Does our Brain House a „Mental Syllabary"? An fMRI Study

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Abstract

The present study combines functional magnetic resonance imaging (fMRI) and reaction time (RT) measurements to further elucidate the influence of syllable frequency and complexity on the production of pseudo-words. Similar to a recent fMRI investigation of our group, the present study was based on the concept of a mental syllabary, housing ready-made motor plans of high- (HF), but not low-frequency (LF) syllables. The fMRI data provided no evidence for a frequency effect, revealed, however, an impact of syllable structure: Compared to CV-items, syllables with a more complex onset (CCV) yielded higher hemodynamic activation in motor "execution" areas, i.e., left sensorimotor cortex and right inferior cerebellum. These results are consistent with our previous study, although the areas associated with the complexity effect show only a partial overlap. In contrast to the fMRI data, RT analyses disclosed a significant impact of syllable frequency, an observation supporting the concept of a mental syllabary. However, a significant interaction between frequency and complexity could be observed, i.e., LF-items - but not HF-syllables - were influenced by syllable structure. These latter findings are at variance with the hypothesis that both simple and complex HF syllables are stored as ready-made motor plans, equally accessible during speech production.

1 Introduction

Based on the speech production model of Levelt et al. [1], a recent fMRI study of our group [2] addressed the influence of syllable frequency and complexity on hemodynamic activation of brain areas involved in speech motor control. Since about 500 syllables of a given language allow a speaker to generate nearly 80% of its verbal output, these authors [1] proposed a mental syllabary, i.e., a "library" of motor plans, operating at the level of phonetic encoding processes. During word production, high-frequency (HF) syllables are retrieved as ready-made, holistic routines whereas the plans for low-frequency (LF) syllables have to be assembled on-line segment by segment. In addition, that study was also motivated by evidence for an impact of sub-syllabic structure – besides frequency- on speech motor planning, based upon the analysis of speech error patterns in patients with apraxia of speech [3, 4] and findings of a recent fMRI study [5].

On the grounds of the mental syllabary concept, two hypotheses were proposed: (i) LF-syllables require more planning resources than HF-items, resulting in stronger activation of left insula and Broca's area, i.e., regions assumed to be crucially engaged in speech motor programming [6, 7]. (ii) The effect of the factor *complexity* should be restricted to phonetic planning of LF-syllables, since the motor plans of HF-syllables are already pre-compiled, regardless of their sub-syllabic structure.

As compared to their simple cognates, CCV-syllables yielded in our preceding study a significantly enhanced hemodynamic signal within left inferior frontal gyrus (IFG, Broca's area), ipsilateral insula and inferior parts of both cerebellar hemispheres (lobule VIII). However, the results did not provide any evidence for a syllable frequency effect – at variance with behavioral data, documenting significantly shorter RTs of HF- as compared to LF-syllables during word production [8]. To directly address the relationship between functional imaging and behavioural data during speech production, the present study combined fMRI and RT measurements. In contrast to our previous study, a sparse sampling design was implemented - instead of a "continuous scanning” procedure (permanent scanner noise) - that allowed for recordings of the subjects' utterances in relative silence.

2 Methods

2.1 Subjects

Twenty right-handed subjects (10 women) participated in this study (mean age = 28.5 yrs.). All of them were native speakers of German, lacking any history of neurologic, psychiatric, medical, speech, and / or language disorders.

2.2 Stimuli

Eighty bisyllabic phonotactically legal pseudo-words were presented. The first syllable was controlled for syllable frequency (HF vs. LF) and complexity in an orthogonal fashion (simple CV- vs. complex CCV-structure), resulting in four different stimulus categories (Table 1): HS (high-frequency / simple onset structure), HC (high-frequency / complex), LS (low-frequency / simple), and LC (low-frequency / complex).

Table 1: *Stimuli categories and their mean ranks*

		SYLLABLE COMPLEXITY	
		SIMPLE	*COMPLEX*
SYLLABLE FREQUENCY	*HIGH*	*high-frequency / simple (**HS**)* CV.tet 1 < CV- rank < 500 mean rank: 265	*high-frequency / complex (**HC**)* CCV.tet 1 < CCV-rank < 500 mean rank: 310
	LOW	*low-frequency / simple (**LS**)* CV.tet CV- rank > 1200 mean rank: 2408	*low-frequency / complex (**LC**)* CCV.tet CCV-rank > 1200 mean rank: 2600

Each category comprised twenty pseudowords. The syllable ranks of these items were determined by (i) a set of computational phonotactic techniques, encompassing a multivariate clustering approach, and (ii) the “Munich Syllable Frequency List“ based on the CELEX-corpus (for details see [2]).

All items comprised /tet/ as a second syllable in order to avoid eventual confounding interactions between frequency rank and segmental complexity of the two successive syllables.

2.2 fMRI

Using a 1.5 T whole-body scanner (Siemens Vision) and a sparse sampling EPI sequence (64 x 64 matrix, FoV = 192 x 192 mm^2, TE = 40 ms, TR = 5.5 s, TR-delay = 2.99 s, flip angle = 90 deg), 34 parallel axial slices (thickness = 3.2 mm, gap = 0.8 mm) were obtained across the entire brain. Each run comprised 147 images (including two initial dummy scans for the equilibration of T_1 saturation effects), resulting in a total number of 588 image volumes per subject. The fMRI maps were superimposed on anatomical images (T1-weighted 3D MPRAGE sequence; 176 sagittal slices, thickness = 1mm, TE = 3.19 ms, TR = 1300 ms, flip angle = 15 deg).

2.4 Procedure

Subjects were asked to overtly read the bisyllabic pseudowords as soon as possible after visual presentation. In four runs the items were displayed blockwise. Each run (13.51 min) comprised 5 blocks of each of the four stimulus categories HS, HC, LS, and LC. Within each block, four different items of the same category were presented, resulting in a total number of 80 stimuli per run (5 x 4 x 4). The pseudowords were visible for 1.3 s each and then replaced by “xxxxxxx”. Stimulus presentation was jittered relative to the onset of the preceding scan (2.05s, 2.65s, 3.25s, and 3.85s). During the baseline periods, the x-sequence was displayed continuously. Stimulus blocks (22 s each) were applied in a randomized order, alternating with a baseline period (16.5 s). The subjects’ productions were recorded by means of a fMRI-compatible, optical microphone (Phone-Or-Dual-Channel Microphone, MR-confon, Magdeburg, Germany). Due to the sparse sampling design of the present study, it was possible to record the subjects’ utterances in the absence of loud scanner noise.

2.5 Data analysis

Using PRAAT-software, the RTs of correctly produced items with well-defined signal onset were determined (n = 5935). Outliers (RT > two standard deviations above / below the mean of a given subject per run and syllable category) were excluded from statistical analysis.

The fMRI data were pre-processed and analysed with the Statistical Parametric Mapping software package (SPM5). A conjunction analysis ("null hypothesis") was performed in order (i) to identify the hemodynamic activation pattern common to all four stimulus categories and (ii) to derive voxels with the highest activation within selected areas to perform region of interest (ROI) analyses for determining the influence of syllable frequency and complexity. HF- and LF-syllables were assumed to be associated with differential planning efforts. As concerns syllable structure, LC-items were expected to impose higher demands on the motor planning AND execution stage. In line with these hypotheses and the results of our previous fMRI study [1], areas crucially engaged in speech motor planning, i.e., Broca's area (IFG) and left insula (INS), as well as areas involved in motor execution, i.e., the right inferior cerebellum (lobule VIII) and left sensorimotor cortex (SMC), were selected as ROIs (sphere of 6mm radius). The contrast 'LF vs. HF' was restricted to the ROIs of IFG and INS, whereas all ROI analyses were performed for 'CCV vs. CV'.

3 Results

3.1 Behavioral data

Statistical analysis of the RT data was based on a 2 (*syllable frequency*: HF vs. LF) x 2 (*syllable complexity*: CV vs. CCV) factorial analysis for repeated measures. This MANOVA revealed a significant main effect of *syllable frequency* ($F(1, 19) = 35.40$, $p < 0.0001$), but not *complexity* ($F(1, 19) = 1.64$, $p > 0.2$). However, there was a significant interaction of frequency with complexity ($F(1, 19) = 9.80$, $p < 0.01$).

Post-hoc T-tests revealed significant differences between following syllable categories (Figure 1): HS showed shorter RTs than HC ($p < 0.02$), LS ($p < 0.0001$), and LC ($p < 0.0005$). Moreover, HC-syllables were produced faster than LS- ($p < 0.005$) or LC-syllables ($p < 0.05$). The RTs of LS and LC, by contrast, did not differ ($p > 0.2$).

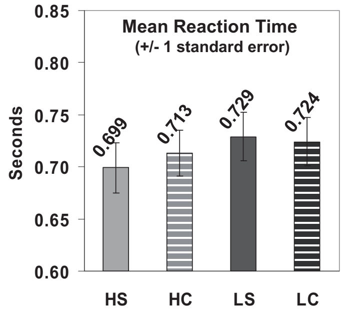

Figure 1: *Mean reaction time (RT) of syllable productions*

3.2 fMRI data

As expected, the cerebral network common to all four stimulus categories included a widespread pattern of bilateral brain responses ($P_{FWE} < .05$; Figure 2), comprising (i) mesiofrontal regions, extending from SMA proper in anterior-ventral direction to the cingulate cortex, (ii) ventral parts of the sensorimotor cortex (SMC), (iii) fronto-opercular regions including Broca's area (posterior IFG) and intrasylvian cortex (insula), (iv) the basal ganglia, (v) the thalamus, (vi) the superior temporal gyrus (STG), (vii) superior (lobule VI) and inferior (lobule VIII) parts of the cerebellum, and (viii) the visual cortex. In addition, activation spots restricted to the left hemisphere emerged at the level of the temporal pole, the inferior and middle temporal gyrus, and the inferior parietal lobule.

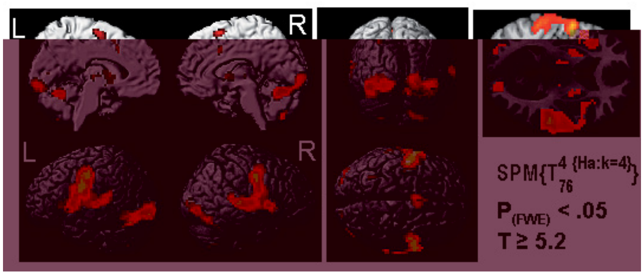

Figure 2: *Activation pattern of the cerebral network common to HS, HC, LS, and LC*

ROI analyses did not yield significant activation effects for the contrast 'LF vs. HF'. CCV-items showed significantly higher activations than CV-syllables within SMC (T = 2.29, p = .012 and right inferior cerebellum (lobule VIII, T = 2.81, p = .003).

4 Discussion

In line with preceding behavioural studies [8], the RT analyses of the present study revealed a syllable frequency effect, i.e., significantly faster production of HF- as compared to LF-syllables. Unexpectedly, the variable *complexity* had an impact on the response latencies of the HF-syllables, whereas their low-frequency cognates remained unaffected. Based on the mental syllabary concept, it was assumed that variation of complexity should have an influence exclusively on LF-syllables, since those items have to be assembled on-line segment by segment, whereas the motor plans of HF-syllables are supposed to be retrieved as ready-made “packages”, irrespective of their segmental make-up. Conceivably, the two effects are not additive and a potential complexity effect within the LF category was masked by a stronger impact of frequency. Nonetheless, any effect of syllable structure on HF-syllables is at variance with the hypothesis that the motor plans of simple *and* complex HF-syllables are stored in the same way as holistic, ready-made plans. As an alternative explanation, the mental syllabary might comprise less than the 500 most frequent syllables. Under these conditions, some of the HC-items used here would not have been retrieved as holistic motor plans.

In line with our previous study, the fMRI data did not show any frequency effects. Rather, both investigations revealed a significant impact of complexity on pseudoword production. Whereas our earlier study found CCV-items – as compared to CV-syllables – to be associated with higher hemodynamic activation at the level of Broca’s area, left insula, and bilateral inferior cerebellum (lobule VIII), the present investigation was able to document that CCV-syllables give rise to enhanced responses of SMC and right inferior cerebellum. These results are in accordance with our hypothesis that CCV syllables pose higher demands on motor execution processes. The discrepancies between the two studies may reflect differences in experimental design: While our earlier study used a “continuous” scanning procedure, the present investigation was based on a sparse time sampling technique. The latter approach has less statistical power, but is indispensable if speech signals are to be recorded during scanning.

In summary, the present study disclosed a frequency effect exclusively at the behavioural level (RT data). It must be taken into account, however, that the latency differences between HF- and LF-syllables amounted to a few milliseconds only. Conceivably, the fMRI analyses performed so far are not sufficiently sensitive to detect the neural correlates of such subtle effects. Connectivity analyses of the fMRI data and comparisons of subject subgroups are currently performed in order to obtain further insights into the impact of syllable frequency on speech production.

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