Journal of Communication Disorders 62 (2016) 101–114

Contents lists available at ScienceDirect

Journal of Communication Disorders

Temporal variability in sung productions of adolescents who stutter

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 9 May 2016
Accepted 24 May 2016
Available online 2 June 2016

Keywords:
Stuttering
Adolescents
Singing
Voice onset times
Temporal variability and coordination

ABSTRACT

Singing has long been used as a technique to enhance and reeducate temporal aspects of articulation in speech disorders. In the present study, differences in temporal structure of sung versus spoken speech were investigated in stuttering. In particular, the question was examined if singing helps to reduce VOT variability of voiceless plosives, which would indicate enhanced temporal coordination of oral and laryngeal processes. Eight German adolescents who stutter and eight typically fluent peers repeatedly spoke and sang a simple German congratulation formula in which a disyllabic target word (e.g., /'ki:ta/) was repeated five times. Every trial, the first syllable of the word was varied starting equally often with one of the three voiceless German stops /p/, /t/, /k/. Acoustic analyses showed that mean VOT and stop gap duration reduced during singing compared to speaking while mean vowel and utterance duration was prolonged in singing in both groups. Importantly, adolescents who stutter significantly reduced VOT variability (measured as the Coefficient of Variation) during sung productions compared to speaking in word-initial stressed positions while the control group showed a slight increase in VOT variability. However, in unstressed syllables, VOT variability increased in both adolescents who do and do not stutter from speech to song. In addition, vowel and utterance durational variability decreased in both groups, yet, adolescents who stutter were still more variable in utterance duration independent of the form of vocalization. These findings shed new light on how singing alters temporal structure and in particular, the coordination of laryngeal-oral timing in stuttering. Future perspectives for investigating how rhythmic aspects could aid the management of fluent speech in stuttering are discussed.

Learning outcomes: Readers will be able to describe (1) current perspectives on singing and its effects on articulation and fluency in stuttering and (2) acoustic parameters such as VOT variability which indicate the efficiency of control and coordination of laryngeal-oral movements. They will understand and be able to discuss (3) how singing reduces temporal variability in the productions of adolescents who do and do not stutter and 4) how this is linked to altered articulatory patterns in singing as well as to its rhythmic structure.

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http://dx.doi.org/10.1016/j.jcomdis.2016.05.012
0021-9924/

1. Introduction

Singing is a form of vocalization that has recently received an increased interest in speech therapy. It can benefit speech production skills, particularly in non-fluent or disfluent speakers suffering from non-fluent aphasia (and apraxia; e.g., Jungblut, Huber, Mais, & Schnitker, 2014; Stahl & Kotz, 2014), dysarthria (in Parkinson's desease, e.g., Kempler & Van Lancker, 2002; Van Lancker Sidtis, Cameron, & Sidtis, 2012), and stuttering (e.g., Colcord & Adams, 1979; Glover, Kalinowski, Rastatter, & Stuart, 1996). In these speech disorders, singing helps patients to produce speech with greater ease, intelligibility or fluency. In general, singing induces several dramatic changes to the temporal dynamics of articulatory patterns of segments and syllables. Vowel durations are prolonged in comparison to consonantal durations (on a 3:1 ratio in song vs. a 1:1 ratio in speech, Eckardt, 1999). In parallel, tonal targets in vowels (i.e., local maxima and minima of the intonation contour) are longer allowing for the perception of discrete pitch classes that underpin melody recognition (Kolinsky, Lidji, Peretz, Besson, & Morais, 2009; Sundberg, 1987; Zatorre, Belin, & Penhune, 2002). These segmental characteristics foster slower articulation rate and enhance phonation times in singing – factors that are known to foster speech production in speech motor disorders. Jungblut et al. (2014), studying apraxia of speech in aphasic patients, have put forward the idea that singing may enhance and reeducate speech motor capacities, in particular temporal planning, programming and sequencing of speech movements via its rhythmic structure. Following this idea, the present study investigates temporal aspects of articulation in singing and perceptually fluent speech in stuttering, a speech fluency disorder that is characterized by deficits in speech motor control (e.g., Civier, Tasko, & Guenther, 2010; Ludlow & Loucks, 2003; Namasivayam & van Lieshout, 2011; Zimmermann, 1980), but also potential deficits in temporal processing (Alm, 2004; Etchell, Johnson, & Sowman, 2014; Etchell, Ryan, Martin, Johnson, & Sowman, 2016; Falk, Müller, & Dalla Bella, 2015; Van Riper, 1982; Wieland, McAuley, Dilley, & Chang, 2015).

Indeed, singing has previously been reported to enhance fluent articulation in stuttering (Colcord and Adams, 1979; Glover et al., 1996; Johnson and Rosen, 1937; Metz, Conture, & Caruso, 1979; Wingate, 1969). Research confirms that singing naturally slows down articulation rate in individuals who stutter, with significant increases in utterance duration as well as in overall voicing time (Andrews, Howie, Dozsa, & Guitar, 1982; Colcord & Adams, 1979; Healey, Mallard, & Adams, 1976; Stager, Jeffries, & Braun, 2003). In particular, the percentage of short phonated intervals (i.e., 30–200 ms of vocal fold vibration) reduces significantly (Davidow, Bothe, Andreatta, & Ye, 2009; Ingham et al., 2001; Ingham, Ingham, Bothe, Wang, & Kilgo, 2015). Reductions in short phonated intervals have been identified as one of the strongest indicators of improved fluency in individuals who stutter (Davidow, 2014). Slower articulation rate and enhanced phonation times typical of singing are also used in different therapeutic approaches to decrease overt stuttering symptoms such as in the MPI stuttering treatment, comprehensive stuttering treatment programs or in the Camperdown Program (Boberg and Kully, 1985; Ingham et al., 2001; O'Brian, Onslow, Cream, & Packman, 2003). Moreover, singing regularizes the timing of prominent syllables due to musical beat structure (London, 2004). Temporal intervals between syllables carrying a musical beat become more regular and hence, more predictable than in speech (e.g., Gordon, Magne, & Large, 2011). These more precise temporal predictions have been deemed beneficial for speech processing through neural mechanisms of enhanced attending towards expected moments as well as better coupling of perception and production (e.g., as stated in predictive coding and dynamic attending theories, see overviews in Kotz & Schwartze, 2016; Schön & Tillmann, 2015). Predictable rhythm is a feature that is shared by other fluency-enhancing conditions in stuttering such as speech paced by a metronome (Davidow, Bothe, & Ye, 2011; Hanna & Morris, 1977). When speaking with a metronome, the rhythmic production yields decreased temporal variability of articulation in individuals who stutter (Janssen and Wieneke, 1987). Note that reduced segmental variability has also been associated with successful therapeutic intervention in stuttering, for example, by using prolonged-speech treatment (Onslow, van Doorn, & Newman, 1992). In sum, singing affects temporal parameters such as phonation times and segmental variability in speech that have been proven beneficial for stutterers' fluency and stability of articulation.

Increased temporal motor variability in verbal and even non-verbal tasks (e.g., Falk, Müller, & Dalla Bella, 2015; Olander, Smith, & Zelaznik, 2010) is characteristic of stuttering. This consistently replicated finding has been attributed to differing functioning of the (neural) timing network involved in motor control in stuttering (e.g., Chang & Zhu, 2013; Cooper & Allen, 1977; Etchell et al., 2014; Harrington, 1988). A recent neurophsyiologically underpinned hypothesis states that the internal timing network that sustains timing and rhythm of self-paced movements comprising the basal ganglia and supplementary motor area may be deficient in individuals who stutter (e.g., Chang & Zhu, 2013; Etchell et al., 2016; Fujii & Wan, 2014). Behaviorally, even perceptually fluent speech shows increased temporal variability in individuals who stutter. In an early study, Cooper and Allen (1977) found that participants who stutter showed consistently higher durational variability across repeated readings of phrases, sentences and paragraphs in the near-absence of overt stuttering symptoms. Variability of articulatory kinematics was equally found to be enhanced in a similar task of repeated sentence reading (Kleinow & Smith, 2000; Smith & Kleinow, 2000). At the segmental level, higher temporal variability of vowel and fricative durations was observed in individuals who stutter during perceptually fluent speech (Di Simoni, 1974; Onslow et al., 1992). Greater variability was also reported for stop articulation. Stops are produced through a complex temporal sequence of articulatory gestures involving a complete obstruction of the airflow in the vocal tract, subsequent accumulation of air pressure during closure (i.e., stop gap), a sudden closure release resulting in an audible burst and a transition phase from the stop into the following vowel, sometimes including an aspiration phase (Ladefoged & Johnson, 2011). Individuals who stutter have been found to be more variable in the duration of stop gaps (Max & Gracco, 2005). Compared to individuals who do not stutter, they were also consistently more variable in Voice Onset Time (henceforth VOT; Klatt, 1975; Lisker & Abramson, 1964), that is, the interval between the release of oral closure and the onset of vocal fold vibration (De Nil & Brutten, 1991; Dokoza, Hedever, & Sarić, 2011; Hillman & Gilbert, 1977; Homma & Yamada, 2014; Jäncke, 1994; Loucks & De Nil, 2006; Max and Gracco, 2005; Metz et al., 1979; Zebrowski, Conture, & Cudahy, 1985). Paralleling production, Neef et al. (2012) found that the perception of VOT in German stops is also more variable in individuals who stutter. This is an intriguing result, as VOT differences are essential to discriminate between voiced and voiceless stop phonemes in many languages of the world (Lisker & Abramson, 1964). In French or Russian, for example, voiced stops such as /d/ or /b/ require voicing to start before oral closure release (i.e., negative VOT; Petrova, Plapp, Ringen, & Szentgyörgyi, 2006). In contrast, voicing in voiceless stops like /t/ or /p/ often start after closure release (i.e., positive VOT). In other languages such as German and English, phonological voice contrasts are achieved in more gradual variations of VOT (fortis-lenis opposition). Fortis stops, often due to aspiration, have highly positive VOTs, while lenis stops range more widely from smaller positive VOTs to zero- and negative VOTs depending on stop position. For example in German word-initial fortis stops are aspirated and display long time lags between release and vocal fold vibration while lenis stops have shorter or zero-lags (Jessen, 1998; Ladefoged & Johnson, 2011). The perceptual results on German reported in Neef et al. (2012) indicate that phonemic perception of these long- and short-lagged stops is less acute in individuals who stutter compared to individuals who do not stutter, although overall phonemic discrimination is functional. The authors discuss the possibility that this result in perception may be linked to higher VOT variability in production mediated by shared underlying deficient gestural motor models (e.g., Liberman & Mattingly, 1985). In sum, these results on perception and production suggest that VOT variability is a good point of departure in order to study temporal processes in speech and singing in individuals who stutter.

To our knowledge, VOT variability has not been investigated in singing, neither in stuttering nor typically fluent speakers. Only VOT duration was examined in studies on singing proficiency in adult singers (McCrea & Morris, 2007a, 2007b). McCrea & Morris (2007a) showed that VOT for voiceless plosives reduces during singing compared to speaking when tempo is held constant. Moreover, this effect is larger in trained singers compared to untrained singers. Interestingly, in a recent study on metronome-paced speech (i.e., syllabic pacing), adults who stutter also showed a reduction of VOT for voiceless plosives in the paced compared to the unpaced speaking condition at a similar tempo (Davidow, 2014). These VOT reductions during metronome pacing despite stable tempo conditions are at first glance surprising. Previous studies showed that VOT varies with speaking rate, that is, it decreases with increasing speaking rate and vice versa (e.g., Kessinger & Blumstein, 1998; Miller, Green, & Reeves, 1986). Stop categories are affected differently by changes in speaking rate, with velar stops showing greater decreases with faster speech than other stop categories (Baum & Ryan, 1993). Note that, naturally, VOT is longer in stops with more posterior place of articulation (/k/>/t/>/p/, Klatt, 1975). Moreover, slower speaking rates induce a larger range of VOT values, especially in voiceless aspirated stops (Pind, 1996; Volaitis & Miller, 1992). Thus, in singing and metronome-paced speech, the reported decreases in VOT under similar tempo conditions could be linked to selective consonantal compression with simultaneous vowel extension that induces prolonged phonation. Whether this effect is due to rhythmic modifications (as suggested by the results of Davidow, 2014) remains an open question. Finally, whether VOT reduction also induces reduced VOT variability in singing will be one aspect considered in the present study.

Another reason to study VOT variability in song and speech in the present study derives from the finding that it is associated with the maturity and efficiency of speech motor skills. It has therefore been assessed in developmental studies as well as in studies of speech disorders (Auzou et al., 2000; Whiteside, Dobbin, & Henry, 2003; Yu et al., 2014; Yu, De Nil, & Pang, 2015). In particular, VOT variability has been discussed as a marker of fine-grained motor and timing control of oral and laryngeal processes. The articulatory challenge lies in the fact that vocal fold vibration has to be precisely timed relative to oral closure release, at least in languages that contrast voiced and voiceless stops (Lisker & Abramson, 1964). In particular in voiceless stops, the vocal folds have to be actively abducted which requires complex muscle activity (e.g., Löfqvist, 1990; Tyler & Watterson, 1991).

During speech development, long-lag positive VOTs in voiceless stop productions were found to be a particularly challenging gestural configuration. They appear after voiced productions in infancy and take overall longer to be mastered in an adult-like manner than other types of VOT (Kewley-Port & Preston, 1974; Lowenstein & Nittrouer, 2008; Macken & Barton, 1980; Preston & Yeni-Komshian, 1967; Yu et al., 2015). Previous studies report that children from 4 to 11 years show longer and more variable VOTs than adults (e.g., Yu et al., 2015). Older children and adolescents show more variable VOTs than adults, and decreases in variability are still observed until the age of 16 (Whiteside et al., 2003; Yu et al., 2015; Zlatin & Koenigsknecht, 1976). This time course in acquisition of VOT for voiceless stops is likely to be due to gestural reorganization during fluent speech development which includes processes that speed up gestural coordination, reduce overlap between adjacent consonant-vowel gestures and stabilize movement trajectories (e.g., Goffman & Smith, 1999; Goodell & Studdert-Kennedy, 1993; Nittrouer, 1993). In individuals who stutter, control of laryngeal articulation has been found to be particularly affected (as indicated by e.g., abnormal muscle activity, longer voice initiation times etc., Freeman & Ushijama, 1978; Starkweather, Hirschmann, & Tannenbaum, 1976). VOT in children who stutter has therefore been studied mostly under the aspect of laryngeal-oral coordination times. A few studies have reported VOT durations in children's and young adults' speech, but only one to our knowledge (De Nil & Brutten, 1991) focused on VOT variability. Adams (1987) reported longer VOTs in children who stutter aged 3–4 years. However, other studies have not replicated these results. No differences in VOT between participants who do and do not stutter were found in studies with age groups of 3–6 years (Zebrowski et al., 1985), 8–12 years (De Nil & Brutten, 1991) nor in young adults (17–25 years; Metz et al., 1979). However, VOT variability (measured as the variance of VOT per subject) significantly differed between children who do and do not stutter at the age of 8–12 years (De Nil & Brutten, 1991; see also a similar observation in Adams, 1987), similar to differences found in adult speakers who do and do not stutter.

In summary, the above findings show that individuals who stutter present difficulties with the temporal stability of phrasal and, in particular, segmental articulations and representations in speech perception as well as production. This is particularly visible in VOT productions in fluent speech which require fine-grained temporal coordination of laryngeal-oral movement. Therefore, VOT variability in fluent productions of song versus speech will be the focus of the present study. Moreover, we focus on voiceless stops as they present a challenging articulatory gestural configuration (e.g., Lowenstein & Nittrouer, 2008). We hypothesize that, if singing enhances the temporal coordination of laryngeal-oral movements (Jungblut et al., 2014), sung VOT should become more stable (i.e., less variable) in participants who stutter compared to their fluent spoken VOT productions. Moreover, as articulatory processes associated with VOT variability become mature during adolescence, we aim at studying whether singing affects VOT variability in both adolescents who do and do not stutter.

We examined VOT variability of the voiceless stops /p/, /t/, /k/ which were measured in sung and spoken utterances of adolescent native speakers of German. Stops were placed in word-initial prominent syllables of disyllabic words that were carrying stress in speech and attracted a musical beat in song. Additional temporal parameters were assessed (i.e., stop gap, vowel and utterance duration and variability) in order to better understand the potential differences between sung and spoken vocalizations and the specificity of VOT variability as a marker of mature temporal coordination of speech. Finally, in order to evaluate if rhythmic aspects may impact on VOT variability in singing, we also analysed stops in the unstressed syllables of the disyllabic words that appeared in off-beat positions.

2. Methods and material

2.1. Participants

Eight adolescents who stutter aged from 11 to 15 years (6 males, 2 females; $M = 12.4$ years, $SD = 1.9$ years) participated in the study. All had developmental stuttering with an onset in the third or fourth year of life. They were recruited from a group of participants (children and adolescents) enrolled in a summer therapy course held in the surroundings of Munich (staerker-als-stottern.de). Testing was done before or at the very beginning of the course. All the participants had followed stuttering treatment before (1–4 therapeutic interventions). Stuttering symptoms were assessed on the first day of the therapy course by a team of four speech therapists. Stuttering severity in the group ranged from mild to severe on the SSI-3 scale (Riley, 1994), being on average in the moderate spectrum ($M = 23.7$, $SD = 6.6$). Three participants exhibited mild stuttering, 2 moderate, and 3 severe stuttering. The control group consisted of 8 age- and gender-matched participants (6 males, 2 females; $M = 13.0$ years, $SD = 2.3$ years). All participants were native speakers of German and were untrained singers (no choral activity, no singing lessons). No language, cognitive or neurological impairments/incidents were reported.

2.2. Material

The three German voiceless stops /p, t, k/ were inserted in disyllabic nonsense words. Each test word had a trochaic strong-weak accent pattern. The stops were placed in the onset of the first, stressed syllable followed by a long vowel (i.e., /a:/ , /i:/ or /u:/). The second unstressed syllable of the disyllabic words was always /ta/. The resulting test words were /'pi:ta/, /'pa:ta/, /'pu:ta/, /'ti:ta/, /'ta:ta/, /'tu:ta/, /'ki:ta/, /'ka:ta/, /'ku:ta/. Each word was inserted into the phrase "liebe X, viel Glück" (dear X, good luck) at the place where usually a name would occur. This is a standard way of expressing congratulations in German. The phrase was then repeated five times in order to have five versions of the target word per trial (see example (1), for /'ki:ta/). The phrases were arranged as to match the rhythmic structure of the German version of the "Happy Birthday" song. Note that the lyrics were close in meaning to the traditional song in expressing the best wishes to someone, but without verbally referring to the event of a birthday as in the original version. In this way, 9 different trials (i.e., one for each test word) were created.

(1) *Liebe* /'ki:ta/, *viel Glück, liebe* /'ki:ta/, *viel Glück,*
liebe /'ki:ta/, *liebe* /'ki:ta/, *liebe* /'ki:ta/, *viel Glück.*
"Dear/'ki:ta/, all the best to you, dear /'ki:ta/ etc . . . "

2.3. Procedure

Participants were asked to perform two tasks. The first task was to read the sentences aloud (as in (1) at a comfortable moderate reading pace. At this time, participants did not know that the text was derived from the song. In the second task, participants read and sang the lyrics to the melody of 'Happy Birthday'. Again, they were asked to sing at a moderate comfortable pace. The material was presented on handouts and participants had the opportunity to practice their speaking and singing with one trial or stanza before recording. All participants declared themselves to be familiar with the song. The order of the tasks (speaking-singing) was not randomized as the rhythmic performance of song could have considerably altered the subsequent speaking strategies. To diminish misreadings of the phonetically similar words, the order of test words were kept constant across trials (i.e., first /k/-words, then /p/-words, then /t/-words). Each participant was recorded separately in a quiet room with the experimenter present. Data recording was done with a Beyerdynamic headset (TG H54c) and a H4N Zoom recorder at 44100 Hz/24bit. The whole experiment lasted between 15 and 20 min.

2.4. Analyses

The recordings were preprocessed using an automatic phonetic segmentation program for German (Munich AUtomatic Segmentation (MAUS), Schiel, 1999). Based on the presegmentation, stops were identified and VOT was measured manually by inspecting the oscillogram and spectrogram of the audio signal in Praat (Boersma, 2001). VOT was annotated for each plosive in the test words (/p/, /t/, /k/, Lisker & Abramson, 1964) in word-initial and word-internal (/t/) position. The time interval was marked between the onset of the stop release and the beginning of vocal fold vibration of the following vowel onset. The second zero-crossing of the glottal pulse was consistently used to mark the beginning of voicing. Furthermore, mean and standard deviations of VOT were calculated for each participant in order to obtain the coefficient of variation (CV)[1] as a measure of variability in sung and spoken VOT productions. Some additional measures were taken. First, stop gap duration and its variability were measured from the point where vocal fold vibration of the preceding Schwa-vowel stopped until the onset of the stop release. Second, vowel duration and variability following the stops were extracted from the recordings. The left vowel boundary was determined by marking the beginning of periodic glottal pulses in the oscillogram (second zero crossing). The right boundary was assessed by inspecting the formant patterns and the subsequent spectrum of the consonantal context (see Fig. 1).

Furthermore, the total duration and variability of each utterance (i.e., one stanza or repetition of the text/song) were assessed. Total utterance length was calculated based on common articulation rate measures, that is, through measuring stretches of continuous syllables excluding pauses (Miller, Grosjean, & Lomanto, 1984). This measure is also often used in stuttering research, particularly when investigating the development of temporal aspects of speech (e.g., Walker & Archibald, 1992). Silent pause intervals (e.g., caused by respirations, hesitations, blockades) were identified and annotated by the automatic phonetic algorithm (MAUS, Schiel, 1999) used for data preprocessing. Pause boundaries were inspected and, if necessary, corrected by a phonetically trained researcher. The summed durations of silent intervals were then subtracted from the total duration of each utterance.

All analyses were performed by a trained phonetician (not blinded for condition). For determining reliability, 10% of the segmental data (1 sung and 1 spoken trial per participant) were re-analysed by another trained phonetician. Pearson correlation coefficients were high (for stop gap: $r = 0.980$; for VOT: $r = 0.961$; for vowels: $r = 0.997$) with mean inter-rater differences of 0.8 ms for stop gap, 1.11 ms for VOT, and 3.5 ms for vowels.

3. Results

Before performing segmental analyses, we determined if sung and spoken vocalizations were significantly different from each other. First, in a perceptual rating task, an additional group of participants ($n = 14$, 1 male, 13 female, all students at the

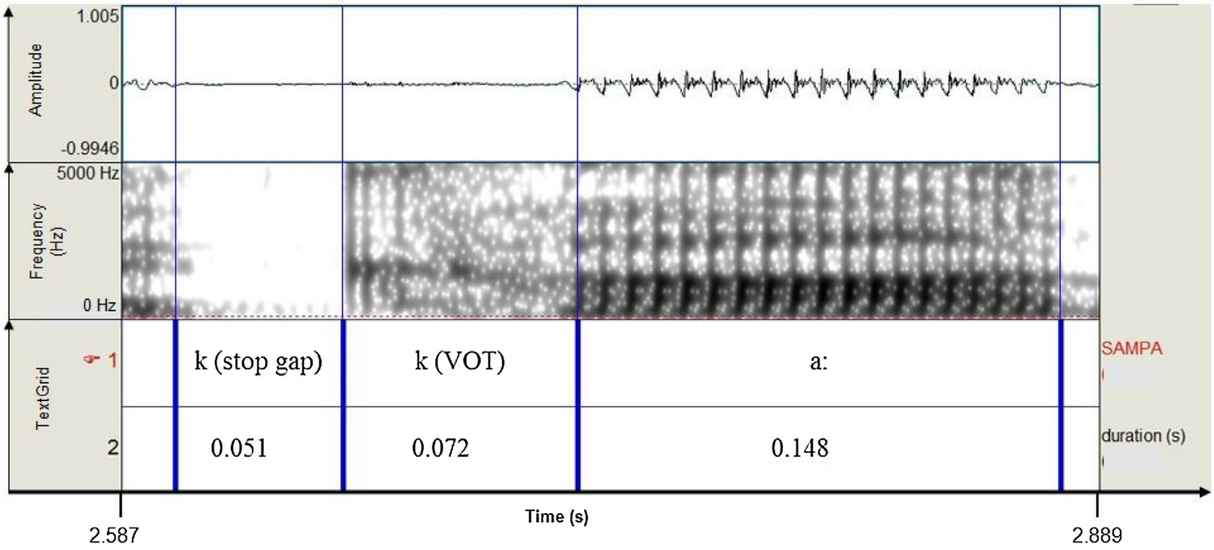

Fig. 1. Example of how stop gap, VOT and vowel duration were segmented in the first syllable of the word /ka:ta/ taken from a spoken trial. The oscillogram ("Amplitude") and spectrogram ("Frequency") are displayed, boundaries are indicated by vertical lines. The first Textgrid tier shows segmental labels (SAMPA), the second tier (duration) gives the durations of the segmented intervals.

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[1] The coefficient of variation is obtained by dividing the standard deviation by the mean. Throughout the results and discussion sections, the term "variability" will henceforth refer to CV measures.

Ludwig-Maximilians-University Munich) was asked to rate 10% randomly selected trials (one in each vocalization per participant) on their perceptual qualities on a scale from 1 ("definitely speech") to 7 ("definitely singing"). Results showed that speaking ($M = 1.7$, $SD = 0.39$) and singing ($M = 6.4$, $SD = 0.45$) were clearly differentiated by the listeners ($t(13) = 24.23$, $p < 0.001$). In an additional test, we determined if the rhythmic structure was distinct in sung and spoken trials, as the simple structure of the text could have lead to similar rhythmic renditions. For that purpose, we examined if rhythmic regularity, measured as inter-beat intervals, was higher in sung than in spoken trials. We calculated the variability (CV) of inter-beat-intervals per participant, based on interval durations between the syllabic nuclei associated with the first metrically strong syllable[2] of the dactylic strong-weak–weak pattern (=the first beat of each measure in song; i.e., *Liebe* | ***Ki**ta, viel* | ***Glück,** liebe* | ***Ki**ta, viel* | ***Glück,** liebe* | ***Ki**ta, liebe* | ***Ki**ta, liebe* | ***Ki**ta, viel* | ***Glück;*** with bars indicating dactylic patterns and bold syllables the metrically strong syllables). Statistical analyses (ANOVA with the within-subject factor Vocalization and Group as a between-subject factor) confirmed that sung trials showed higher rhythmic regularity ($M_{\text{sing}} = 0.058$, $SE = 0.008$) than spoken trials ($M_{\text{read}} = 0.128$, $SE = 0.011$; main effect of Vocalization, $F(1,14) = 36.89$, $p < 0.001$), as expected. No interaction was found. Thus, both groups of participants showed more rhythmic regularity in singing than in speaking. In sum, we conclude that the vocalization tasks were performed as instructed by the participants.

The data were then prepared for statistical analyses. As we were focusing on fluent speech production, test words containing stuttering,[3] misreadings of the written word (e.g., reading /pi:ta/ instead of /ku:ta/) with and without correction, as well as other occasional errors (such as noisy recording, fricative instead of plosive production) were discarded from analysis. No further exclusion criteria (e.g., perceptual criteria) were applied. Eight percent of the test words had to be discarded in the group of adolescents who stutter (two percent of which were stuttered disfluencies), and three percent in the control group. Potentially due to the short and highly repetitive utterances, stuttering symptoms were not very frequent, and occurred equally often across speech and song. Before averaging the sung and spoken stop data per participant, the sung and spoken test words were matched with respect to their position within a trial (i.e., first, second, third occurrence). Only matched test words were used for averaging in order to control for potential effects of phrasal position on duration (e.g., phrase-final lengthening). Overall 1284 tokens (half sung, half spoken, 604 in the group of adolescents who stutter, 680 in the control group) were used for averaging.[4] Mean VOT (in stressed and unstressed positions), as well as mean stop gap, vowel and utterance durations and, subsequently, CVs were calculated per participant and stop category. The mean values are displayed for both groups in Table 1.

We first present results for word-initial/stressed positions. As can be seen in Fig. 2A, sung stops displayed smaller VOT values than spoken stops in both groups. The VOT data were entered in a three-way mixed-design Analysis of Variance (ANOVA) with the within-subject factors Stop (/p/,/t/,/k/) and Vocalization (speaking vs. singing) and the between-subject factor Group (participants who do vs. do not stutter). Results confirmed that sung stops displayed shorter VOTs than spoken stops in both groups ($F(1,14) = 62.1$, $p < 0.001$). Furthermore, differences between stop classes were found ($F(2,28) = 34.6$, $p < 0.001$). Additional pairwise comparisons confirmed that VOT differed between stop classes, consistent with the literature

Table 1
Mean values of stop (VOT, stop gap), vowel and utterance durations, and Coefficients of Variation (CVs) of the sung and spoken performances in both groups of participants.

Measures	Control group		Adolescents who do stutter	
	Speaking	Singing	Speaking	Singing
Stop (first syllable)				
/p/: VOT | CV	70.6 ms | 0.18	60.0 ms | 0.21	72.7 ms | 0.22	63.3 ms | 0.19
/t/: VOT | CV	82.7 ms | 0.18	68.2 ms | 0.19	82.7 ms | 0.21	75.8 ms | 0.18
/k/: VOT | CV	89.9 ms | 0.12	75.3 ms | 0.15	88.0 ms | 0.17	78.7 ms | 0.14
/p/: Stop gap | CV	91.0 ms | 0.14	81.7 ms | 0.16	103.9 ms | 0.18	86.3 ms | 0.20
/t/: Stop gap | CV	76.1 ms | 0.14	61.8 ms | 0.13	94.5 ms | 0.19	74.4 ms | 0.18
/k/: Stop gap | CV	68.7 ms | 0.13	57.3 ms | 0.14	80.7 ms | 0.20	66.8 ms | 0.16
Stop (second syllable)				
/t/: VOT | CV	49.9 ms | 0.22	59.4 ms | 0.21	46.6 ms | 0.35	54.8 ms | 0.30
Vowel				
Mean duration | CV	117 ms | 0.14	225 ms | 0.08	100 ms | 0.16	173 ms | 0.11
Utterance				
Mean duration | CV	7.04 s | 0.07	8.94 s | 0.04	8.32 s | 0.11	8.89 s | 0.06

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[2] This syllable also corresponds to the localization of the musical down-beat of each measure in song.

[3] Disfluencies were determined by a speech therapist and a researcher both specialised in stuttering.

[4] For calculating mean stop gap duration, from these 1284 tokens, an additional 20 were excluded as these displayed highly atypical values (i.e., they were extreme outliers checked per stop category and participant).

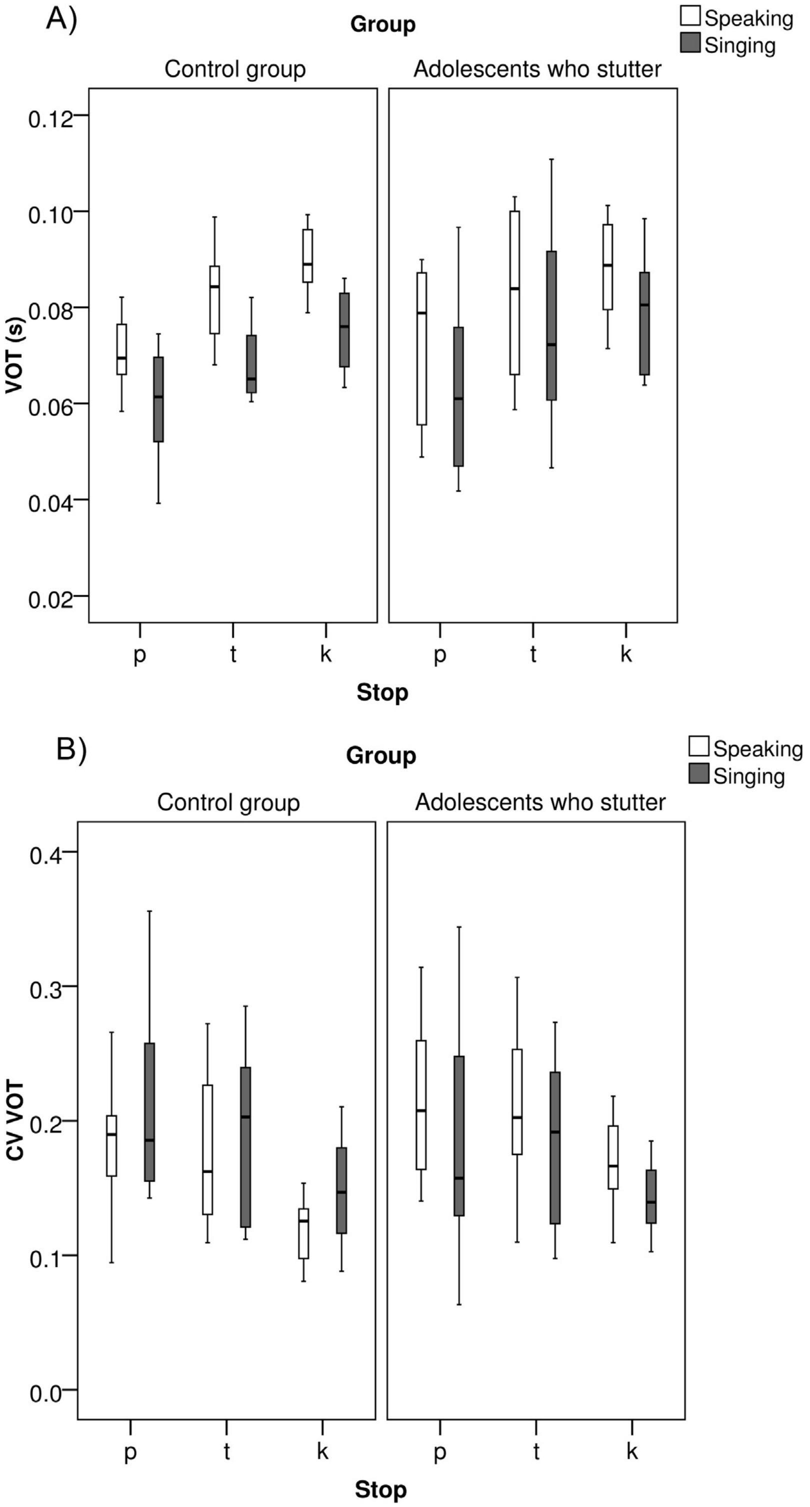

Fig. 2. VOT (Panel 2A) and VOT variability (CV, Panel 2B) of the three voiceless German stop categories in adolescents who do and do not stutter during speaking and singing. Error bars display SE of the mean.

on place-of-articulation effects on VOT (/k/>/t/>/p/), (Lisker & Abramson, 1964). There were no interactions or group differences.

Another ANOVA was performed for VOT variability (i.e., CV, Fig. 2B). Adolescents who do and do not stutter differed in variability depending on Vocalization (Vocalization × Group interaction, F (1,14) = 14.87, $p < 0.005$, see Fig. 2). Post-hoc comparisons revealed that adolescents who stutter significantly decreased VOT variability during singing compared to speaking (F (3,12) = 5.04, $p < 0.05$), while controls instead increased variability from speaking to singing (F (3,12) = 4.38, $p < 0.05$). Furthermore variability was lower for posterior /k/ than for /t/ and /p/ for both groups (main effect of stop category, F (2,28) = 5.87, $p < 0.01$).

Similar ANOVAs with the factors Stop, Vocalization and Group were conducted for stop gap duration and variability, duration and variability of vowels following stops as well as utterance duration and variability. Comparable to VOT reduction, a reduction in stop gap duration from speech to song was found (F (1,14) = 26.65, $p < 0.001$). In addition, stop gap duration varied with stop category (/p/>/t/>/k/; F (2,28) = 49.59, $p < 0.001$), a common finding in phonetic analyses of stop gap (Hoole & Bombien, 2014). Stop gap variability (CV) was not different for song and speech. However, a significant group difference revealed that participants who stutter were generally more variable in stop gap duration than controls (F (1,14) = 5.42, $p < 0.05$).

Furthermore, for all the participants, the duration of vowels almost doubled during singing (F (1,14) = 83.32, $p < 0.001$). Participants who stutter displayed slightly shorter vowels than controls in both conditions (F(1,14) = 4.98, $p < 0.05$). Vowel variability (CV) significantly decreased in both groups during singing (F (1,14) = 13.49, $p < 0.01$). No effect of stop consonant preceding the vowel was found. Finally, utterance duration became longer for both groups during singing compared to speaking (F (1,14) = 14.51, $p < 0.01$) and utterance variability (CV) was smaller in singing than in speaking (F (1,14) = 13.19, $p < 0.01$). Participants who stutter were overall more variable in utterance duration than controls (F (1,14) = 4.69, $p < 0.05$).

Second, we examined if similar differences in VOT and VOT variability as reported above were also found in the second unstressed syllable /.ta/ of the test words. Two 2 × 2 ANOVAs (within-subject factor: Vocalization, between-subject factor: Group) were run on alveolar VOT as well as VOT variability. A main effect of Vocalization indicated that VOT in this position was slightly longer during singing than during speaking (F(1,14) = 4.67, $p < 0.05$). Analyses of VOT variability (CV) showed that participants who stutter were overall more variable in this position than controls (effect of Group: F (1,14) = 8.02, $p < 0.05$). No further effects or interactions were found. The slight increase in VOT in the singing condition (unlike the reduction found for the stressed syllables) may reflect the fact that unstressed syllables are less reduced in singing.

4. Discussion

In the present study, we investigated the differences between speaking and singing in terms of temporal characteristics in the speech of adolescents who do and do not stutter with a special focus on VOT variability. Group differences were found for temporal variability measures. Adolescents who stutter significantly reduced VOT variability from speaking to singing by around three percent, while adolescents who do not stutter rather showed a slight increase in variability. However, this was only the case in word-initial stressed positions. When examining unstressed word-medial syllable onsets, adolescents who stutter displayed generally increased VOT variability compared to controls independent of vocalization. Further results showed that VOT of voiceless German plosives in word-initial stressed positions reduced during singing in both groups of participants. The same result was found for stop gap duration, while vowel and utterance duration increased in song compared to spoken speech. Although both groups reduced vocalic variability and overall utterance variability in singing compared to speaking, participants who stutter were still overall more variable than controls in utterance as well as in stop gap duration.

These findings shed new light on the way singing influences temporal articulatory patterns in the speech of participants who stutter. First, although singing improves most of the temporal variability measures in participants who stutter, they are still more variable than the control group in fluent productions. This result is consistent with findings of higher temporal variability in the fluent speech of persons who stutter (Max & Gracco, 2005; Onslow et al., 1992; Riley & Ingham, 2000). However, singing shows a major benefit for adolescents who stutter in reducing VOT variability which was not observed in adolescents who do not stutter. In spoken speech, it is known that individuals who stutter produce more variable VOTs compared to controls, indicating less efficient or mature motor control processes (Whiteside et al., 2003; Yu et al., 2014). In the present study, singing also produced advantages for articulatory stability in adolescents who do not stutter, notably, by generating smaller vowel and utterance variability in sung productions.[5] The fact that VOT variability reduction was uniquely observed in participants who stutter support the idea that they particularly benefit from singing in the temporal coordination between laryngeal and supra-laryngeal activity. Note that, despite increased VOT variability, it is unlikely that the intelligibility of stop categories is disturbed in a major way as variability does not result from major phonematic misplannings in stuttering such as found in dysarthria or apraxia of speech. However, as discussed by Neef et al. (2012), perceived acuity of stop categories (i.e., in voicing contrast) is also more variable in individuals who stutter, potentially due to a close link between perception and production in the speech motor system's forward models.

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[5] Note that overall reduction of variability in both groups may also have been partly influenced by the fact that participants were already more familiar with the text when performing the singing after the speaking condition.

Remarkably, the benefit of singing in reducing VOT variability was only visible in word-initial stressed syllables. The alveolar VOT productions in word-medial unstressed syllables showed the same trend as other variability measures, that is, participants who stutter were more variable than the control group. Although we could not directly compare both positions in the present study because of design and task complexity, these findings point to the possibility that the reduction in VOT variability in sung productions of participants who stutter could be characteristic to the position of the stop in the word (initial vs. medial) or/and the level of prominence (stressed/unstressed). Previous research showed that word-initial syllables and stressed syllables are particularly prone to stuttering (e.g., Hubbard, 1998; Natke, Grosser, Sandrieser, & Kalveram, 2002; Natke, Sandrieser, van Ark, Pietrowsky, & Kalveram, 2004). De Nil & Brutten (1991) found that increased VOT variability in spoken speech of children who stutter was even visible across different levels of cluster complexity in word-initial syllables (i.e., single stop, two- and three- segments-cluster including the stop). From a motor point of view, the laryngeal dynamics of the devoicing interval associated with stop production (i.e., the timing of the glottal abduction-adduction cycle) may be more demanding in stressed syllables than in (reduced) unstressed syllables in stress-languages such as German or English, since voiceless plosives in unstressed syllables may exhibit hardly any active glottal abduction at all (see e.g. Fuchs, 2005). In general, in singing, as VOT becomes shorter, the amplitude and duration of the associated devoicing movements are likely attenuated. This may produce two advantages, first, a less demanding motor coordination of the smaller movement trajectory, and second, a shorter interruption of phonatory activity. In particular the latter aspect could enhance articulatory patterns of participants who stutter who substantially benefit from prolonged phonation in speech (e.g., Davidow, 2014; Ingham et al., 2001).

Another possible explanation is that singing could produce advantages for predictive timing in stressed syllables carrying a musical beat. Note that in English or German, stressed syllables are regularly used to be aligned with the beat structure of music in song (e.g., Hayes & Kaun, 1996). The last 10 years have produced impressive evidence that rhythmically regular (i.e., predictable) structures in music and speech generate temporal predictions that enhance musical as well as verbal processing (e.g., Cason & Schön, 2012; Falk & Dalla Bella, 2016; Jones, 2009; Kotz & Schwartze, 2010; Quené & Port, 2005; Roncaglia-Denissen, Schmidt-Kassow, & Kotz, 2013). Enhanced predictive timing is attributed to the capacity to highten attending to expected times in speech or music, possibly, via phase-locking of neuro-cognitive oscillations (e.g., Calderone, Lakatos, Butler, & Castellanos, 2014; Large & Jones, 1999; see also Schön & Tillmann, 2015; for a recent overview). Another consequence of enhanced predictive timing via rhythms is that it facilitates the coordination of complex movement sequences and their smooth execution through the coupling of perception and action (see Maes, Leman, Palmer, & Wanderley, 2014; Schröger, Kotz, & SanMiguel, 2015; Vuust & Witek, 2014; for reviews). Thereby, enhanced predictive timing could be particularly beneficial for auditory-motor integration and articulation in participants who stutter (e.g., Harrington, 1988). Indeed, participants who stutter displayed deficits in anticipatory motor behavior in recent studies as well as altered neural circuits of temporal processing (i.e., the basal ganglia-thalamo-cortical circuit; Etchell et al., 2014; Etchell et al., 2016; Falk et al., 2015; Neef, Hoang, Neef, Paulus, & Sommer, 2015; Vanhoutte et al., 2015). In our study, participants who stutter may have shown the particular pattern of reduced VOT variability in stressed vs. unstressed syllables, because predictive timing was facilitated for the stressed positions that are the rhythmic anchors of musical beats. In light of our results and the long-standing finding that rhythmicized speech, such as speaking with a metronome or singing, act as fluency-enhancing conditions in individuals who stutter (for neural effects, see also Stager et al., 2003; Toyomura, Fuji, & Kuriki, 2011), these aspects of predictive timing clearly deserve further investigation. Future studies should aim at testing the respective contributions of articulatory processes involved in word-initial/stressed syllables and predictive timing in fluency-enhancing conditions in stuttering.

Mean values of VOT, however, were not indicative of group differences. This is in line with some of the previous research on VOT in fluent speech of persons who stutter (De Nil & Brutten, 1991; Zebrowski et al., 1985). When comparing adults and children who do and do not stutter, it has been found that individuals who stutter tended to show longer VOTs, but results were equivocal across studies (Adams, 1987; Borden, Baer, & Kenney, 1985; Borden, Kim, & Spiegler, 1987; Boutsen, Brutten, & Watts, 2000; De Nil & Brutten, 1991; Healey & Gutkin, 1984; Healey & Ramig, 1989; Hillman & Gilbert, 1977; Max & Gracco, 2005; Metz et al., 1979; Starkweather & Myers, 1979; Zebrowski et al., 1985). With respect to type of vocalization, participants who do and do not stutter alike reduced VOT from speaking to singing, a result that replicates previous findings on adult untrained singers when tempo was held constant (McCrea & Morris, 2007a, 2007b). Note that in our study utterance duration increased in singing, therefore, VOT reduction was counterintuitive. Slower speech tempo is usually associated with longer instead of shorter VOTs (e.g., Kessinger & Blumstein, 1998). Hence, the pattern of temporal reduction in singing is likely to be induced by prolonged voicing of sonorant segments (e.g., Brayton & Conture, 1978; Colcord & Adams, 1979; Di Simoni, 1974; Riley & Ingham, 2000) and the temporal compression of voiceless consonantal material (VOT, gap duration; see Falk, 2011 for an overview on temporal variability of consonants and vowels in sung German speech). The finding is also in line with results from Howell and Sackin (2001), showing that singing produces rather local than global speech rate changes.

4.1. Limitations of the study

Our results are restricted to acoustic measures as a reflection of speech motor activity. Although VOT is accepted to be a good indicator of laryngeal-oral coordination, it would be desirable to add both kinematic and electromyographic measures of the time course of the relevant motor activity during singing and speaking. By concentrating on voiceless stops in the present study, we could not derive conclusions for the voiced stop categories or for the difference in voiced and voiceless stops in sung and spoken speech. As this difference is perceptually highly relevant and differences are found between individuals who do and do not stutter (Neef et al., 2012), future studies may examine the link between acoustic and perceptual qualities of stop consonants in speech and song.

Furthermore, to corroborate the present findings and tease apart different explanations for VOT variability differences, future studies should directly test differences in stressed and unstressed/word-initial and −medial syllables, by carefully controlling stop quality, rhythmic and melodic structure in different sung and spoken environments. In light of recent findings on the role of anticipation and predictive timing in stuttering, it would also be valuable to relate differences in VOT variability found in stressed and unstressed positions to the time course of brain processes, using electrophysiological measures. This would help clarify the role of predictive timing and rhythmic processes in singing versus speaking, and in participants who do and do not stutter. Furthermore, the issue of syllabic prominence in stuttering has been underscored in past studies (Hubbard, 1998), and missing correlations between stop gap duration and VOT in stressed syllables have been noted in individuals who stutter compared to a control group (Boutsen, 1995; Zebrowski et al., 1985). Therefore, it would be desirable to further investigate these issues, taking into account VOT variability.

The number of participants and age range was restricted in this study which hindered further analyses on the developmental time course of VOT. Given the fact that younger children and adolescents/adults differ in their efficiency of articulatory coordination, we would expect that benefits of singing are even more evident for younger children (who do and do not stutter) in reducing articulatory variability. Further testing with a larger age range would also allow investigators to test accounts of stuttering that focus on limited or less mature speech motor control skills over the life span as a potential source of the disorder (Namasivayam & van Lieshout, 2011; Van Lieshout, Hulstijn, & Peters, 2004).

Finally, as our tasks were designed to yield fluent productions, we could not investigate VOT variability as a marker of fluency. In future studies comparing different fluency-evoking conditions, VOT variability could be included to determine the differences between conditions, to discuss unique benefits of singing (e.g., in contrast to other fluency-evoking mechanisms, e.g. Prins & Hubbard, 1990; who did not report reductions in VOT variability in repeated readings despite stuttering adaptation) and to advance our understanding of acoustic markers of fluent speech in stuttering (see, e.g., Davidow, 2014).

4.2. Relevance of the findings & conclusions

The present findings increase our understanding of the acoustic dimensions that characterize fluent singing in the context of stuttering. Singing clearly alters the way vocalic and consonantal segments are realized in time. Speech clinicians and researchers working on the management and basis of fluent speech production in stuttering may be interested in the fact that VOT variability in stressed syllables reduces around 3% during singing compared to speaking in adolescents who stutter. As no reduction was found in unstressed positions or on other acoustic parameters, nor in adolescents who do not stutter, we can exclude that singing just reduces general articulatory variability. In fact, the results are indicative of the idea that singing rather enhances subtle temporal coordination mechanisms between laryngeal and oral movements at the CV-transition, a process from which individuals who stutter may particularly benefit in their productions. This opens new perspectives for research and clinical practice alike to consider more in detail the role of timing of prominent syllables in sung and spoken speech patterns, including comparisons with other fluency-evoking speaking conditions and techniques, such as metronome speech or prolonged speech. On a neural level, it has been shown that singing activates bilateral areas linked to auditory and motor processes as well as auditory-motor integration (e.g., the anterior superior temporal sulcus, STS), the supramarginal gyrus (SMG) and the supplementary motor area (SMA) (Jeffries, Fritz, & Braun, 2003; Stager et al., 2003). Higher activation is found in persons who stutter in some of these areas than in controls, as well as a normalization of hypoactivated left-hemisphere structures during singing compared to speech (Stager et al., 2003). This has been interpreted as a reflection of enhanced self-monitoring and facilitated auditory-motor coupling during sung productions in persons who stutter. Such findings invite discussion of further ideas on whether singing or engaging in rhythmic activity may be useful as a playful training opportunity in stuttering, in particular for children and adolescents, as proposed for other developmental speech disorders (e.g., Overy, 2003). It remains an open question which aspects of singing may particularly train processes linked to fluent articulations. As an example from intervention in acquired speech disorders, Melodic Intonation Therapy combines melodic and rhythmic alterations of verbal productions, supported by synchronous movement, in order to enhance fluency in patients with severe non-fluent aphasia (Albert, Sparks, & Helm, 1973). Both rhythm and melody have been found to impact on this task (Stahl, Kotz, Henseler, Turner, & Geyer, 2011; Zumbansen, Peretz, & Hébert, 2014). In a previous study, Glover et al. (1996) proposed that fluency-enhancement in singing arises from a better representation of melodic structure, normally not present in speech. Another possibility may be that melodic structure induces the singer to better control vocal fold tension and breathing which also could help patients with speech and voice disorders (Rinta & Welch, 2008; Sundberg, 1987). Others underscore the role of altered timing and regular rhythm for fluency enhancement (Davidow et al., 2011; Etchell et al., 2014; Howell, 2007). Audio-motor integration and learning may both be particularly stimulated through rhythmic production in solo as well as choral singing (Racette, Bard, & Peretz, 2006; Tierney & Kraus, 2014). This could also be an interesting perspective for language promotion in early childhood in children at risk, but in the absence of speech disorders. Future research on stuttering should further unravel the role of melody/intonation and rhythm for motor processes and timing in fluent sung and spoken productions in individuals who do and do not stutter.

Acknowledgments

The research leading to these results has received funding from a SSHRC-MCRI AIRS (www.airsplace.ca) research grant as well as from the European Union Seventh Framework Program [FP7/2007-2013; FP7-PEOPLE-2012-IEF] under grant agreement n° 327586 to Simone Falk. We thank Thilo Müller and the team of the SAS course, in particular Ingeborg Mayer, for their help with recording stuttering participants as well as Jonathan Harrington, Ulrich Reubold and Florian Schiel of the IPS Munich, and Simone Dalla Bella, Euromov, Montpellier, for their advice and helpful comments.

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