An articulographical analysis of age-related speaker variation

Effects of speech rate on speech kinematics in younger and older adults

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Introduction

Aging has been known to bring changes in the production of speech sounds. Several studies have reported that older speakers tend to decrease articulation rate. The effect of age on the rate of speaking and oral reading has been studied by Ramig (1983). Reading rates were obtained from participants reading a text fragment, and spontaneous speech was obtained from the description of a picture. Results show that the group of older adults had significantly slower reading rates compared to the young group. The rate of spontaneous speech was also reduced in the group of older adults. Similar results have been found in the study by Duchin & Mysak (1987), where speech rates (in syllables per second and words per minute) were obtained from spontaneous speech, conversational speech and an oral reading task. It was shown that mean speech rate was reduced with increasing age across all speech tasks. Smith, Wasowicz, & Preston (1987) compared sentence-, syllable- and segment durations between younger adults and older adults in a series of repetition tasks at self chosen habitual and fast rates. It was found that the older participants consistently produced longer durations than the younger adults for both speech rates. Amerman and Parnell (1992) investigated consonant duration in VCV syllables produced at habitual speech rate by young and older adults. Speech samples were obtained in isolation and in the context of a carrier sentence. Durational measurements show that consonants durations were significantly longer for the older adults, as compared to the younger group. Furthermore, mean durations of the part of the carrier sentence preceding the VCV fragment were also significantly shorter for the older adults. Harnsberger, Shrivastav, Brown, Rothman, & Hollien (2008) analyzed sentence-, word-, and segment durations in spontaneous speech produced by young and older male adults. Results of all three measures shows an effect of age, where older adults systematically decrease duration in sentence, words and segments. A subset of the speech samples was used in a subsequent perception experiment and presented to naïve listeners. Listeners were asked to estimate speaker age. It was shown that speaking rate is an important cue to perceived age, where a decrease in speaking rate was associated with increasing age. Benjamin (1982) investigated the phonological performance of young and older adults in voiced and unvoiced stop consonants. Voice onset time (VOT) and length of consonants and vowels were measured in speech samples obtained from a reading task. Vowel durations and silent intervals in stop consonants were longer for older adults, while VOT values were shorter. Shuey (1989) investigated the intelligibility of the CVC productions of older male and female speakers by means of a perception judgment task and found a trend of age on the amount of perceived speech errors. Older females make more errors in final consonants, compared to young speakers. Older males tend to make more vowel errors than younger speakers do. In general, these studies indicate that aging affects both the rate and precision of articulation. The acoustical measures indicate that the reduction of speech rate is mainly affected by a decrease in duration on segment-, word-, and sentence level.

As to what fuels these effects of age on speech production, the picture remains unclear. On possibility is that it might be induced by change in anatomical structures of vocal tract organs. In particular, it has been proposed that the structure and function of the tongue changes with aging. Atrophy and fibrosis of the tongue muscle may lead to a decrease in muscle strength (Weismer & Liss, 1991), and a decreased regularity in rhythmic tongue movements (Hirai, Tanaka, Koshino, & Yajima, 1991), resulting in reduced speech rates and affected articulatory precision. Another possible cause of age-related changes in speech production is of neurological nature. A slowing of nerve conduction velocities in the peripheral nervous system and a decrease of central neurotransmitters may account for a general slowing of speech articulation (Weismer & Liss, 1991). Benjamin (1982) suggests that the age related increase of speech errors in speech production is induced by a reduced control over vocal tract organs, similar to mild dysarthric characteristics of speech.

In order to understand better how the aging process affects the timing and execution of articulatory movements, more research on speech motor control is necessary. In addition to acoustic and perceptual measures, a detailed analysis of individual speech articulators by means of kinematic analyses can give more insight in the speech characteristics that are associated with aging. One way to study how the aging process affects the timing and execution of articulatory movements is by using speech rate as an experimental parameter. Gay, Ushijima, Hirose, & Cooper (1974), for example, investigated upper lip, lower lip and tongue movement patterns in two male speakers during the repeated production of VCV syllables. Speech samples were obtained at self-chosen habitual and fast speech by means of electromyography (EMG), X-ray films and high-speed motion pictures. Increasing speech rate led to an increase in the rate of lip movement and an increase in muscle activity, whereas for tongue movement, displacement and muscle activity decreased. In his study, McClean (2000) analyzed by means of electromagnetic articulography (EMA) the orofacial movement velocities of lower lip, upper lip, jaw and tongue across speech rate variations. Kinematic data was obtained from a group of healthy adults in self chosen slow, normal, and fast speech rates. Results showed that orofacial velocity for the four speech articulators positively correlated with speech rate. Goozee, Lapointe, & Murdoch (2003) used electromagnetic articulography to analyze how kinematic parameters change with increasing speech rate. A group of healthy adults produced the syllable /ta/ and /ka/ at a self-chosen habitual- and fast rate. Results showed that increasing speech rate from habitual to fast led to a reduction in the duration of tongue movements. Surprisingly, amplitude, maximum velocity and maximum acceleration of tongue movements did not change or to a lesser extend, with the increase of speech rate, leaving the question as to how speech rate is controlled by the speech motor system open. In a subsequent study, Goozee, Stephenson, Murdoch, Darnell, & Lapointe (2005) carried out a detailed analysis of individual articulatory movements in the speech of older as compared to younger adults. The two groups performed a repetition task, while lip-and tongue movements were recorded by EMA. Participants repeated the syllables /ka/ and /ta/ at around three syllables per second, and as fast as possible. Kinematic parameters measured were maximal velocity, maximal acceleration, duration and distance of tongue movements. It was found that kinematic parameters for older adults were not different from the younger control group at the higher articulation rate, except for a reduction in distance. With increasing speech tempo, a smaller decrease in the distance of tongue movements was measured in the group of older adults. They also showed a decreased in speech tempo, and a trend towards decreased velocity and decreased acceleration compared to the young group. Goozee et al. explain these findings in terms of motor control performance and suggest that older adults might display a decrease in sensory and neuro-motorical performance. It was also proposed that older adults exploit a different compensatory strategy in order to maintain intelligibility at the cost of speech rate reduction. The experimental setup does not allow any definite conclusions on this question. One of the main problems is that their repetition task was not controlled for speech tempo. The participants used their own interpretation and execution of ’slow’ and ’fast’ speaking rate. Average speech tempi were systematically slower in the group of older adults. Since speech tempo was not fixated around a certain level, the question whether the observed differences results from a limitation in speech motor control or from different compensatory strategies cannot be answered. In fact, the divergent self-chosen speech rates may reflect a speech-accuracy trade-off (Amerman & Parnell, 1992). It is possible that older adults monitor their speech production more carefully than younger adults, at the cost of rate reduction. It is therefore reasonable to assume that older speakers are capable of producing speech at a rate similar to those usually realized by younger speakers, if they are forced to do so. Another factors influencing speech rate characteristics is the internal control of personal preferred articulatory timing (Allen, 1975). In addition to a speech-accuracy trade-off it is possible that this internal timing shifts with aging, resulting in the speech rate reductions as described before. An external cue, (e.g. a metronome) could reduce internal timing influences on the rate of speech movements. In speech research, a metronome is often used to measure timing precision, i.e. the ability to synchronize speech acts with the beat of a metronome (Wolff, 2002; Wolff, Michel, & Ovrut, 1990). Wolff (2002) asked dyslexic adolescents and adults to repeat the bi-syllabic CV sequences /pa-ta/, /ta-ka/ and tri-syllabic /pa-ta-ka/ correctly in time with a metronome beat. It was shown that both dyslexic groups deviated significantly more from the external timing signal than the control groups in their production of the syllable repetitions. It was generally observed that they repeated syllables too slowly, even at lower metronome repetition rates. On the other hand, the healthy control groups succeeded in synchronizing the rate of their speech movements with the external signal. In addition, it is shown that an external auditory sensory signal enhances the stability and coordination of finger tap movements (Fink, Foo, Jirsa, & Kelso, 2000). Therefore, a metronome signal can potentially be recruited to control speech rate and diminish the effects of a possible speech-accuracy trade-off or internal timing shifts found with aging.

The current study was designed to evaluate the influence of age on kinematic measures of reiterated non-word utterances with a controlled timing of speech rate by the use of a metronome. The first question under research was whether the rate of articulation modeled by an external metronome could be controlled for younger and older adults. In addition, it was investigated how kinematic parameters change with increasing syllable repetition rate for both young and older adults.

Method

Participants

Sixteen adults participated in the study, eight young and eight old speakers. All participants were native speakers of Dutch and healthy, normal adults, without self-reported previous or current speech problems. The group of young adults included two males and six females aged 21-27 with a mean of 23.3 years. The group of older adults included five males and three females aged 69-84 with a mean of 75.6 years. In the group of older adults, four subjects had full or partial dental plates or prosthesis. All had been wearing them for a period longer than one year, and wore them during the study. Two subjects had a hearing aid, but reportedly used them only seldomly. Neither used their hearing aid during the experiments.

Instrumentation

Articulatory and acoustic data were collected using an AG100 Carstens Electro-Magnetic Midsaggital Articulograph (EMMA) with time-aligned audio signal (Carstens Medizinelektronic, GmbH, Germany). The system is equipped with a large helmet (62 cm) containing three transmitting coils in midsagittal direction and a semi-automated calibration unit. The system is capable of collecting data from ten channels with transducer coils simultaneously. Position data were sampled at 400Hz, while acoustic data were sampled at 16kHz. Testing was conducted in a quiet room. The system was switched on for at least two hours prior to analysis to allow the system to warm up. Calibration was carried out according to a standardized protocol in the instrumentation manual.

Procedures

The transducer coils were attached following the procedure described by van Lieshout, Bose, Square, & Steele (2007). Micropore tape was used to attach coils to the midline positions of the vermillion border of upper lip and lower lip. Surgical tissue glue and micropore tape was used to attach coils to gums of the lower and upper incisors, of which the latter coil served as a reference coil. A second reference coil was placed on the nose bridge using micropore tape. The remaining coils were attached to the tongue blade (approximately 1 cm behind tongue tip), the tongue body (approximately 2 cm behind tongue blade coil), and the tongue dorsum (approximately 3 cm behind tongue blade coil), using surgical tissue glue. Subjects were given speaking practice time for around 5 minutes in a casual conversation, to get used to the transducer coils attached to their articulatory organs.

Task

The participants repeated three different non-word items (/pa/, /sa/, and /ta/) in a single trial of 12 seconds. There were two pacing conditions: self-pacing and metronome timing. For the self-paced condition, participants were instructed to produce the items at their self chosen habitual, slow and fast rate. For the metronome condition, a digital metronome (Adobe Audition v1.5) was used to model speech tempo, in order to obtain controlled speech rates at 2, 2.5, 3, 3.5, and 4 beats per second (bps). Participants were instructed to repeat the test items at the dictated speed of the metronome, one syllable to a beat. Prior to recording, the metronome was started and the subjects were instructed to mentally tune into the rhythm of the beats. When the subjects deemed to be tuned into the metronome beat, a hand or thumb up signal was given. Subsequently, the experimenter switched off the metronome and started the recording, after which the subjects repeated the stimulus. Before starting actual recordings, subject practiced for all test items the procedure of timing with the metronome beat for all the test items, until the experimenter deemed that the subject was able to do so. Metronome speed was set at 2, 2.5, 3, 3.5, and 4 beats per second (bps). The participants were instructed to take a deep breath prior to repeating the stimulus for around 12 seconds. An orthographic description of the actual stimulus was visible on the screen, and if necessary, the experimenter modeled the syllable once or twice. After the recording of a trial finished, the acoustic speech sample was played back automatically over a connected speaker system. The experimenter judged the trial on phonemic production errors, pauses, interruptions, rate accelerations and decelerations, and if present, the trial was repeated at the end of the series. The test items were blocked for speech task, in the order /pa/ - /sa/ - /ta/. Of each speech task, first the self-paced conditions were recorded, in the order habitual – slow – fast. Subsequently the metronome paced conditions were paced, linearly ordered from slow to fast rate.

Analysis

The speech task /pa/ involves a bilabial closure gesture for the voiceless plosive /p/. For this speech task, movement data was analyzed of the principal articulator, represented by the transducer coil attached to the lower lip. The alveolar plosive /t/ in speech task /ta/ and the alveolar fricative /s/ in speech task /sa/ involves a tongue tip constriction gesture. For these speech tasks, movement data were analyzed of the transducer coil attached to the tongue blade.

All movement signals were filtered using the Tailor Data Processing Program v1.3 (Carstens Medizinelektronic, GmbH, Germany). The channels for articulator lower lip and tongue blade were sampled down to 100Hz. The reference channels, being nose bridge and upper jaw incisor, were sampled down to 40Hz. Subsequently, movement data was corrected, to compensate for subject-specific anatomic differences and variations in helmet positions, as well as rotational misalignments i.e. ‘twist’ and ‘tilt’ movements (Hoole & Nguyen, 1997). Head movements relative to the helmet position were corrected for each participant, using information of the two reference points from the first error-free speech trial. After normalizing, the data were processed in Matlab, following procedures of van Lieshout & Moussa (2000); van Lieshout (2004); van Lieshout et al. (2007). For the kinematic measurements of the lower lip channel, signals were corrected for jaw movement (Westbury, Lindstrom, & McClean, 2002). Positional and temporal data of individual articulators were stored into a track, showing peaks and valleys of the movements. When necessary, manual peak correction was applied.

For each of the recordings, syllable repetition rate was calculated based on the acoustic waveforms. Only fluent, error-free parts of the recordings were selected, yielding a string of seven to ten repetitions per syllable for each participant. For each syllable the following parameters of tongue blade movements in syllables /sa/ and /ta/ and lower lip movements in syllable /pa/ were analyzed:

- Movement duration (in s) of closure and opening phases (DUR).
- Maximum amplitude (in mm): the distance or movement range from valley to peak (for closing phases) and from peak to valley (for opening phases (AMP).
- Peak velocity (in mm/s) of closure and opening phases (PV).
- Stiffness (in 1/s): a derived kinematic parameter (peak velocity / maximum amplitude) of closure and opening movements (STIF).
- Cyclic spatio-temporal index (cSTI): an index that captures the variability of direction specific, cyclic movement patterns, yielding detailed information on the relative phasing of individual articulators. This measure is based on the spatio-temporal index (STI), developed by Smith,

Goffman, Zelaznik, Ying, & McGillem (1995). The movement patterns of motion trajectories of repeated utterances are time- and amplitude normalized to produce a target movement template. The template is then estimated as the mean displacement amplitude value on the normalized time axis. Each movement track is matched against the template along the time axis at a certain number of intervals. The sum of standard deviations of the distance of a pattern to the template is the STI value. A lower STI value indicates a smaller deviation from the target movement template. With cSTI a smaller motor unit is measured, like the motion cycle of one syllable repetition.

Results

Syllable repetition rates

The syllable repetition rates expressed as the number of syllables per second were compared across groups using the Mann-Whitney U procedure. An ANOVA was not permitted due to the small sample size. Mean syllable repetition rates, standard deviations (in parenthesis) and test results per condition are shown in table 1. For all comparisons a significance level of p=.05 was used.

Table I. Means and standard deviations (in parentheses) for syllable repetition rates for younger and older adults and Mann-Whitney significance levels for group comparison, broken down by task and rate condition.

Subject Group	Young adults	Older adults		
Rate condition	/pa/		Mann-Whitney U	Sign.
Slow	1.23 (0.32)	1.21 (0.20)	32	1.00
Habitual	2.02 (0.43)	2.08 (0.64)	28	.674
Fast	2.76 (0.63)	4.10 (1.11)	11	.027
2 bps	2.00 (0.08)	1.91 (0.17)	18	.161
2.5 bps	2.52 (0.11)	2.78 (0.33)	9	.015
3 bps	3.06 (0.29)	3.37 (0.30)	9	.015
3.5 bps	3.53 (0.24)	3.75 (0.27)	16.5	.103
4 bps	4.18 (0.42)	4.37 (0.52)	23	.382
	/sa/			
Slow	1.63 (0.44)	1.45 (0.29)	24	.400
Habitual	2.26 (0.47)	1.97 (0.48)	22	.293
Fast	3.23 (0.69)	3.51 (0.57)	24	.400
2 bps	2.03 (0.09)	1.94 (0.10)	17	.113
2.5 bps	2.54 (0.17)	2.70 (0.21)	17.5	.126
3 bps	2.98 (0.11)	3.19 (0.26)	13	.046
3.5 bps	3.48 (0.26)	3.64 (0.38)	23.5	.372
4 bps	4.01 (0.48)	4.13 (0.48)	26.5	.563
	/ta/			
Slow	1.82 (0.50)	1.29 (0.34)	13	.046
Habitual	2.44 (0.83)	1.86 (0.35)	16	.093
Fast	3.50 (1.20)	3.96 (0.90)	19.5	.189
2 bps	2.05 (0.08)	1.99 (0.13)	28	.674
2.5 bps	2.53 (0.09)	2.61 (0.12)	18	.140
3 bps	2.98 (0.12)	3.20 (0.13)	6.5	.005
3.5 bps	3.40 (0.15)	3.87 (0.48)	9	.015
4 bps	3.50 (1.20)	3.96 (0.90)	.074	.074

Significant differences of syllable repetition rates between the younger and older adults were found for /pa/ at 2 bps (U=9, p=.015), 2.5 bps (U=9, p=.015) and self-paced fast rate condition (U=11, p=.027). A marginally difference was found for /sa/ at 3 bps (U=13, p=.046). For /ta/, the 3 bps (U=6, p=.005) and 3.5 bps (U=9, p=.015) conditions as well as the self-paced slow rate condition (U=13, p=.046) were significantly different. All significant effects can be attributed to a higher syllable repetition rate for the older adults, compared to the young adults, except for /ta/ in the slow rate condition (see figure 1).

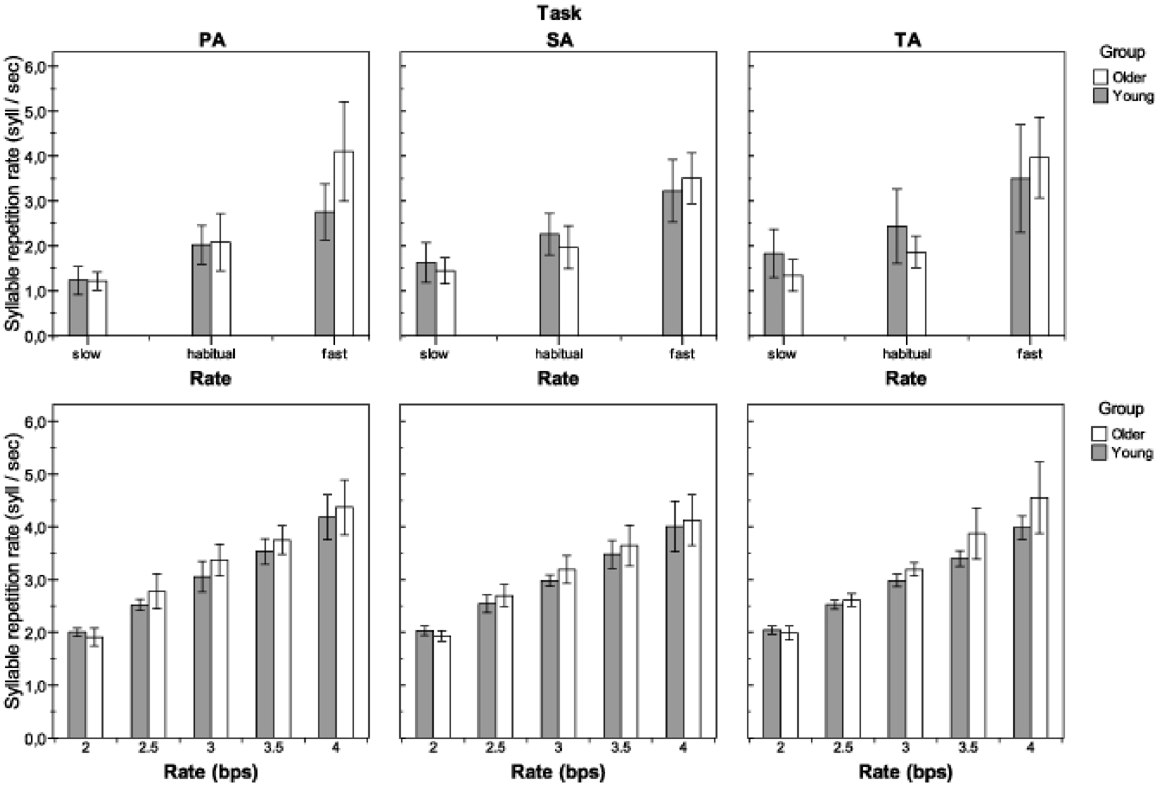

Figure 1 Means and standard deviations of syllable repetition rates across speech tasks for self-paced condition (upper panels) and metronome condition (lower panels), broken down by group and rate.

Kinematic data and cSTI

Kinematic data were analyzed using a repeated measurement model. The younger and older adults formed the between-subject factor ‘GROUP’. Within-subjects factors were ‘RATE’ (slow, habitual and fast in the self-paced rate condition and 2, 2.5, 3, 3.5 and 4 beats per second in the metronome condition) and ‘DIRECTION’ (opening and closure movements). The same model was used to analyze the cyclic spatial-temporal index, but excluding factor DIRECTION. Results of the repeated measures analyses are summarized in table II. Means and standards deviation of duration, maximum amplitude, peak velocity, and cyclic spatio-temporal index for the young and older subjects are presented in Figure 2 to 6.

The mean values of the duration of articulator movements (see Figure 2) show that both groups effectively reduced duration with increasing syllable repetition rate, both in the self-paced condition and the metronome condition, and for all speech tasks. For both groups, closing durations were longer than opening durations, across speech task and pacing condition. With increasing syllable repetition rate, durations of closure movements are more reduced than opening movements. A three-way interaction effect in speech task /sa/ self-paced condition and /ta/ in the metronome condition indicates that older adults for these tasks decreased durations of tongue more than do young adults, with increasing repetition rate. No such effect was found for movements of the lower lip, in speech task /pa/.

Table II. Results of repeated measures ANOVA for kinematic variables broken down by task and pace condition. * indicates that sphericity was not met at the.05 level of probability. In these cases a Huynh-Feldt correction was applied, and corresponding F- values and probabilities are reported.

		/pa/				/sa/				/ta/			
		Self paced		Metronome		Self paced		Metronome		Self paced		Metronome	
	Effect	F	P	F	P	F	P	F	p	F	P	F	p
DUR	Group	.25	.627	2.32	.150	.82	.381	.734	.406	2.43	.142	5.64	.032
	Rate	105.78	.000	144.65	.000*	75.94	.000	570.00	.000	74.45	.000*	546.	.000
	Direction	20.48	.000	6.74	.021	22.60	.000	100.63	.000	11.89	.004	24.8	.000
	G x R	1.98	.157	.92	.459	2.18	.132	5.01	.002	8.45	.001	4.69	.002
	G x D	.54	.475	.24	.629	8.13	.013	2.43	.142	4.74	.047	4.41	.054
	R x D	19.85	.000	15.77	.000*	22.42	.000	82.15	.000*	13.36	.000	29.8	.000
	G x R x D	1.26	.300	1.30	.283	5.89	.007	1.84	.133	2.55	.096	4.66	.003
AMP	Group	.10	.760	.01	.923	.23	.637	.79	.390	2.18	.162	1.29	.275
	Rate	.33	.724	2.95	.068*	6.63	.013*	4.08	.006	1.67	.217*	1.43	.253
	Direction	2.77	.119	.67	.428	22.68	.000	50.64	.000	.41	.534	.28	.608
	G x R	.28	.757	1.25	.299	1.46	.249	.65	.63	1.65	.211	1.04	.393
	G x D	.59	.455	.25	.137	.33	.578	.05	.831	8.79	.010	.92	.353
	R x D	3.28	.053	.65	.583*	2.43	.106	3.58	.028*	2.70	0.85	2.21	.128
	G x R x D	.68	.514	1.09	.371	.36	.703	1.15	.342	1.59	.222	1.16	.338
PV	Group	.00	.976	.01	.947	8.99	.010	9.79	.007	6.61	.022	4.72	.048
	Rate	10.81	.000	5.33	.023*	17.75	.000*	19.27	.000*	12.93	.000*	6.98	.003
	Direction	77.22	.000	75.01	.000	147.80	.000	101.33	.000	44.18	.000	8.62	.011
	G x R	3.12	.060	.043	.996	5.58	.009	2.19	.082	4.97	.014	1.68	.168
	G x D	.916	.900	.147	.707	.024	.880	1.00	.335	1.84	.197	1.35	.264
	R x D	13.77	.000	1.50	.244*	1.39	.267	3.25	.041*	1.24	.291*	1.25	.286
	G x R x D	.69	.509	1.43	.237	.46	.634	1.40	.247	.93	.406	1.13	.351
STIF	Group	4.04	.064	5.37	.036	.15	.704	.06	.805	.12	.735	4.34	.056
	Rate	27.70	.000*	74.72	.000*	81.58	.000*	33.34	.000*	27.15	.000	62.8	.000
	Direction	15.40	.002	.18	.677	26.81	.000	39.71	.000	16.75	.001	4.71	.048
	G x R	7.18	.003	.88	.482	1.33	.280	1.34	.267	2.19	.131	1.92	.120
	G x D	.04	.845	.08	.783	4.92	.044	11.9	.004	8.78	.010	1.64	.222
	R x D	13.38	.000	8.38	.003*	21.81	.000	18.84	.000*	15.58	.000	8.50	.000
	G x R x D	1.20	.315	2.00	.106	6.32	.005	2.43	.058	7.11	.003	2.19	.082
cSTI	Group	.303	.591	1.44	.249	1.00	.334	2,72	1.21	.57	.462	1.61	.226
	Rate	22.72	.000	6.35	.006*	5.80	.020*	6.42	.004*	4.95	.033*	2.57	.060
	G x R	8.15	.002	.63	.640	.99	.384	1.88	.127	1.73	.054	.27	.898

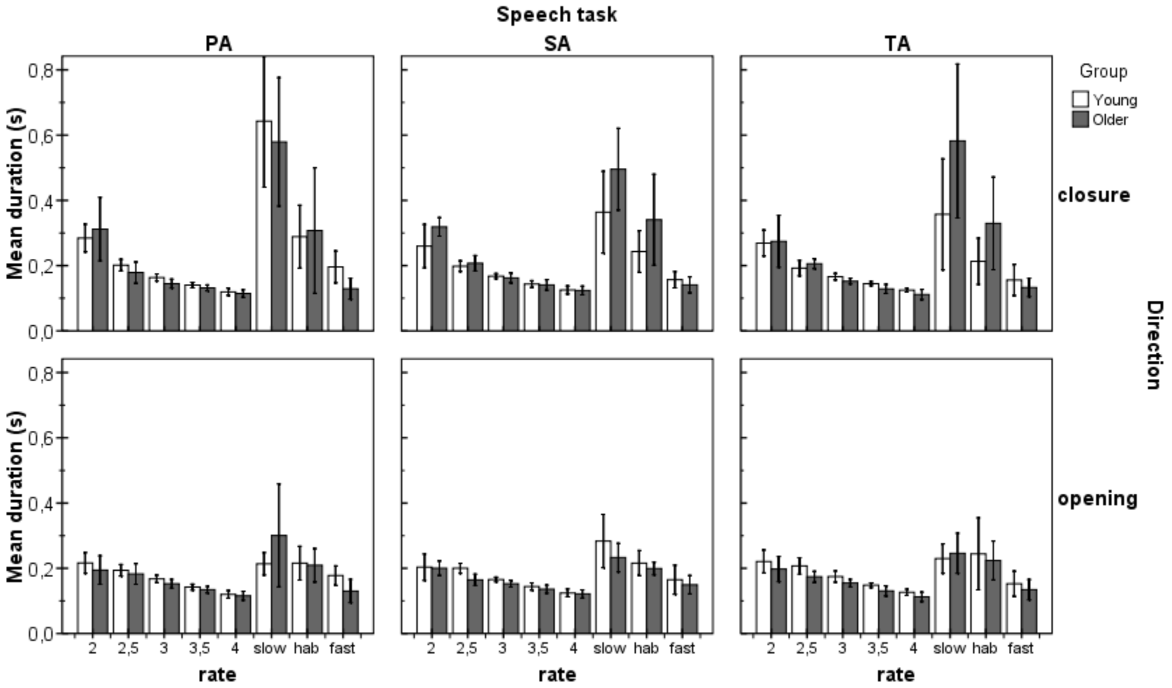

Figure 2. Mean duration and standard deviations of principal articulator movements for the young and older groups for both pacing conditions. Results are separated for direction and speech task.

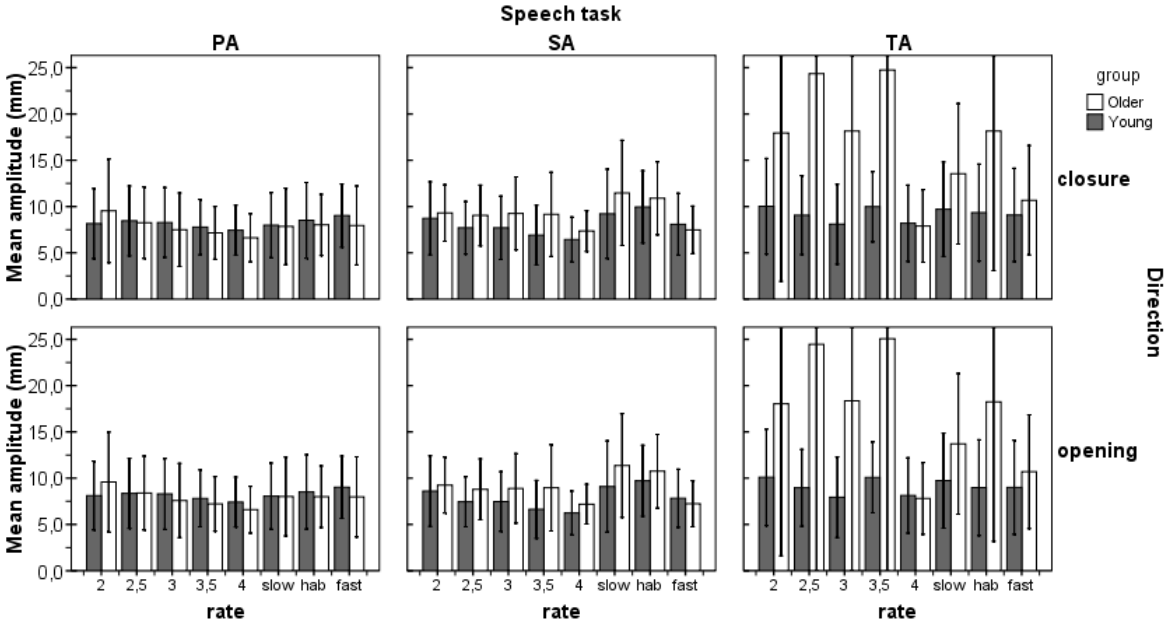

Figure 3. Mean amplitude and standard deviations of principal articulator movements for the young and older groups for both pacing conditions. Results are separated for direction and speech task.

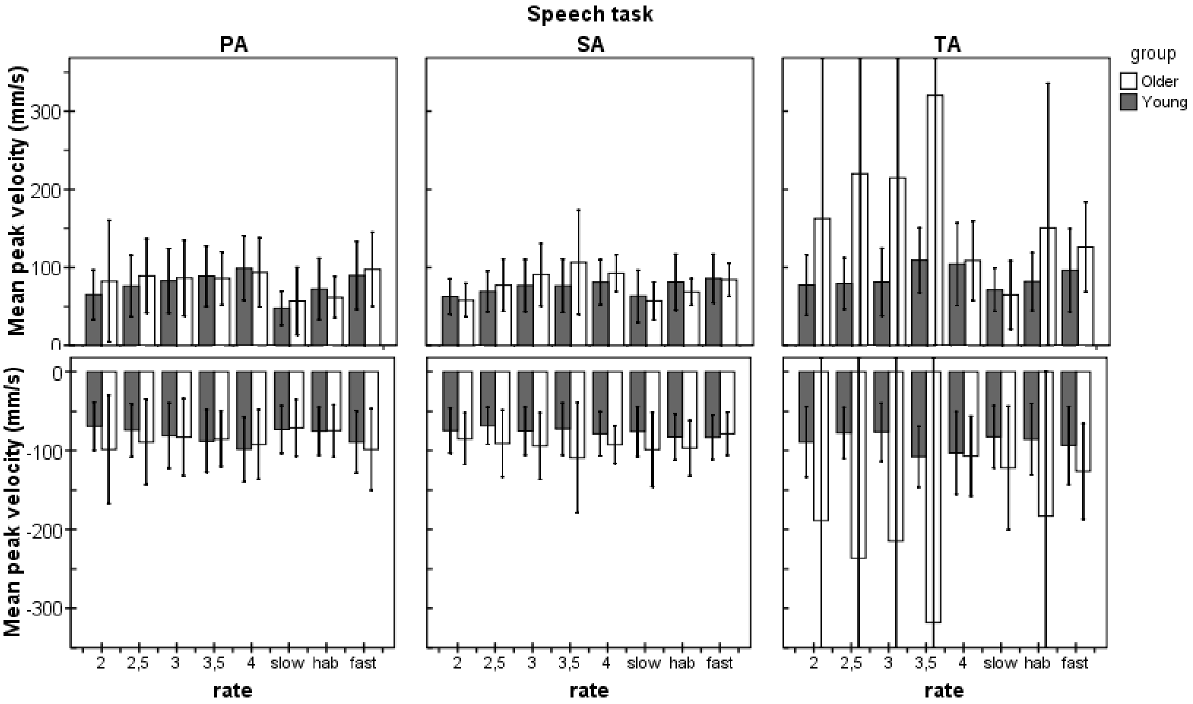

Figure 4. Mean peak velocity and standard deviations of principal articulator movements for the young and older groups for both pacing conditions. Results are separated for direction (closure movements in upper panels, opening movements in lower panels) and speech task.

For mean maximum amplitude (see Figure 3), no significant main and interaction effects were found. In most rate conditions of speech task /ta/, mean values and standard deviations of the older group were very high, compared to the other speech tasks. Inspection of the data shows that mean values of two older participants can considered as outliers.

Peak velocity values for closing movements are positive and for opening movements values are negative (see Figure 4). Means and standard deviations of the older adults for syllable /ta/ were also very high, relative to the other speech tasks, and can be attributed to the same participants as found for maximum amplitude. For syllable /sa/ and /ta/ in the self-paced and for /sa/ in the metronome condition, the group of older adults showed a larger increase of peak velocity with increasing speech rate, compared to the younger group. In the self paced and metronome condition of speech task /sa/ and /ta/, mean peak velocity values were higher for the group of older adults, for both opening and closing movements.

For mean values of stiffness (see Figure 4), both groups showed an increased stiffness with increasing syllable repetition rate, both in the self-paced condition and the metronome condition, and for all speech tasks. For both groups, mean stiffness was higher for opening movements in all conditions, except for /pa/ in the metronome paced condition. The reduction in stiffness with increasing repetition rate was greater for closing movements, compared to opening movements.

Mean values for the cyclic spatio-temporal index did not differ between the groups of younger and older adults. Mean values of cSTI differed across rate conditions, but no clear patterns were visible. For the group of young adults in speech task /sa/, mean values of cSTI decreased with increasing speech, but this trend was not found elsewhere. In the self paced conditions, both groups showed a decrease in cSTI from the habitual to the fast condition for all speech tasks.

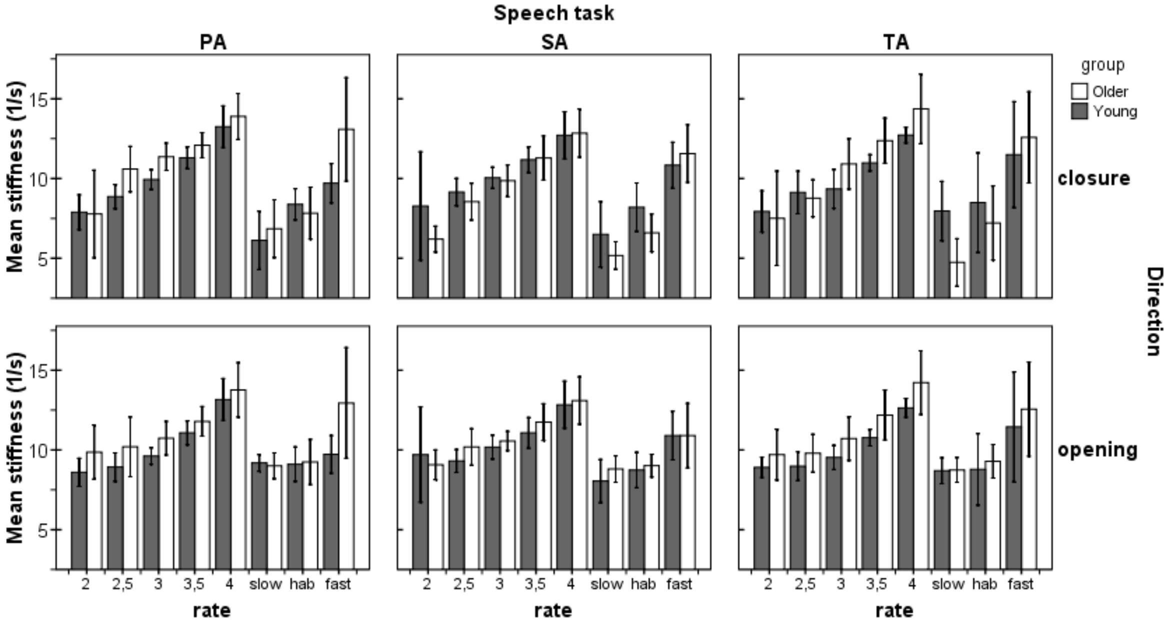

Figure 5. Mean stiffness and standard deviations of principal articulator movements for the young and older groups for both pacing conditions. Results are separated for direction and speech task.

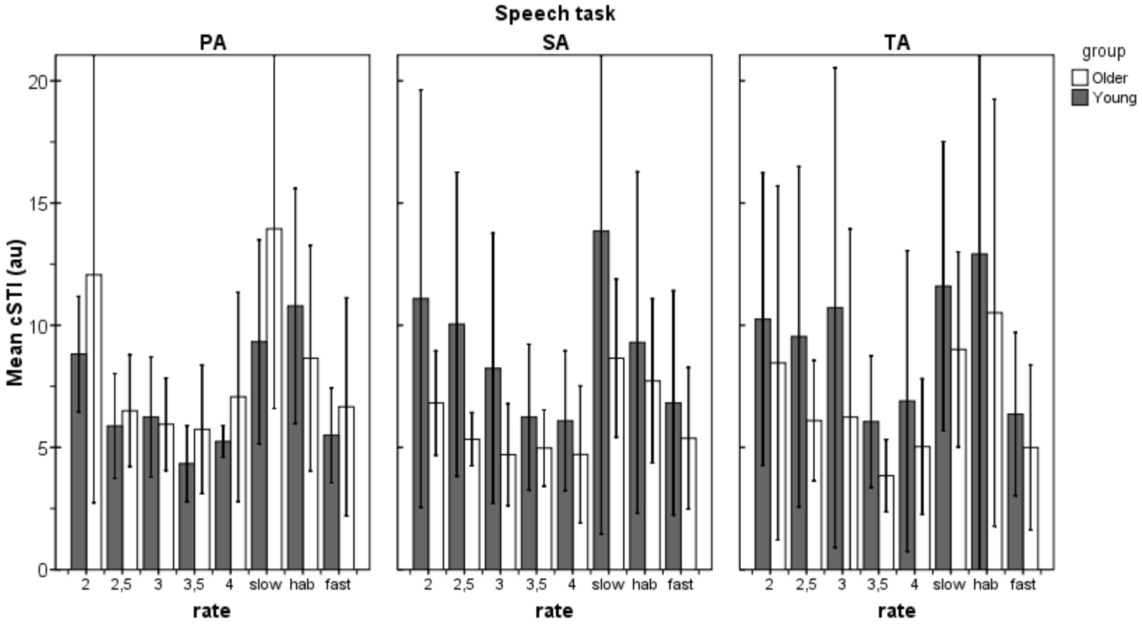

Figure 6. Mean cyclic spatio-temporal index and standard deviations of principal articulator movements for the young and older groups for both pacing conditions. Results are separated for speech task.

Discussion

In this study, the influence of speech rate on speech motor movements of younger and older adults was investigated. Participants produced a series of reiterated non-word utterances at different speech rates. In the self-paced condition, repetition tasks varied between a self chosen slow, habitual and fast rate. A metronome was used to dictate and model an additional series of repetition rates at approximately 2, 2.5, 3, 3.5 and 4 beats per second. A comparison of the realized syllable repetition rates between the group of younger adults and older adults shows that in the self-paced conditions, the group of older adults is in general equally fast as the young group. This is surprising, since the study by Goozee et al (2005) on syllable repetition rates reports significantly faster rates for the younger group for speech task /ta/ and /ka/ at moderate rate and for /ta/ at fast rate. In the metronome condition, syllable repetition rates are equal or faster for the older adults, compared to the young adults. Within the tempo ranges used, a metronome can be used to obtain a *minimal* speech rate; for both groups, realized repetition rates were generally equal or above, but not below, the modeled speech tempi. The speech tempi where older adults had a significantly higher repetition rate, were all in the mid region of the tempo range: between 2.5 and 3.5 bps. It is unlikely that older adults chose a different strategy to maintain repetition rates; possible differences would become visible initially in the extreme low and high rate conditions. In fact, the mid-range tempo conditions represent habitual speaking rates (Amerman & Parnell, 1992). Both groups were not controlled for gender; in the group of younger adults, the majority of participants were female, while the older group exhibited more male participants. When the male participants were consistently faster, this may account for differences in syllable repetition rate

Both groups effectively reduced duration of the movements of lower lip and tongue tip with increasing speech rate in respectively the syllables /pa/, and /sa/ and /ta/. The reduction of duration as a strategy to increase speech rate has also been found by Smith et al. (1987) and Goozee et al. (2005). For both groups, the durations of closing movements were longer than for opening movements. For syllable /sa/ and /ta/ in the metronome condition, durations were significantly shorter for the group of older adults. This contradicts the results of Goozee et al. A possible explanation is that older adults had significantly higher repetition rates, which leads to an extra reduction in duration.

Maximum amplitude, or distance of articulatory movements, was manipulated similarly across groups. No GROUP x RATE interaction effects were found for any of the three syllables, both in the non-metronome and metronome conditions. This is in contradiction with the results of Goozee et al. (2005), who found that with increasing syllable repetition rate, the group of younger adults displayed a greater decrease in distance. It is indeed expected that the maximum amplitude of speech movements is closely related to duration (Munhall, Ostry, & Parush, 1985; Ostry & Munhall, 1985). A main effect of DIRECTION indicates that during the repetition task of /sa/ (although not clearly visible in the comparison of closure and opening movement figures), the opening movements were increasingly smaller, resulting in smaller articulatory space, thus limiting the movements of the tongue.

The group of older adults increased peak velocity as a strategy to increase syllable repetition rate. This mirrors the findings of the shorter distances measured in this group. As Goozee et al. (2005) argues, the velocity parameter could be considered ‘reactive’, in anticipation on a reduced distance. The peak velocity is a measure of articulatory effort, as it is assumed to be closely related with the degree of muscle activity (Perkell & Zandipour, 2002). With increasing syllable repetition rates, the group of older adults showed a larger increase in peak velocity. It may take an extra effort for older adults to increase speech rate.

With increasing syllable repetition rate, both groups showed an increase in stiffness, while the group of older adults showed a significantly larger increase during the production of /pa/ in the non-metronome condition. Stiffness differed across direction of movement; overall higher values were found for opening movements. Furthermore, the difference between opening and closure movements were greater for the group of older adults. These findings mirror the results found in the duration parameter, where older adults show a larger decrease in duration when increasing speech rate, and durations of closing movements were longer than for opening movements. Main effect of rate seems to confirm stiffness as a control parameter for speech rate, which is an noteworthy finding (van Lieshout et al., 2007), since this may represent a direct motor control strategy.

In conclusion, the results on the movement parameters indicate that older adults use a different strategy to increase repetition rate, compared to younger adults. Older adults effectively reduce duration, increase peak velocity and stiffness to increase syllable repetition rate. Furthermore, there is an effect of age on the pattern of opening and closing movements. The duration of opening movements is relatively shorter for older adults, while the duration of closing movements is relatively longer for older adults, compared to the younger group. Stiffness values of closing movements are smaller for older adults, while for opening movements, stiffness values are higher. However, the differences found might also be explained by the higher repetition rates of older adults.

Results of the cyclic spatio-temporal index (cSTI) fail to indicate a consistent trend. Of the different experimental condition, only an effect of speech rate can be found, but no clear direction. A possible explanation of the failure to capture speech variability is the lack of sensitivity. In their studies on STI, Smith et al. (1995) and McHenry (2003) used respectively 15 to 20 speech fragments per condition. In this study, only 7 to 9 monosyllabic reiterations per condition are obtained, which may be too low to find statistically significant differences across groups, speech tasks and speech rates.

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