brain plasticity of white-matter tracts.

General Conclusions

The phonological loop subcomponent of working memory has an important role in the two essential steps of language acquisition (word segmentation and rule learning). While the phonological store supposes a strengthening mechanism that contributes to a better performance, the articulatory rehearsal constitutes the essential mechanism which in case of saturation or blocking, causes catastrophic results in adult second language learning.

We have found no differences between the impairment caused by phonological loop constraints in speech segmentation and rule learning indicating the importance of this component both both types of learning.

The subcortical paths showed in our DTI/behavioural correlations, contributes to a major knowledge of the subcortical contributions to language acquisition and working memory. The known projections from these structures to cortical areas maintain the coherence with earlier studies focused in the cortical areas related to the different subcomponents of working memory.

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