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Age-related rhythmic variations: The role of syllable intensity variability

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Speech rhythm varies with age. In this paper, we examined the role of mean and peak syllable intensity variability in age-related rhythmic changes. Sixteen younger adults and 10 older speakers read 60 sentences in Zurich German. Results revealed that peak syllable intensity variability is significantly smaller in older compared to younger adults; there was no such effect for syllable mean intensity. Reduced fluency, changes in the biomechanical properties of articulators controlling the mouth opening cycles, and compensation strategies for subglottal pressure generation were the most plausible reasons for the obtained age-related syllable intensity variability.

1. Introduction

The acoustic properties of speakers' vocal output undergo substantial development with advancing age, most typically because of degenerative changes in speech production mechanisms and speech motor control (e.g., Schötz 2007). The aim of the present study is to investigate the effect of healthy ageing on speech rhythm variability. In view of population ageing, knowledge about age-related rhythmic variability is crucial for augmenting our understanding of how speech production develops over the life cycle of an adult. This is of particular importance for differentiating rhythmic changes directly associated with ageing from those associated with age-related pathologies that, like dysarthrias, additionally contribute to rhythmic changes (Liss et al. 2009).

How can age-related rhythmic differences possibly be quantified? Speech rhythm is a multidimensional phenomenon (Nolan & Jeon 2014) and its acoustic correlates have been associated with numerous physical features related, for instance, to the timing properties of specific speech units (e.g., consonantal and vocalic intervals, Ramus et al. 1999; Grabe & Low 2002), or to the characteristics of the speech amplitude envelope (e.g., low frequency components of the amplitude envelope, Tilsen & Arvaniti 2013; syllable intensity, He & Dellwo 2016). Among the various models, existing research on age-related rhythmic changes has predominantly focussed on consonantal and vocalic intervals' durational variability. Cross-sectional studies on Italian and Zurich German suggest that the speech of older adults is characterised by lower speech rate, higher proportion over which speech is vocalic (%V), and higher variability of consonantal and vocalic interval durations (henceforth: CV interval) (Pettorino & Pellegrino 2014; Pellegrino et al. 2018). Nevertheless, it was mainly speech rate that accounted for these results, because the effect of age disappeared when the rhythmic variables were normalized for speech rate (Pellegrino et al. 2018). Since longitudinal data on large time-span ageing are difficult to obtain, there is little evidence on within-subject rhythmic variability. Evidence for decreasing speech rate with age is available from a single-subject longitudinal study based on public lectures of a well-known linguist and political activist, Noam Chomsky, over a timespan of about 60 years (Pellegrino 2019). Rhythmic changes as a function of age in terms of %V did not show in these data, which might be idiosyncratic and possibly attributed to this particular speaker being experienced in public speaking.

In view of the limited effect ageing seems to exert on the timing properties of CV intervals, the present paper examines age-related rhythmic variability from the perspective of syllable intensity variability. This is motivated by the observation that ageing drastically affects the biomechanical properties of articulators controlling the generation of subglottal air-pressure and the degree of mouth aperture, which both covary with intensity properties of the speech signal (Plant & Younger 2000; Chandrasekaran et al. 2009). There is evidence, indeed, that with advancing age, and especially in men, the development and maintenance of subglottal pressure can be greatly affected by the degenerative changes in laryngeal airway resistance, vocal folds closure, pulmonary recoil, and chest wall compliance (Bode et al. 1976; Ximenes Filho et al. 2003; Huber & Stathopoulos, 2015). Furthermore, it has been documented that as age progresses, the temporal-mandibular joints degenerate (Yadav et al. 2018), the degree of maximum mouth opening (MMO) decreases irrespective of gender (Yao et al. 2009; Khare et al. 2012), and the same holds for upper and lower lip displacement during connected speech tasks (Dromey et al. 2014). These changes, associated to older adults' reduced fluency (Bóna 2014), determine inevitable differences in the cyclical mouth opening-closing gestures of younger and older adults, and may result in measurable differences in intensity between syllables across the two age groups.

To quantify rhythmic variability between younger and older adults, we applied metrics based on mean and peak syllable intensity variability to recordings of 60 read speech utterances produced by young and old Zurich German speakers. Mean and peak syllable intensity measures were previously devised by He and Dellwo (2016) to capture speaker idiosyncratic variability of intensity across syllables. The rationale for this was that the individual differences in the anatomy and kinematics of the articulators controlling the area of mouth aperture and the generation of subglottal and pulmonic air-pressure should influence the intensity characteristics of the signal. Mean and peak measures were demonstrated to vary significantly across speakers and carry more speaker-specific information compared to duration based-measurements (He & Dellwo 2016). Mean syllable intensity variability measures, both when calculated over an entire utterance and between adjacent syllables, were also shown to vary between adults, older children, intermediate-aged children and younger children and these differences were accounted for by varying degree of motor control maturity (He 2018).

In line with studies on between-speaker syllable intensity variability (He & Dellwo 2016), and on developmental pattern of speech rhythm in a first language (He 2018), we calculated mean and peak syllable intensity as a correlate of the mouth opening-closing cycle. We differentiated between mean and peak intensity of each syllable, as the latter contains more of the instantaneous intensity maximum variability between stressed and unstressed syllables. For every utterance, we measured the distribution characteristics of intensity (coefficient of variation) and sequential intensity variability (pairwise variability index).

In view of the evidence about the lower degree of mouth opening with ageing (Yao et al. 2009; Khare et al. 2012), the weaker correlation between upper and lower lip displacement in older adults (Dromey et al. 2014), and the degenerative changes to respiratory and laryngeal systems supporting the production and maintenance of pulmonic and subglottal air-pressure (e.g., Bode et al. 1976; Ximenes Filho et al. 2003; Huber & Stathopoulos 2015), we hypothesize that mean and peak syllable intensity variability is reduced in older in comparison with younger adults. If the results confirm that syllable intensity variability changes across the age groups, this would imply that the ageing process affects syllable intensity variability differently compared to CV durational variability. To provide more conclusive support for this assumption, we also calculated CV interval durational variability measures from the same corpus of 60 read speech utterances (Table 1).

Metrics	Description
%V	Percent of utterance duration composed of vocalic intervals.
nPVI_V	Normalized pairwise variability index for vocalic intervals. Average durational differences between successive vocalic intervals divided by their sum (× 100).
rPVI_C	Pairwise variability index for consonantal intervals. Average durational differences between successive vocalic intervals.
VarcoC	Coefficient of variation of durational variability of consonantal intervals. Standard deviation of C-intervals duration divided by their local mean.
VarcoV	Coefficient of variation of durational variability of vocalic intervals. Standard deviation of V-intervals duration divided by their local mean.

Table 1. Description of CV interval durational variability measures

2. Method

2.1 Speakers

Older adults (OAs): 10 speakers (5f, 5m) of Zurich German, ranging in age from 66 to 81; mean age: 71.7 years; standard deviation: 4.9 years. All speakers were Zurich German monolinguals until the age of 6 years, completed their education in Zurich and lived in Zurich city or surroundings for at least five years before the recording session. Participants reported no vision or hearing disabilities, nor recognized dyslexia. All of them passed the Mini-Mental Status Examination (Folstein et al. 1975).

Younger adults (YAs): 16 speakers of Zurich German (8f, 8m; age range: 18-32; mean age: 30.3 years; standard deviation: 6.6 years). The younger speakers were previously recorded for the TEVOID corpus (Dellwo et al. 2015).

2.2 Recordings

Speakers read 256 sentences in Zurich German. OAs were recorded with identical methods and equipment as YAs (sound treated booth at Zurich University, Neumann STH transducer microphone). From the 256 recorded sentence utterances, we selected the ones that OAs produced with comparable phonotactics, without audible pronunciation mistakes, segment and syllable elisions or filled pauses (60 utterances). They were all declarative sentences of between 4 and 22 syllables. All utterances were automatically segmented and annotated with segment labels using WebMaus (Kisler et al. 2017). Machine alignment errors were subsequently corrected by two trained phoneticians. The phonetic data labelling was converted into consonantal and vocalic intervals. Syllables were identified automatically based on the sonority hierarchy principle, as in Leeman et al. (2014). In total, we analysed 1560 utterances, of which 600 produced by the group of OAs (60 utterances * 10 older adults) and 960 by that of YAs (60 utterances * 16 young adults).

2.3 Signal processing and syllable intensity measurements

The procedure in He and Dellwo (2018) was followed to calculate the intensity contour of each utterance and to measure the mean intensity (Iµ) and peak intensity (Ip) of the portion of the signal corresponding to a speech syllable. The standard deviations (stdev) of both Iµ and Ip across syllables were calculated for each utterance. To normalise for average between-speaker energy variability, we obtained the coefficients of variation (100 × stdev Iµ/ Iµ, henceforth: VarcoIµ and VarcoIp). Sequential syllable intensity differences were calculated by the normalized Pairwise Variability Index (nPVI) to mean (nPVI-Iµ) and peak (nPVI-Ip) syllable intensity. The nPVI is the average of either peak or mean absolute intensity differences between consecutive syllables. Normalization was carried out by dividing each pairwise mean or peak intensity difference by their local mean (cf. Table 1 in He & Dellwo 2016: 251).

2.4 Statistical Analysis

Mixed-effects models were applied in which syllable intensity measures (VarcoIμ,, nPVI-Iμ, VarcoIp and nPVI-Ip) and CV interval duration measures (%V, VarcoV, VarcoC, nPVI_V, rPVI_C) were the dependent variables. AGE GROUP (YA and OA) was a fixed factor, and SENTENCE and SPEAKERS were random factors. Given that the effect of ageing on the respiratory and laryngeal support for speech can be greater for men than women, we also tested the interaction between AGE GROUP and GENDER and the main effect of GENDER. Given that the age-related differences in syllable intensity variability could vary between long and short sentences (longer sentence typically demand higher aerodynamic effort), we also tested the interaction between AGE GROUP and SENTENCE LENGTH (LONG and SHORT). The significance of the two main effects was tested too. The length of the sentences was measured in number of phonological syllables. Based on (1) the frequency distribution of sentences according to their syllable number and (2) the relative density distribution, we divided the sentences in two different groups of comparable size. Sentences with 4 to 10 syllables were considered ‘short' (for a total of 29 sentences), those with 11 to 22 syllables as 'long' (for a total of 31 sentences) (cf. Appendix 1 for histograms showing the frequency distribution of the sentences according to their syllable number and relative density distribution). The significance of the interactions and the main effects was assessed with likelihood ratio χ^2 tests that compared the full model with fixed factors or the interaction and a reduced model without it. A significant χ^2-statistic would indicate that the interaction or the main effect was significant. We also explored whether there was a dependency between age-related temporal and syllable intensity variability, by correlating mean and peak syllable intensity measures (VarcoIμ, nPVI-Iμ, VarcoIp and nPVI-Ip) with %V. Among the numerous rhythmic measures based on the temporal characteristics of CV intervals, we selected precisely %V since this has been proven to change significantly as a function of age (e.g., Pellegrino & Pettorino 2014; Pellegrino et al. 2018), but very limitedly as a function of speech rate (e.g., Dellwo & Wagner 2003; Dellwo 2006).

3. Results

VarcoIp and nPVI-Ip significantly decreased with advancing age (Fig. 1 and Table 2, rows 5-6). The effect of AGE GROUP, instead, was not significant for

VarcoIµ and nPVI-Iµ, although a trend toward a slight increase in OA was observed (Fig. 2 and Table 2, rows 3-4).

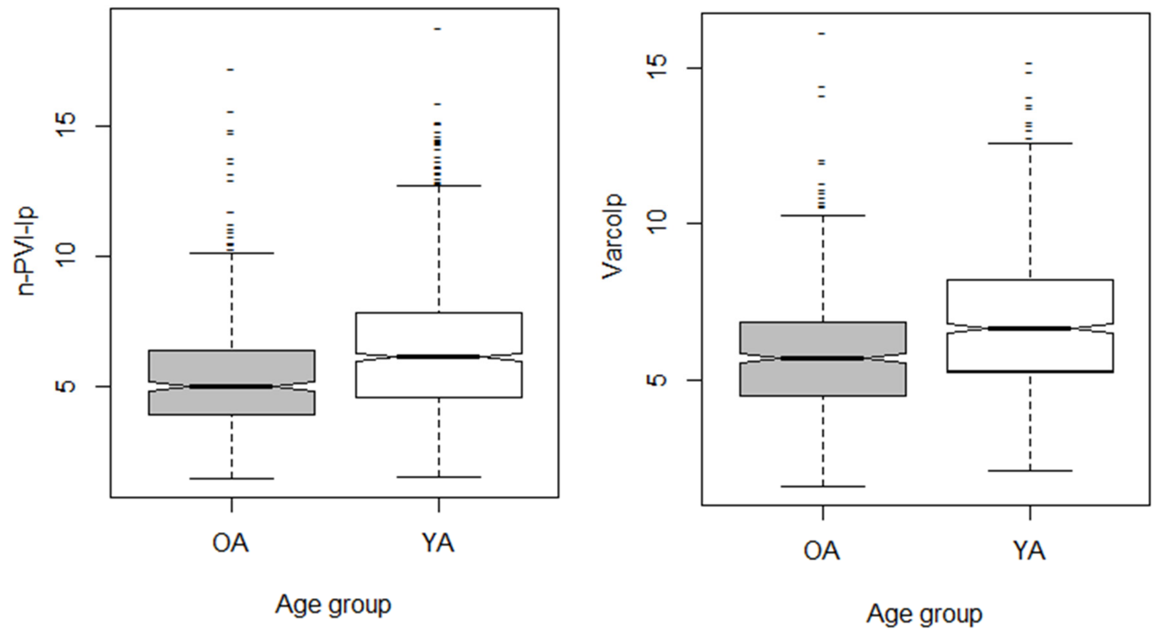

Fig. 1. Boxplots showing the distribution of the variables n-PVI-Ip (left) and VarcoIp (right) across age groups (OA = old adult; YA = young adult)

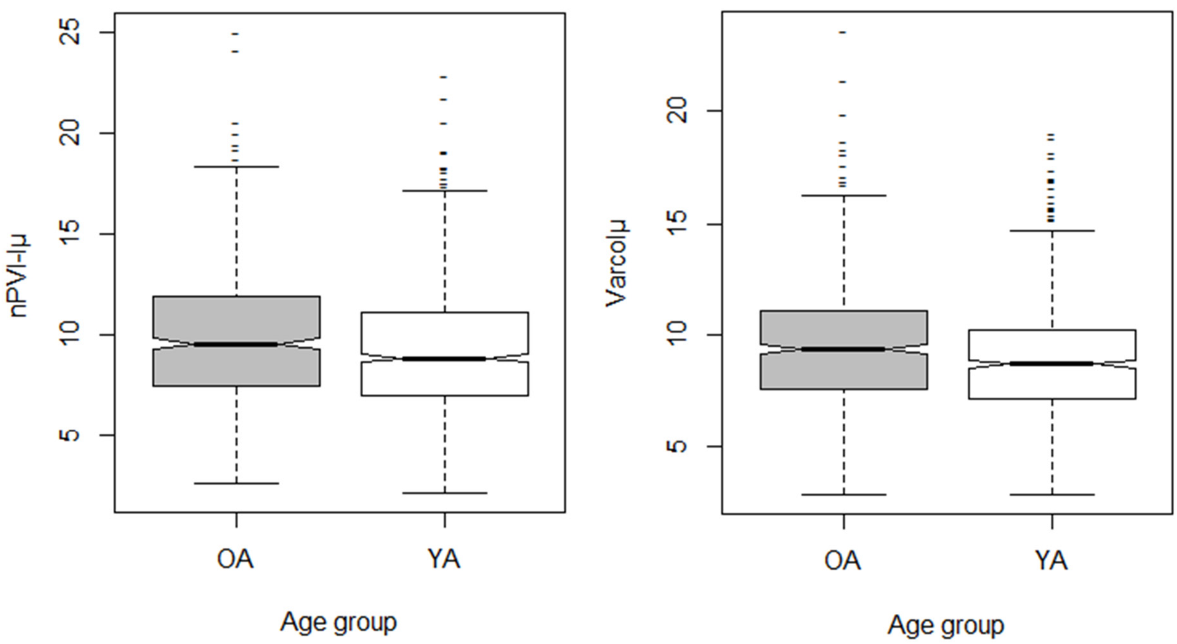

Fig. 2. Boxplots showing the distribution of the variables nPVI-Iµ (left) and VarcoIµ (right) across age groups (OA = old adult; YA = young adult).

	Gender	Age Group	Interaction (Gender *Age Group)
Dependent	x^2 (*p*-values)	x^2 (*p*-values)	x^2 (*p*-values)
VarcoI$_{\mu}$,	0.38 (0.5361)	3.37 (0.06633)	0.06 (0.7931)
nPVI-I$_{\mu}$	2.08 (0.1492)	0.12 (0.7185)	2e-04 (0.9899)
VarcoI$_{p}$	0.21 (0.6435)	**6.954 (<.001)**	1.90 (0.1675)
nPVI-I$_{p}$	0.57 (0.449)	**6.11 (<0.05)**	0.13 (0.713)

Table 2. Summary of the statistics (x2 and p-values) for the tested syllable intensity measures. Significant effects are highlighted in bold

Among the CV interval durational variability measures, %V and rPVI_C were significantly higher in OAs than in YAs (Fig. 3). No significant effect of AGE GROUP was found, for VarcoV, VarcoC and nPVI-V (Table 3). For either set of measures (syllable intensity and CV intervals durational variability), the interaction between AGE GROUP and GENDER and the main effect of GENDER were not significant (Table 2 and Table 3). This means that no rhythmic differences were observed between genders.

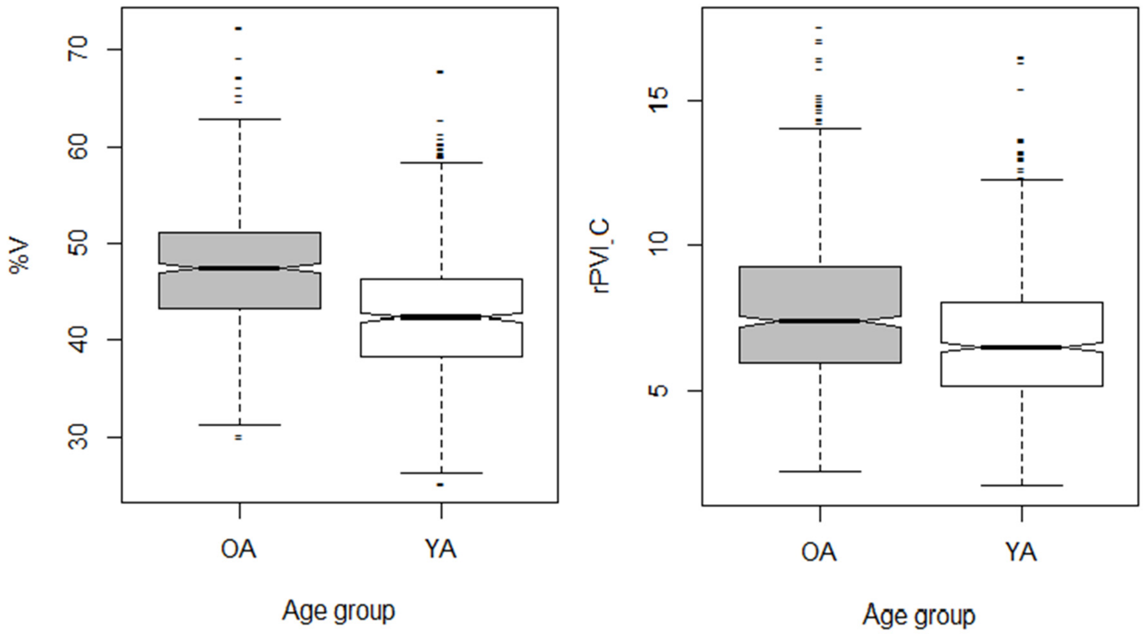

Fig. 3. Boxplots showing the distribution of the variables %V (left), and rPVI_C (right) across age groups (OA = old adult; YA = young adult).

	Gender	Age Group	Interaction (Gender *Age Group)
Dependent	x^2 (*p*-values)	x^2 (*p*-values)	x^2 (*p*-values)
nPVI_V	0.54(0.4593)	3.36 (0.0667)	0.00 (0.9417)
rPVI_C	0.3335 (0.5636)	**13.027 (<0.001)**	0.1633 (0.6861)
VarcoV	0.13 (0.7126)	1.52 (0.217)	2.25 (0.1329)
VarcoC	0.83 (0.367)	2.21 (0.1364)	0.18 (0.6672)
%V	0.03(0.8558)	**25.73 (<.001)**	0.41 (0.517)

Table 3. Summary of the statistics (x2 and p-values) for the tested CV durational variability measures. Significant effects are highlighted in bold.

Regarding the interaction between AGE GROUP and SENTENCE LENGTH, this was significant only for nPVI-Iµ and VarcoIp, but not for VarcoIµ nor nPVI-Ip (Table 4).

	Sentence Length	Age Group	Interaction (Sentence Length*Age Group)
Dependent	x^2 (*p*-values)	x^2 (*p*-values)	x^2 (*p*-values)
$VarcoI_{\mu,}$	0.64 (0.4204)	3.32 (0.0682)	0.33 (0.564)
$nPVI\text{-}I_{\mu}$	0.16 (0.681)	2.07 (0.1502)	**4.26 (<0.05)**
$VarcoI_{p}$	0.37 (0.543)	**6.90 (<.01)**	**5.23 (<0.05)**
$nPVI\text{-}I_{p}$	0.05 (0.80)	**5.99 (<0.05)**	3.22 (0.072)

Table 4. Summary of the statistics (x2 and p-values) for the tested syllable intensity variability measures. Significant effects are highlighted in bold.

Tukey's post-hoc test, however, revealed that for nPVI-Iµ any pairwise comparison reached the significance level (Table 5). For VarcoIp, instead, the intergroup differences were found but – unexpectedly – in short utterances. These latter were produced by OAs with significantly lower variability as compared to YA short and long utterances. Intra-group differences as a function of SENTENCE LENGTH were instead not significant (Table 6). The same was true for the main effect of SENTENCE LENGTH (Table 4). The effect of AGE GROUP remained significant only for syllable peak intensity measures (Table 4).

Contrast nPVI-Iµ	estimate	SE	df	t.ratio	p.value
OA lon - YA lon	0.8756	0.467	30.4	1.876	0.4221
OA lon - OA sho	0.0723	0.558	70.1	0.130	1.000
OA lon - YA sho	0.4755	0.705	84.2	0.674	1.000
YA lon - OA sho	-0.8033	0.705	84.4	-1.139	1.000
YA lon - YA sho	-0.4000	0.547	64.7	-0.732	1.000
OA sho - YA sho	0.4033	0.469	30.9	0.860	1.000

Table 5. Summary of the statistics for the Tukey post hoc test on nPVI-Iµ. Significant effects are highlighted in bold.

Contrast VarcoIp	estimate	SE	df	t.ratio	p.value
OA lon - YA lon	-0.8784	0.402	30.3	-2.185	0.1502
OA lon - OA sho	0.3770	0.249	90.4	1.515	0.4331
OA lon - YA sho	-0.8932	0.454	47.6	-1.969	0.2142
YA lon - OA sho	**1.2553**	**0.454**	**47.7**	**2.766**	**0.0389**
YA lon - YA sho	-0.0148	0.235	71.6	-0.063	0.9999
OA sho - YA sho	**-1.2702**	**0.403**	**30.7**	**-3.151**	**0.0180**

Table 6. Summary of the statistics for the Tukey post hoc test on VarcoIp. Significant effects are highlighted in bold.

Regarding the relationship between temporal and syllable intensity measures, the results of correlation analysis showed that nPVI-Ip, VarcoIp and nPVI-Iµ were only weakly negatively correlated with %V (Fig. 4, plots A-C). In other words, the longer the proportion of vocalic intervals, the lower the mean and peak syllable intensity variability. The correlation, however, did not reach the significance level for VarcoIµ (Fig. 4 plot D).

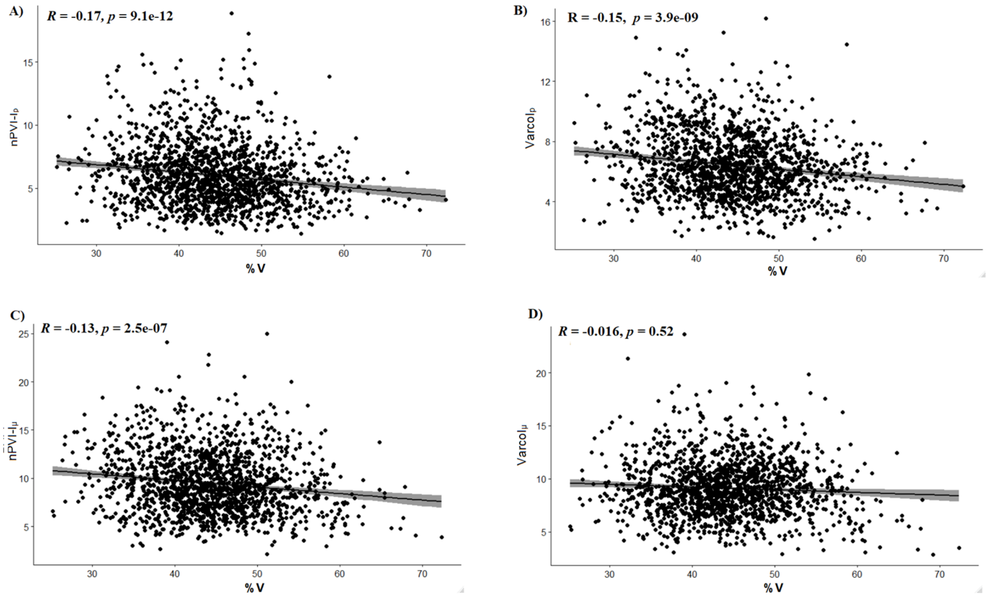

Fig. 4. Scatter plot showing the relationship between the variables %V and syllable intensity variability measures *nPVI-I*$_p$ (plot A - top left), *VarcoI*$_p$ (plot B - top right), *nPVI-I*$_{\mu}$, (plot C - bottom left) and *VarcoI*$_{\mu}$, (plot D - bottom right). The solid line represents the regression line and the shaded area represents the regression line's 95% confidence interval.

4. Discussion

We showed that age-related rhythmic differences can be quantified in terms of peak syllable intensity variability but not mean syllable intensity variability. This is true for differences in the distributions of between-syllable peak characteristics (Varco) and for sequential between-syllable differences (PVI). The finding suggests that peak intensity variability is a correlate that might also explain possible perceptual differences between the rhythmicity of younger and older adults' speech since the CV interval durational variability with age is typically insignificant, except for %V and rPVI_C that remain higher in older than in younger adults. Increased duration of vocalic intervals in OAs (%V), however, did not contribute to maintaining the overall and sequential mean syllable intensity variability (VarcoIμ and nPVIμ). These latter, indeed, were only weakly and negatively correlated with %V, and the same was true for peak syllable intensity measures (nPVIp and VarcoIp).

The documented intergroup differences in syllable intensity variability also contain interesting information about the within-syllable intensity organization between age groups: While mean intensity did not vary significantly between syllables as a function of ageing, peak intensity variability between syllables decreased with higher age. This suggests that the syllable internal intensity structure varies between the groups, in that peak-trough intensity variability within the syllable is stronger in younger compared to older adults. It further suggests that the articulatory mechanisms to reach a peak within the syllable vary between the groups. It is unclear what these articulatory mechanisms are, but we think that they may be plausibly related to mouth opening, as larger differences between open and closed mouths may result in peak variability, while maintaining similar overall syllable intensity. To test whether the OAs in our study had reduced mouth opening gesture as compared to YAs, we compared Long Term (LT) F1 (tongue height/mouth opening dimension) per age group and gender[1]. The analysis of LT Formants - which are assumed to be independent of individual speech sounds (Nolan & Grigoras 2005) - was preferred to the conventional measurement of vowel formant frequencies, since a remarkable inter-speaker variability in the production of vowel timbres was observed[2]. In line with predictions, LTF1 was significantly lower among older men and women compared to their younger same-sex peers (Male speakers: $x^2(1) = 10.802$, $p< 0.01$; Female speakers: $x^2(1) = 10.462$, $p< 0.01$) (cf. Appendix 2 for histograms showing the distribution of LTF1 values range per gender and age group). These findings go in the direction of oral surgery research that consistently has shown that the area of MMO, measured as inter-incisal distance, reduces with ageing, irrespective of gender (e.g., Yao et al. 2009; Khare et al. 2012). Although in read speech, MMO differences across age-groups may not be as evident as when maximum opening is enforced, Dromey et al. (2014) provide support for lower inter-lip aperture in older adults based on utterance repetition. They found that the correlation between upper and lower lip displacement during bilabial closing gesture was weaker in older than in younger adults. Intergroup variations in degree of mouth opening, taken together with age-related degeneration in lip, jaw, and facial muscle motions (McComas 1998; Ballard et al. 2001) can lead to smaller variability in the amplitude of the opening-closing gesture between stressed and unstressed syllables in older adults, and hence to lower syllable peak intensity variability.

The lack of effect in mean syllable intensity variability between age groups is in line with previous research comparing sound pressure measures and mean vocal intensity across age groups. Except for the study by Higgins and Saxman

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1 Mixed-effects models were applied in which LTF1 was the dependent variable, AGE GROUP (YA and OA) was a fixed factor, and SENTENCE and SPEAKERS were random factors. Given the existing disagreement about the effect of gender on age-related changes in vowel formant characteristics (see a. o. Rastatter & Jacques 1990, Rastatter et al. 1997; Xue & Hao 2003; Torre & Bradlow 2009), we ran two distinct models, one for male, another for female participants.

2 Explaining this variability is outside the scope of this paper but we speculate that this may stem from: (1) the medial diglossia characterizing the sociolinguistic situation of German-speaking Switzerland (e.g., Siebenhaar & Wyler 1997), with standard German being used in written contexts and the distinct dialects in spoken form; (2) the lack of an official orthography for Swiss German (Hollenstein & Aepli 2014). It thus seems plausible that our participants have followed idiosyncratic strategies to decode and pronounce sentences written in a language which they typically use for oral communication and that lacks a stable orthography.

(1991), in which elderly male speakers produced higher subglottal pressures than young male speakers at various levels of phonation (soft, comfortable and loud), a number of other studies showed that subglottal pressure measures, sound pressure levels and mean vocal intensity did not vary significantly as a function of the speakers' age (e.g., Ramig 1986; Melcon et al. 1989; Holmes et al. 1994; Mazzetto de Menezes et al. 2014). Most of these studies, however, were based on vowel phonation and syllable repetition at different loudness levels, tasks for which age-related differences in the larynx and the respiratory system could have not been great enough to alter vocal intensity. Nevertheless, even when compared across more productive speech tasks (e.g., monologue, sentence production of variable length), older adults modulate sound pressure levels similarly to younger adults. This comes at the cost of an increased effort for providing the necessary air pressure and using physiological compensation strategies that ensure the production of airflow necessary to meet the demands of speech tasks (Huber 2008; Huber & Spruill 2008). It is thus possible that the group of older adults in our study have used physiological compensation strategies that ensured the generation of an amount of airflow and subglottal pressure comparable with younger adults, which may have contributed to similar mean intensity variability across syllables. Among the strategies reported in the literature – that is, increased frequency of breathing pauses, shorter speech utterances, speech initiation at higher lung volume, greater percent of lung volume per speech breath and syllable (Hoit & Hixon 1987; Hoit et al. 1989; Sperry & Klich 1992; Huber & Spruill 2008) - the one readily testable in our study is the production of intra-sentence breathing pauses (henceforth ISBP). As shown in Table 7, older participants showed a different distribution of ISBP compared to younger adults ($\chi^2(4) = 26.438$, $p < 0.001$). The quantity of utterances produced with a number of pauses from 1 to 4 was always higher in older than in younger adults.

	Number of breathing pauses per utterance				
Age Group	***0***	***1***	***2***	***3***	***4***
OA	483	93	21	2	1
YA	859	85	14	2	0
Total	1342	178	35	4	1

Table 7. Breathing pauses distribution per utterance across age groups (OA = old adult; YA = young adult).

To further examine the contribution of ISBP on cross-group similarity in mean syllable intensity measures, we tested the interaction between AGE GROUP

(OA, YA) and PRESENCE of ISBP (Yes, No) on VarcoIµ and nPVI-Iµ, using Mixed Effect Model (SENTENCE and SPEAKERS were entered as random factors). We expected that especially for OA the sentences with ISBP have higher syllable intensity variability as compared to those without. The results showed that the interaction was significant only for nPVI-Iµ, *viz* when syllable intensity variability was measured between adjacent syllables (nPVI-Iµ: $x^2(1) = 9.4404$, $p<0.01$; cf. Table 1 in Appendix 2 for the full set of statistic data). Tukey's post-hoc test confirmed the prediction: in OAs nPVI-Iµ was higher in sentences with ISBP than in sentences uttered breathlessly (Cf. Table 2 in Appendix 2 for the full set of statistic data). For YAs, instead, the presence of ISBP was not a significant source of within-group group variability. Interestingly, OAs and YAs reached comparable nPVI-Iµ values in sentences without ISBP. However, OAs outdid YAs in the sentences with ISBP, which is probably why the overall intergroup differences on nPVI-Iµ were not significant. The reasons why OAs and YAs differed only in sentences with ISBP are not fully clear and these will be investigated further in future research. Here, we speculate that this may have to do with the difference in intensity level which OAs and YAs reach between pre- and post-pausal syllables. It seems possible that - compared to YAs - OAs produced post-pausal syllables with remarkably higher energy than pre-pausal or final sentence syllables, which contributed to higher nPVI-Iµ in sentences with ISBP. An overall effect of PRESENCE of ISBP on syllable intensity variability was found for Varco-Iµ (Cf. Table 1 in Appendix 2)[3]. In this case as well, the presence of ISBP enhanced the syllable intensity variability. In lack of aerodynamic data, we can tentatively assume that the more frequent inhaling in sentences with ISBP may determine high intra-sentence variability in terms of vocal strength, and hence higher Varco-Iµ.

Age-related differences in mean syllable intensity variability are, instead, not affected by sentence length. This was against the predictions as we expected substantial cross-group differences in longer sentences which require more aerodynamic support. However, these results echo findings from research on the effect of normal aging on respiratory support for speech. Huber and Sprull (2008), indeed, found that the effect of sentence length did not interact with that of age for sound pressure level (SPL in db) and other respiratory kinematics measures related to lung volume and chest wall movements. Sentence length, but not ISBP, was instead a source of intergroup difference in peak syllable intensity variability (cf. Appendix 3, Table 1 for effect of ISBP on syllable peak intensity variability). The gap between OAs and YAs was found only in short utterances, which OAs produced with lower VarcoIp than YAs. This means that the intergroup differences in the amplitude of the opening-closing gesture between stressed syllables and unstressed syllables are more evident in short

[3] We did not interpret the significant main effect of sentence length on nPVI-Iµ, due to the observed significant interaction between sentence and age group on this measure.

than in long utterances. In lack of articulatory measures, here we can only hypothesize that compensatory articulatory, aerodynamic strategies are at work in long utterances and these may have enabled OAs to reach performance comparable to that of YAs. It is also possible that in longer sentences YAs may have reduced the variability in the amplitude of mouth opening gestures between stressed and unstressed syllables. Dynamic analyses on mean and peak syllable intensity are, however, necessary to explain the bases of intergroup similarity in long utterances.

Taken together, the findings of this study suggest that within-syllable intensity organization does not vary between the two age groups only, but also as a function of the structural characteristics of the sentence (varying length) and their prosodic realization (with or without ISBP). It would thus be interesting to further test articulatory, aerodynamic and subglottal pressure correlates of intensity variability between syllables, as this will eventually explain the precise mechanisms underpinning age-related syllable intensity rhythmic variability.

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Appendix 1

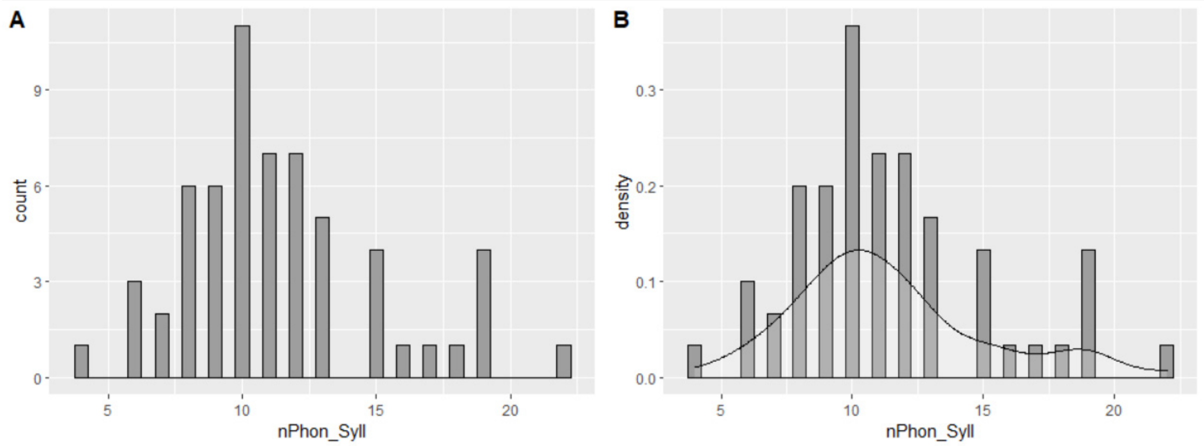

Fig. 1. Histograms showing the frequency distribution of the sentences according to their syllable number (left) and the relative density distribution (right).

Appendix 2

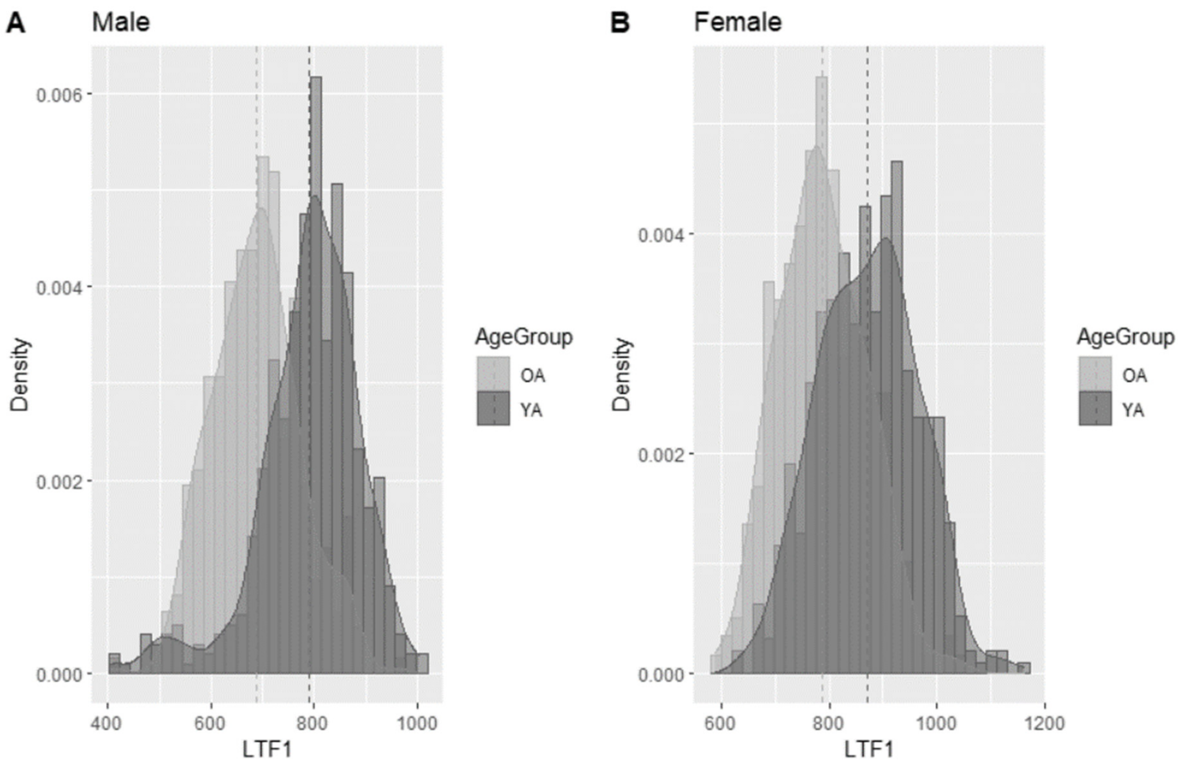

Fig. 1. Histograms showing the distributions of LTF1 values between age groups per gender (left panel= male speakers, right panel= female speakers). The dashed lines marked the mean LTF1 values per age groups.

Appendix 3

	Pauses	Age Group	Interaction (Pauses*Age Group)
Dependent	x^2 (*p*-values)	x^2 (*p*-values)	x^2 (*p*-values)
$VarcoI_{\mu}$,	**5.092 (p<0.05)**	3.0979 (0.078)	2.6179 (0.1057)
nPVI-I_{μ}	**9.5642 (p<0.01)**	1.7889 (1.811)	**9.4404 (p<0.01)**
$VarcoI_{p}$	0.2555 (0.6132)	**6.9631 (p<0.01)**	1.9639 (0.1611)
nPVI-I_{p}	2.6217 (0.1054)	**6.2366 (p<0.05)**	3.6354 (0.05656)

Table 1. Summary of the statistics (x^2 and p-values) for the tested syllable intensity measures. Significant effects are highlighted in bold.

Contrast nPVI-I_{μ}	**Estimate**	**SE**	**df**	**t.ratio**	**p.value**
OA no - YA no	0.4474	0.455	27.6	0.984	0.7596
OA no - OA yes	**-1.1041**	**0.254**	**1513.1**	**-4.345**	**0.0001**
OA no - YA yes	0.3708	0.516	46.5	0.719	0.8889
YA no - OA yes	**-1.5515**	**0.499**	**40.8**	**-3.107**	**0.0173**
YA no - YA yes	-0.0766	0.264	1521.5	-0.291	0.9915
OA yes - YA yes	**1.4749**	**0.535**	**54.2**	**2.758**	**0.0385**

Table 2. Summary of Tukey's post-hoc comparisons. Significant effects are highlighted in bold.