Physiological continuum of atypicality between fluent and stuttered stop consonants

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Introduction: Stuttering is commonly perceived as a speech disorder which is temporary and of a psychological nature, since perceptible disfluencies occur in some situations only, with a severity that is influenced by emotional factors. However, over the last decades, research findings from different fields, such as (neuro)-physiology, genetics, phonetics and motor control, support the idea that stuttering is a neuro-motor disorder of permanent nature, resulting in atypical gestural coordination patterns, which are modulated by psychological and situational factors[1]. In the current study, we explore the existence of a "physiological continuum" between the fluent speech of people who not stutter (FS_{PNS}), the perceptually fluent speech of people who stutter (FS_{PWS}) and their perceptually stuttered speech (SS_{PWS}), by quantifying physiological variations of intra-oral pressure, inter-lip pressure, and glottal contact. The hypothesis is that during FS_{PWS}, differences in glottal and articulatory behavior already exist, although they are not perceptually noticeable, and that these differences are larger in SS_{PWS}.

Previous studies have revealed that, at the aerodynamic level, lower levels of intra-oral pressure (Pio) and oral airflows were observed in FS_{PWS}, with a typical increasing speed of Pio during stop closures, but a slower decrease at stop release[2]. At the laryngeal level, higher muscle activity was observed in SS_{PWS} but not particularly in FS_{PWS}[3,4]. In line with this, PWS showed longer voice reaction times[5], resulting in longer voice onset times (VOT) and voice termination times (VTT) when producing stop consonants[6]. Lastly, a slower rise time at the onset of vocal folds vibration and les prolonged open phases of glottal cycles were observed in SS_{PWS}, without noticeable differences in FS_{PWS}[7]. Less consistent observations were reported at the articulatory level. Some studies observed a greater activity of lip muscles in FS_{PWS}[8] whereas others showed a weaker activity[9]. Higher articulatory velocities and atypical jaw and lip movements were reported in SS_{PWS}[10,11]. Many authors observed reduced vowels in FS_{PWS}[6,12], in line with reduced articulatory movements of the jaw, the lips or the tongue[13], whereas others did not observe significant differences in articulatory movements[14-16] or even amplified articulatory movements[13].

To complement these previous studies, we further explore here the glottal and articulatory contact forces of PWS. In addition, we explore the combined (instead of isolated) variation of aerodynamic, laryngeal and articulatory parameters to investigate the coordination of speech gestures in both force and timing.

Material and methods: 4 French people who stuttered since childhood (3M, 1F) and 4 PNS (2M, 2F) were recorded, while producing 30 tri-syllabic words beginning with labial consonants (/p/, /b/, m/) or consonant clusters (/pR/, /bR/), in 3 following vowel contexts (/a/, /i/, /o/), preceded by /lə/, in a reading task and a semi-spontaneous task[17].

Four signals were simultaneously recorded: 1- the audio signal with a pressure microphone (Bruel and Kjær 4944-A), placed 30 cm from the lips and calibrated in intensity, using a measuring amplifier (Nexus, Bruel & Kjaer) ; 2- the intra-oral pressure (Pio) using a small capillary tube placed at the lip commissure and connected to the EVA acquisition system ; 3- the inter-lip pressure signal, using a force sensor attached to the lower lip[18]; 4- the electroglottographic signal (EGG), using a two-channel Electro-Glottograph (EG2 Glottal Enterprise).

Acoustic and physiological data were manually annotated with Praat. The burst interval (when observable) was identified from the audio signal, the occlusion interval from the inter-lip pressure signal and the voicing/devoicing intervals from the EGG signal. A set of about 40 parameters were extracted from these signals, using Matlab scripts, in order to describe these waveforms (peak amplitudes, rising and decreasing velocities, degree of asymmetry) but also the gestures coordination in force and timing (amplitude ratios, delays).

3% of productions of PWS were perceived (by the author ADF, trained in speech therapy) as disfluent and consequently distinguished from the rest of the productions for the analysis. The data corresponding to the fluent productions were analyzed with mixed models using R software, considering the participant group (FS_{PNS} vs. FS_{PWS}), the initial segment or cluster (/p/, /b/, /m/, /pR/, /bR/) and the production task (reading vs. semi-spontaneous) as fixed effects and the participants as a random effect. The data corresponding to the disfluent productions (SS_{PWS}) were compared only qualitatively to FS_{PNS} and FS_{PWS}, because of the too limited size sample.

Results: During the FS_{PWS}, speakers, in general, spoke faster and with a slightly reduced vocal intensity compared to the FS_{PNS}. The noises produced at occlusion release were comparable in intensity between the two groups, but noise duration was considerably longer in FS_{PWS}, suggesting a frequent transformation of stop consonants into fricatives. Likewise, voiced consonants were significantly more frequently produced as voiceless ones.

Atypical patterns in the speech production gestures of FS_{PWS} and SS_{PWS} were found, even during their fluent utterances, at the aerodynamic, laryngeal and articulatory level: The FS_{PWS} and SS_{PWS} demonstrated weaker inter-lip compression forces and lower lip articulation velocities than the FS_{PNS}, as well as lower levels of Pio and a slower decrease of Pio at occlusion release, and slightly higher laryngeal open quotients during the occlusion phase (OQ_{Occlu}), reduced f0 rise and increase of EGG amplitude at occlusion release for voiced consonants. Significant differences were also observed in the coordination of these gestures: The two ratios (Inter-lip pressure force / Pio) and (OQ_{Occlu} / Pio) were considerably greater in PWS than in PNS. Voice Termination Times (VTT) on voiceless stops were significantly longer for the 4 PWS, whereas Voice Onset Times (VOT, measured here precisely, from physiological annotations) were comparable.

The qualitative comparison of stuttered and fluent syllables of PWS supported the idea of a physiological continuum between FS_{PNS}, FS_{PWS} and SS_{PWS} for some parameters only. Thus, inter-lip compression force was even more reduced, OQ_{Occlu} was even higher, and the decrease of Pio at occlusion release was even slower on stuttered syllables of PWS. For most of the other physiological parameters, however, such a “fluency continuum” was not observed, with opposite variations observed from FS_{PNS} to FS_{PWS} and from FS_{PWS} to SS_{PWS}.

Syllable complexity (i.e., beginning with a single consonant vs. with a consonant cluster) and production task (reading vs. semi-spontaneous) had a significant effect on stuttering frequency as well as on most of the acoustic and physiological parameters. For some parameters, such as the degree of inter-lip compression force and the Pio level, a significant interaction was found between these factors and the participant group (PWS vs. PNS), with greater differences observed between the two groups for the complex syllables and for the semi-spontaneous task.

Discussion: The physiological differences observed between FS_{PWS} and FS_{PNS} confirm the idea that stuttering is not a temporary disorder but rather a permanent one, expressed through atypical speech gestures. Our results also show that all levels of speech production -- including exhalation and laryngeal behaviors -- are affected, as well as the coordination in force and timing between these 3 production levels.

The second idea that the severity of stuttering may be characterized by a physiological continuum of increasing atypicality of speech gestures, was only partially supported by our results. Three physiological parameters (Inter-lip compression force, OQ_{Occlu} and the decreasing velocity of Pio at occlusion release) followed such an expected continuum whereas most of the others (at least those we measured) did not.

At first sight, this continuum observed between FS_{PNS}, FS_{PWS} and SS_{PWS} may look like a reduction of production efforts (weaker articulation force, weaker Pio level, higher OQ), which does not fit with the higher muscle activity reported in PWS[3-4,9] and with the great tension that they feel when speaking. Our interpretation of these results is that on the contrary, muscle tension is so high in PWS that it “blocks” their movements, finally resulting in reduced and slower gestures. Furthermore, the fact that we did not observe a continuum in the variation of most of the measured parameters may also come from the fact that the 4 PWs of this study received some form of speech therapy in the past 3 to 5 years. As a result, variations observed from FS_{PNS} to FS_{PWS} may reflect compensation strategies to cope with stuttering rather than stuttering itself.

Finally, this preliminary study was based on a limited cohort of 4 PWS and 4 PNS who were not carefully paired nor controlled for stuttering severity. Results must therefore be taken with precaution before being generalized to a larger and more controlled cohort.

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