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Intragestural variation in natural sentence production: Essential Tremor patients treated with DBS

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Abstract

In the present study, we investigate intragestural parameters during the production of CV syllables in natural sentence production of Essential Tremor (ET) patients treated with Deep Brain Stimulation (DBS). Within the task dynamic approach, we analyzed temporal and spatial parameters of consonantal and vocalic movements of the respective target syllables. Our analysis revealed that intragestural coordination patterns are affected in the patients' group: While patients with inactivated stimulation (DBS-OFF) already showed signs of dysarthria in terms of longer and less stiff movements, there was an additional slowing down of the speech motor system under activated stimulation (DBS-ON). When comparing CV production in natural sentence to fast syllable repetition tasks (DDK), we find similarities in that there is a slowing down of the system, but also differences in that coordination problems increase in DDK leading to an overmodulation of peak velocities and displacements.

Index Terms: pathological speech, intra-gestural parameters, speech motor control, essential tremor patients, deep brain stimulation, natural sentence production, fast syllable repetitions

1. Introduction

1.1. Studies on fast syllable repetition tasks in ET patients treated with DBS

Essential Tremor (ET) is one of the most common movement disorders leading to a kinetic or postural tremor of the limbs, hands and upper parts of the body [1]. If the tremor is medication-resistant, a deep brain stimulation (DBS, see Fig. 1) in the ventralis intermedius nucleus (VIM) of the thalamus is an effective treatment for tremor reduction and increased life quality [1]. But in some patients, stimulation-induced dysarthria appears as a side effect, decreasing the treatment outcome [2].

[3] investigated overall speaking rate in terms of CV durations in fast syllable repetition tasks (oral diadochokinesis, DDK) containing sequences such as /ba/, /da/ and /ga/ in ET patients treated with VIM-DBS. They found that speech is slowed down in ET patients with additional cerebellar signs, but they did not find an effect of stimulation on the global speaking rate parameter on the acoustic surface. The picture changes when looking at the parameters on the subsyllabic level. In two studies [4,5] stimulation-induced dysarthria in ET patients treated with VIM-DBS was investigated, also by using DDK, containing the sequences /pa/, /ta/ and /ka/.

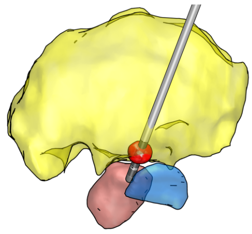

Figure 1: *Location of electrodes in DBS treatment. Red: stimulation in the thalamus; blue: subthalamic nucleus; dark red: red nucleus.*

They recorded patients with activated and inactivated stimulation with a 3D-Electromagnetic Articulograph to track the movements of the primary constrictors of the labial and lingual system. In the acoustic dimension, they showed that VIM-DBS can lead to reduced voicing during the syllable cycle and imprecise oral articulation of stop consonants. In the articulatory dimension, they found two strategies that reveal a deterioration in speech: (i) Comparing patients in DBS-OFF with control speakers revealed that ET patients already showed coordination problems with inactivated stimulation in terms of imprecision and slowness. Surprisingly, the consonantal gestures were longer and less stiff, but at the same time they were also faster and more displaced than the consonantal gestures of the control participants. (ii) Comparing the articulation with activated and inactivated stimulation in the patients, the speech deficits deteriorated. Further, there was an overall-slowing down of the labial and lingual system. Consonantal gestures were longer and less stiff, but this time also slower and less displaced. The authors concluded that the coordination problems were either due to an aggravation of pre-existing cerebellar deficits or to the affection of the upper motor fibers of the internal capsule.

1.2. Natural sentence production in ET patients treated with DBS

DDKs have the advantage that they are widely used, thus allowing for data comparability. By using sequences of fast syllable repetitions, the speech motor system is pushed to its limits, and thus avoid effects of the prosodic system on the syllable coordination patterns. However, there is a debate on whether DDKs are comparable to natural sentence production [6]. The main problem is that natural speech does not consist of repeating sequences. Moreover, prosody plays an important role and affects the syllable internal coordination pattern. Speakers constantly modify phonetic cues on a continuum of hypo- and hyperarticulated speech, e.g. when making a syllable prominent or non-prominent [7,8]. Furthermore, speech

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dynamics are also affected by speech rate: In a recent study on DDKs in healthy speakers, [9] recorded several speaking rates. They showed interdependencies between speech rate and the geometric shape of articulatory gestures.

To our knowledge, not much is known on the effect of DBS on articulatory patterns in natural sentence production. In their study on intergestural coordination patterns of consonantal and vocalic gestures in syllables with low and high complexity such as /li/ and /kli/, [10] detected that intergestural coordination patterns where affected when complexity increased. Furthermore, these deviant patterns even worsened with activated stimulation.

In the present study, we investigate intragestural parameters in consonantal and vocalic gestures in CV syllables containing sequences of oral stops and vowels in German. We therefore recorded target words in natural sentence production with a 3D-Electromagnetic Articulography. Within the task dynamic approach, we measured temporal and spatial parameters of articulatory movements such as duration, maximum velocity, maximum displacement and relative speed (stiffness) of the tongue and the lips/ the tongue tip when fulfilling a linguistic, goal-directed tasks. The measures are discussed in the light of a mass-spring model capturing intragestural variation [11-15]. Further, the results of the patterns in natural sentence production will be compared to those of DDKs reported in [5].

2. Method

2.1. Participants and recordings

We recorded 12 ET patients who underwent a DBS surgery with stimulation ON and OFF (in a randomized order) under a 3-dimensional Electromagnetic Articulograph (Carstens Medizinelektronik; AG501) at the IfL – Phonetics laboratory at the University of Cologne, and 12 age- and gender-matched healthy control speakers. Due to problems with the EMA recordings for some patients, we had to discard 3 ET patients and thus 3 matched control speakers accordingly. This left us with 9 patients with ET in DBS-ON and ET in DBS-OFF and 9 healthy controls. We placed sensor coils on upper and lower lips, tongue tip, tongue blade, and tongue dorsum. Movements of the lower lip sensor determine the labial C gestures and tongue tip sensors alveolar C gestures. In addition, the sensor on the tongue dorsum was used to analyze V gestures. The sensors remained on the articulators for both measurements (DBS-ON and DBS-OFF) to warrant comparability of the data. The waiting time between the recording sessions was kept constant for a minimum of 20 minutes. The EMA data were recorded at 1250Hz, downsampled to 250Hz and smoothed with a 40Hz low-pass filter. All data were converted to SSFF format using custom software (EMA2SSFF) for annotation within the EMU Speech Database System [16].

2.2. Speech material

The speech material consisted of simple CVCV syllables (girl's names), such as <Bina>, <Pina> (/bina, pina/) and <Dina>, <Tina> (/dina, tina/) that were embedded in a carrier sentence "Er hat wieder _____ gesagt" ('He said _____ again') with the target words in focus condition. The two datasets were analyzed according to the place of articulation (POA) of the initial consonant, either i.e. labial or alveolar articulation. For the patients' data 360 tokens were analyzed: 2 labial * 2 alveolar * 5 repetitions * 9 ET patients * 2 stimulation conditions (OFF, ON). For the control speakers 180 tokens were analyzed: 2 labial * 2 alveolar * 5 repetitions * 9 controls.

2.3. Labelling and variables

The following landmarks in simple CV syllables (labials: /bina, pina/, alveolars: /dina, tina/) are annotated for the consonantal vocalic gestures in the vertical plane (movement on the y-axis) by identifying zero-crossings in the respective velocity and acceleration traces): onset, peak velocity, maximum target (see Fig. 2). We computed the following articulatory variables. *Gestural activation interval (GAI)*: This includes the duration of the gestural activation interval, measured from the start to the target maximum of the articulatory movement. *Displacement:* The spatial displacement of the movement from start to target in the vertical plane. *Peak velocity*: The maximum velocity of the movement. *Stiffness:* The ratio of peak velocity to displacement [17]. Note, that stiffness is an abstract control parameter related to the relative speed of the movement. It is calculated as the ratio of peak velocity to the maximum displacement [12,17-19]. Increasing a gesture's underlying stiffness leads to faster and shorter movements; the target is achieved in a shorter time.

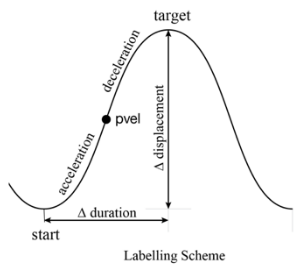

Figure 2: *Schematised trajectory and landmarks.*

2.4. Statistical analysis

The data was analyzed using R [20] and the package lme4 [21] to perform linear mixed effect models. We fitted scaled log-transformed continuous variables of interest: gestural activation interval (GAI), displacement, peak velocity and stiffness to the critical predictors DBS (control vs. DBS-OFF and DBS-OFF vs. DBS-ON) and POA (labial vs. alveolar). In these models, we included random intercepts and slopes for speakers by POA. Furthermore, we added a fixed factor of voicing (/b, d/ vs. /p, t/). We tested whether including an interaction between DBS and POA significantly improved the model predictions. If there was an interaction, we concluded that there is a joint effect of DBS and POA. Further, we tested, whether there is an effect of DBS (independent of an interaction of POA and DBS). For the analyses, we validated the models by comparing the test model (with interaction) to a reduced model (without interaction) via likelihood-ratio tests (p-values are based on these comparisons). Since we tested several measurements against the null hypothesis, we corrected for multiple testing using the Dunn–Šidák correction, lowering the analysis wide alpha level to 0.0127.

3. Results

3.1. Intragestural variation in the consonantal gestures

Figure 3 provides bar plots for the articulatory variables GAI, displacement, peak velocity and stiffness. Results will be reported as follows: controls vs. ET patients in DBS-OFF and

ET patients in DBS-OFF vs. DBS-ON. The statistical results are discussed below, separately for each parameter.

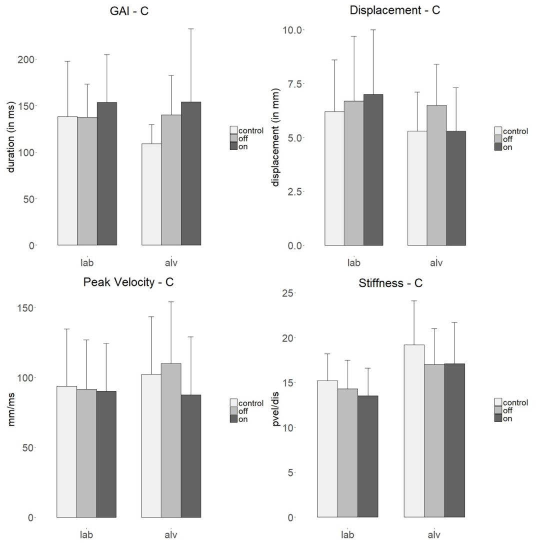

Figure 3: *Articulatory parameters for C gestures in labial and alveolar dataset for controls, patients in DBS-OFF (off) and DBS-ON (on) condition.*

Gestural activation interval (GAI): Measuring the GAI for the C gesture revealed no difference in both data sets comparing controls to patients with DBS-OFF. The mixed model revealed no interaction for POA ($X^2(1)=3.787$; $p=0.05165$) and no effect of DBS ($X^2(1)=1.7522$; $p=0.1856$). When comparing patients in DBS-OFF to DBS-ON, there was an increase of the duration of the consonantal gesture in both conditions, with and without activated stimulation. The model reveals no interaction of POA ($X^2(1)=1.3795$; $p=0.2402$), but an effect of DBS ($X^2(1)=20.794$; $p=5.114e-06$).

Displacement: Comparing the controls to patients in DBS-OFF, there was a tendency for larger displacements in the patients' group. This model revealed no interaction of POA ($X^2(1)=1.9538$; $p=0.1622$) and no effect of DBS ($X^2(1)=1.3481$; $p=0.2456$). The pattern for the displacement parameter comparing patients in DBS-OFF to DBS-ON, showed a different direction for the labial and the alveolar set. Whereas in the labial set, there was an increase in displacement, in the alveolar set there was a decrease in the displacement set. Indeed, the model revealed this interaction of POA ($X^2(1)=17.814$; $p=2.435e-05$), and further an effect of DBS ($X^2(1)=16.816$; $p=4.119e-05$).

Peak velocity: Comparing control speakers to patients in DBS-OFF, there was a tendency towards a higher peak velocity in the alveolar set. The model revealed an effect of DBS ($X^2(1)=7.5034$; $p=0.006158$), but no interaction of POA ($X^2(1)=0.433$; $p=0.5105$). Comparing DBS-OFF and DBS-ON, there was no modification in the peak velocity in both sets. The model revealed no interaction of POA ($X^2(1)=0.0107$; $p=0.9177$) and no effect of DBS ($X^2(1)=0.5813$; $p=0.4458$).

Stiffness (pvel/displ): Comparing controls to DBS-OFF patients for the modification of the stiffness parameter revealed no interaction of POA ($X^2(1)=2.0115$; $p=0.1561$), and no effect of DSB ($X^2(1)=1.307$; $p=0.2529$). Comparing DBS-OFF to DBS-ON did neither show an interaction of POA ($X^2(1)=3.0465$; $p=0.08091$) nor an effect of DBS ($X^2(1)=4.742$; $p=0.02944$).

3.2. Intragestural variation in the vocalic gestures

Analogously to the results of the consonantal gestures, Figure 4 provides bar plots for the respective articulatory variables for the vocalic gestures. Results will be reported as follows: controls vs. ET patients in DBS-OFF and ET patients in DBS-OFF vs. DBS-ON.

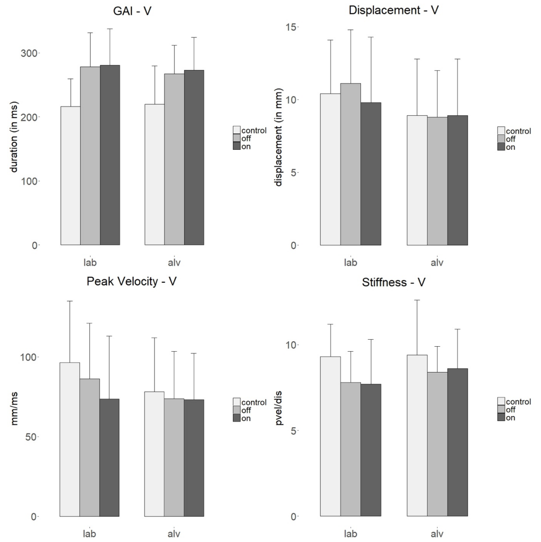

Figure 4: *Articulatory parameters for V gestures in labial and alveolar dataset for controls, patients in DBS-OFF (off) and DBS-ON (on) condition.*

Gestural activation interval (GAI): The GAI for the V gesture revealed an increase in duration for patients with DBS-OFF compared to control speakers. The mixed model revealed no interaction for POA ($X^2(1)=6e-04$; $p=0.9797$), but an effect of DBS ($X^2(1)=13.209$; $p=0.0002786$). When comparing DBS-OFF to DBS-ON, we can see that the duration remained quite stable. The model revealed neither an interaction of POA ($X^2(1)=0.3283$; $p=0.5667$), nor an effect of DBS ($X^2(1)=2.8633$; $p=0.09062$).

Displacement: The analysis of the displacement parameter, comparing controls and patients in DBS-OFF revealed neither an interaction of POA ($X^2(1)=0.0015$; $p=0.9688$), nor an effect of DBS ($X^2(1)=0.0948$; $p= 0.7582$). When comparing patients in DBS-OFF to DBS-ON, the model revealed an effect of DBS ($X^2(1)=6.8982$; $p=0.008628$), but no interaction of POA ($X^2(1)=5.923$; $p=0.01494$).

Peak velocity: Measuring the peak velocity of the V gesture, there are lower peak velocities measured in DBS-OFF patients compared to controls. The model revealed an effect of DBS ($X^2(1)=9.3166$; $p=0.002271$), but no interaction of POA ($X^2(1)=0.276$; $p=0.5993$). Comparing patients in DBS-OFF to DBS-ON, the model revealed no interaction of POA ($X^2(1)=0.0026$; $p= 0.9597$) as well as no effect of DBS ($X^2(1)=0.2138$; $p = 0.6438$) on the peak velocity.

Stiffness: A comparison of the stiffness parameter for controls and patients in DBS-OFF showed a decrease in stiffness for the patients. The model revealed an effect of DBS ($X^2(1)=8.4818$; $p=0.003587$), but no interaction of POA ($X^2(1)=0.717$; $p=0.3971$). When comparing patients in DBS-OFF to DBS-ON, the model did neither show an interaction of POA ($X^2(1)=4.7263$; $p=0.0297$), nor an effect of DBS ($X^2(1)=2.3565$; $p=0.1248$).

3.3. Summary

A summary of the results is presented in Table 1. Our data revealed that the speech motor system is already affected in ET patients with DBS-OFF condition. With inactivated stimulation (DBS-OFF), we found slower movements for the consonantal gesture and longer, slower and less stiff movements for the vocalic gesture. Furthermore, there was an additional effect in DBS-ON condition. Under activated stimulation, we found longer and larger movements for the consonantal gesture and smaller movements for the vocalic gesture.

Table 1: *Summary of effects for C and V gestures, comparing controls to ET patients in DBS-OFF and DBS-ON condition. Main effect of DBS marked as < or >. Interaction of POA in bold.*

		C	V
(1)	GAI	C=OFF<ON	C<OFF=ON
(2)	Displ	C=**OFF>ON**	C=OFF>ON
(3)	Pvel	C<OFF=ON	C>OFF=ON
(4)	Stiff	C=OFF=ON	C>OFF=ON

4. Discussion

Controls vs. DBS-OFF: There was an overall slowing down of the speech motor system in the ET patients, especially for the V gesture. During the V production, the movements of the tongue dorsum were on average of 55ms longer than in the controls and the respective maximum velocities were slowed down, i.e. they were on average 7mm/ms slower. As a result, of these longer and slower V gesture movements, the stiffness also decreased compared to the controls, while the displacement of the movement remained unchanged. Furthermore, there was also a slowing down for the C gesture in the ET patients (on average 3mm/ms slower for patients).

When comparing the results to the DDKs reported in [5], we can observe similarities, but also differences. In both tasks, the DDK and the natural sentence production, we find that speech in ET patients is already affected with inactivated stimulation (DBS-OFF). This is likely due to pre-existing cerebellar deficits. The movements are slower and less stiff. This fits also to the findings of [3], who reported on prolonged syllables in ET patients with additional cerebellar deficits. However, in [5], there were further deficits in the coordination of DDKs, in that patients spend too much effort in the productions of the fast syllable sequences (hyperarticulation). There was an increase in displacements and maximum velocities of the movements in the ET patients with DBS-OFF, pointing to the fact that patients have problems to adapt to the novel speech motor task and therefore produce less efficient syllables. This cannot be confirmed for the target syllables in the natural sentence production in the present study. Here, the system tends towards hypoarticulation for both, consonantal and vocalic gestures. Note, that the target syllables contained different vowels. In the DDK task, we used syllables with an open vowel /a/, while in the natural sentence production task we used syllables with a closed vowel, /i/. However, variation in segmental make-up cannot explain the different behavior of the speaker groups in the different speech tasks. We expected to find hypoarticulation in the DDK task and hyperarticulation in during the production of prominent syllables in natural sentence production. But the opposite was the case for the ET patients: They maximized articulatory effort during the DDK task and minimized the effort in target words placed in contrastive focus condition.

DBS-OFF vs. DBS-ON: Turning the stimulation on revealed an additional slowing down of the speech motor system. We found temporal and spatial modifications in the alveolar set, comparing DBS-OFF to DBS-ON. The consonantal movements of the tongue tip were slower (on average of 22 mm/ms slower in DBS-ON), longer (on average 14ms longer in DBS-ON), and – like the V gesture – less displaced (on average 2mm smaller in DBS-ON). For the labial system, we found only temporal modifications (C gestures are on average 16ms longer in DBS-ON). For the articulatory parameter adjustments of the V gesture there were smaller displacements, but no corresponding modifications in the temporal domain. This is in line with the DDK results reported in [5]. They found an additional overall-slowing down of the speech motor system induced by the activation of the VIM stimulation. The slowing down of the system in the DDK task as well as in the natural sentence production could be either due to the current spread of the electrodes to the motor fibers of the internal capsule (affection of the upper motor neuron) or to compensatory strategies, i.e. patients slow down the speech movements due to DBS-induced deficits.

5. Conclusions

The current analysis of intragestural coordination of prosodic constituents in ET patients with DBS in natural sentence production revealed changes in the speech dynamics. These changes worsened under stimulation. We can assume that ET patients (DBS-ON and DBS-OFF) have problems to control articulatory forces. This leads to a mixture of high-cost and low-cost strategies required form the physical control system that cannot be attributed to natural or prosodic variation.

We were able to show that fast syllable repetition tasks, i.e. DDKs and natural sentence production show similarities, but also differences when investigating intragestural modifications of the speech motor control system. For both cases, we found a slowing down of the system, however, coordination problems are more visible in DDK tasks.

6. Acknowledgements

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