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Rate-Related Kinematic Changes in Younger and Older Adults

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Introduction

It is well documented that speech production changes across the lifespan. Research has reported modifications to jaw and tongue muscle anatomy [1] as well as changes in articulator function, such as a decrease in muscle activity [2] or strength and rhythm of tongue movements with increasing age [3,4]. Regarding speech output, many studies have found a decrease in speech rate and speech accuracy in older compared to younger speakers [5,6], although not all research confirms these findings [7].

A number of studies set out to capture these changes in rate through the detailed investigation of articulator movement. For example, it has been shown that an increase in speech rate is related to either a decrease in movement amplitude or an increase in movement velocity of articulatory opening and closing movements [8]. A reduction in speech rate on the other hand, is associated with an increase in movement duration [9,10]. Goozee, Stephenson, Murdoch, Darnell, and Lapointe [11] assessed age-related differences in speech kinematics and found that with increasing syllable repetition rates, participants from all age groups reduced tongue movement distances during consonant production, but the effect was significantly smaller in older adults compared to younger adults. In addition, the older adults showed a trend towards a relatively lower velocity and lower acceleration with increasing syllable repetition rates. The authors hypothesized that the older adults might have used a compensatory strategy in the face of reduced neuromuscular control in order to maintain articulatory stability or speech accuracy. Alternatively, a possible age-related decrease in proprioception of the tongue could lead to a decreased ability to judge tongue distances, thus making it difficult for older adults to actively reduce distances while increasing rate [11]. The experimental setup did not allow for definite conclusions, since in the fast condition syllable repetition rates were self-chosen and realized consistently slower in the group of older compared to younger adults. The question thus remains whether the observed differences resulted from a limitation in speech motor control (i.e., older individuals could not go any faster) or from differences in effort (i.e., older individuals preferred not to go any faster). In fact, other studies suggest that older adults prefer to monitor their speech production more carefully than younger adults with the intent of maximizing speech intelligibility, naturalness and accuracy, at the cost of rate [12].

The aim of the current study was to investigate the effects of aging on the kinematic characteristics and stability of speech movements, addressing some of the central, theoretically distinctive questions that arose from the previous studies by using both a self- and a metronome-paced syllable repetition task, allowing to study specific aspects of speech motor control across ages and clinical populations. The metronome-paced task constitutes an important addition to previous studies as this provides a way to control for possible age-related preferential differences in speaking rates.

With a possible age-related reduced neuromuscular control or decreased articulator proprioception in mind, one could assume that in the self-paced task older adults will either match the syllable repetition rates of younger speakers, but with decreased stability, or choose to speak slower in order to maintain movement stability and/or accuracy. Based on the above-mentioned age-related declines in oral sensation, we would expect older adults to show a decline in the stability of speech motor movements compared to the younger adults if they are forced to speed up their syllable repetition rates in the metronome-paced task. Alternatively, as some kinematic studies have shown that healthy aging individuals are able to compensate for age-related anatomical and functional changes in speech tasks [7], we would expect to find similar stability compared to younger adults, but with different underlying kinematics.

Method

Participants

Eight young adults, two males and six females aged 21-27 (mean = 23.7 years, SD = 2.3 years) and eight older speakers, four males and four females, aged 66-84 (mean = 74.7 years, SD = 6.0 years) participated in the study. The participants were native speakers of Dutch without a current history of speech problems. In the group of older adults, four subjects had full or partial dental plates or prostheses. All had been wearing them for more than one year, and wore them during the study. Two subjects in the group of older adults had hearing aids, but reportedly used them only rarely. Neither used their hearing aids during the experiments. Based on participants' self reports and informal assessment during conversation prior to the recordings, the hearing and speech of all participants was judged to be within normal ranges for taking part in the study.

Instrumentation and procedures

Data collection was carried out in accordance with previous studies [13]. An AG100 Carstens Electro-Magnetic Midsagittal Articulograph (EMMA; Carstens Medizinelektronic, GmbH, Germany) was used to collect articulatory movement data and time-aligned audio recordings. The system is equipped with a helmet containing three transmitting coils in midsagittal direction. Transducer coils were attached to the midline positions of the vermillion border of upper lip and lower lip as well as the nose bridge and to the lower and upper incisor gums. The coils attached on the upper incisor gums and the nose bridge were used as reference points for positional data. Three were placed onto the tongue (tongue blade, tongue body, and tongue dorsum). After attachment of the transducer coils, participants engaged in an everyday conversation of around 5 minutes to allow them to get used to speaking with coils on their articulators. Once the speech of participants was judged to be unaffected, formal assessment started.

Tasks

The participants were instructed to repeat a set of monosyllabic utterances in trials of 12 seconds. The syllables were made up in a CV format: /pa/, /sa/, and /ta/. The syllables were recorded in two pacing conditions: self-paced and after being trained by a metronome. In the self-paced condition, participants were instructed to repeat the items at their chosen habitual, slow and fast rate. In the metronome condition, a digital metronome (Adobe Audition v1.5) was used to train participants to maintain a specified syllable repetition rate. Metronome speed was set at 2, 2.5, 3, 3.5, and 4 beats per second (bps). Prior to recording, the metronome was started to allow participants to mentally tune in to the beat rate. Participants were instructed to fluently and on a single breath repeat the syllables as close as possible to the indicated metronome speed, at a rate of one syllable per beat. The subjects gave a hand signal and took a deep breath when they felt to be tuned into the metronome rhythm. Then the metronome was stopped by the experimenter and the recording of syllable repetitions was started. By following this procedure, we were able to cue different syllable repetition rates, while at the same time preventing the impact of enhanced fluency conditions as typically invoked by the presence of an external timing signal similar to methods sometimes used in the treatment of people who stutter [14]. The acoustic recording was played back afterwards, and judged on apparent articulation errors, pauses or rate changes, and if present, the trial was repeated at the end of the recording session.

The test items were presented in the order /pa/ - /sa/ - /ta/. To avoid stimulus presentation errors, the self-paced conditions were recorded first, in the order habitual – slow – fast, followed by the metronome paced conditions, also ordered from slow to fast rate.

Data analysis

The acoustic signal was used to calculate syllable repetition rates for each trial. The first and last syllable in each trial was discarded. Within each trial, the fragments used to calculate syllable repetition rates were also used in the kinematic analyses.

The movement patterns were analysed using the principal articulators of each syllable repetition task. For the production of the syllable /pa/, the analysis focused on the bilabial closing movement for /p/ and subsequent opening movement for the vowel production. The lower lip coil was used to track this activity. For the syllables /sa/ and /ta/, the alveolar closing and opening movements were analysed by using the tongue tip coil. All movement signals were visually screened for unusual movements and the acoustic data were perceptually screened for interruptions, hesitations or production errors. Trials that contained such errors were excluded, in order to retain only data that were perceptually correct and produced fluently. The kinematic analysis was performed on the first 10 syllable repetitions where available. For one older speaker, five trials had only nine syllable repetitions available, and in one trial there were eight syllable repetitions available. In one trial, only eight syllable repetitions were available from a older speaker.

The Tailor Data Processing Program v1.3 (Carstens Medizinelektronic, GmbH, Germany) and Matlab were used to analyze the data, following procedures described in [15]. For the kinematic measurements of the lower lip, mandible movement contributions were subtracted using a 2D based method that estimates a jaw rotation component, which has been found to be more precise than a simple subtraction procedure [16]. This method was not used for tongue tip movements since it cannot not guarantee uniform results with respect to compensating tongue tip movements for jaw contributions [15]. As tongue tip and jaw are only loosely coupled [17], this would introduce extra, possibly serious, measurement artefacts [18]. An automated peak-picking algorithm was used to identify and label maximum peak and valley values of the articulatory movement signals using the cyclic spatiotemporal index, or cSTI [17,19]. Peak assignment was manually corrected where necessary. For each syllable repetition, the following kinematic parameters were analysed separately for opening and closing movements of the tongue tip (for sa/ and /ta/) and the lower lip (for /pa/): movement duration (in sec), movement amplitude or displacement (in mm), peak velocity (in mm/sec. Furthermore, the cyclic spatiotemporal index was measured to assess variability of cyclic movement patterns of individual articulators.

Statistical analysis

Linear Mixed Model analyses (IBM SPSS v20) were used for statistical analysis, which is general linear model type that does not assume homogeneity of variance, sphericity, or compound symmetry, and allows for missing data [20]. When comparing the means of syllable repetition rates, fixed factors were 'group' (younger adults and older adults), 'rate' (slow, habitual and fast in the self-paced rate condition and 2, 2.5, 3, 3.5 and 4 bps in the metronome condition) and 'task' (/pa/, /sa/ and /ta/). Syllable repetition rates were analysed separately for the self-paced condition and the metronome-paced condition. The kinematic variables were analyzed separately for the two pacing conditions and the three syllable repetition tasks. Fixed factors were 'group', 'rate' and 'direction' (opening and closing movements). A Bonferroni correction to adjust for multiple statistical tests was not applied, as this creates an unacceptably high probability of making a Type II error in analyses with small group sizes. Rather, multiple comparisons are accounted for in the interpretation of the results [cf. 21]. Significant main and interaction effects were further explored by means of a pair wise comparison using Fisher's Least Significant Difference Test.

Results

Prior to comparing syllable repetition rates and kinematic parameters across groups, it was determined whether speakers were sufficiently comparable with each other to allow for further comparisons. Two of the eight older participants had been prescribed hearing aids, although they did not wear them during the experiment. In addition, although the group of older adults was balanced for gender with four females and four males participating, the group of younger adults had an imbalance with six females and two males. Lastly, since four speakers in the group of older adults were wearing full or partial dentals, potential effects of wearing dental plates on articulatory performance were examined. The possible effects of these variables were analyzed by a one-way analysis of variance of mean syllable repetition rates, separately for each syllable type and pooled over pacing method and rate task. There were no significant differences found for these variables, and all participants were included in the subsequent analyses.

Syllable repetition rates

The means and standard deviations of the syllable repetition rates are displayed in table 1. A significant effect of group on syllable repetition rate was absent in both pacing conditions. A main effect of rate was present in the metronome condition [$F(4, 224) = 721.7$, $p < .001$] and the self-paced condition [$F(2, 128) = 227.8$, $p < .001$]; both groups changed syllable repetition rates according to the syllable repetition rate condition. A main effect of task was present in the self-paced condition [$F(2,128) = 3.77$, $p = .026$]. Post-hoc analysis showed that syllable repetition rates of /ta/ were faster compared to /pa/. Significant interaction effects of group by rate (metronome: [F (4, 224) = 5.84, p < .001], self-paced: [F (2, 128) = 18.80, p < .001]) indicated that the group of older adults had faster syllable repetition rates than the young participants at 3, 3.5 and 4 bps in the metronome condition and in the fast rate task of the self-paced condition pooled over the three syllables. A significant interaction effect of group by task in the self-paced condition [F (2, 128) = 7.86, p = .001] indicated that the older group was significantly faster during /ta/ pooled over the three rate tasks.

Table 1. Means and standard deviations (in parentheses) of syllable repetition rates (in syllables per second) for younger and older adults, broken down by task and rate condition.

	/pa/		/sa/		/ta/	
Rate	Young adults	Older adults	Young adults	Older adults	Young adults	Older adults
Slow	1.23 (0.32)	1.21 (0.20)	1.63 (0.44)	1.45 (0.29)	1.82 (0.50)	1.29 (0.34)
Habitual	2.02 (0.43)	2.08 (0.64)	2.26 (0.47)	1.97 (0.48)	2.44 (0.83)	1.86 (0.35)
Fast	2.76 (0.63)	4.10 (1.11)	3.23 (0.69)	3.51 (0.57)	3.50 (1.20)	3.96 (0.90)
2 bps	2.00 (0.08)	1.91 (0.17)	2.03 (0.09)	1.94 (0.10)	2.05 (0.08)	1.99 (0.13)
2.5 bps	2.52 (0.11)	2.78 (0.33)	2.54 (0.17)	2.70 (0.21)	2.53 (0.09)	2.61 (0.12)
3 bps	3.06 (0.29)	3.37 (0.30)	2.98 (0.11)	3.19 (0.26)	2.98 (0.12)	3.20 (0.13)
3.5 bps	3.53 (0.24)	3.75 (0.27)	3.48 (0.26)	3.64 (0.38)	3.40 (0.15)	3.87 (0.48)
4 bps	4.18 (0.42)	4.37 (0.52)	4.01 (0.48)	4.13 (0.48)	3.99 (0.22)	4.55 (0.68)

Table 2. Means and standard deviations (in parentheses) of kinematic parameters for younger and older adults, broken down by task, movement direction and rate condition. DUR = duration, AMP = amplitude, VEL = peak velocity, CSTI = cyclic spatiotemporal index, OP = opening, CL = closing.

		/pa/				/sa/				/ta/			
		Young Adults		Older Adults		Young Adults		Older Adults		Young Adults		Older Adults	
		OP	CL	OP	CL	OP	CL	OP	CL	OP	CL	OP	CL
DUR	Slow	.214 (.034)	.643 (.202)	.301 (.158)	.579 (.197)	.284 (.082)	.364 (.125)	.233 (.044)	.496 (.126)	.214 (.045)	.643 (.170)	.246 (.061)	.582 (.236)
	Hab	.216 (.052)	.289 (.096)	.209 (.051)	.307 (.192)	.216 (.038)	.243 (.064)	.199 (.019)	.341 (.139)	.215 (.110)	.289 (.071)	.224 (.059)	.329 (.142)
	Fast	.178 (.049)	.196 (.030)	.130 (.036)	.129 (.032)	.165 (.045)	.157 (.025)	.150 (.028)	.141 (.024)	.178 (.038)	.196 (.048)	.135 (.031)	.133 (.028)

	2 bps	.216 (.032)	.285 (.042)	.194 (.044)	.312 (.097)	.203 (.040)	.260 (.066)	.200 (.022)	.319 (.029)	.216 (.035)	.285 (.040)	.198 (.038)	.274 (.080)
	2.5 bps	.194 (.018)	.201 (.018)	.183 (.031)	.179 (.032)	.200 (.015)	.198 (.016)	.165 (.017)	.207 (.023)	.194 (.025)	.201 (.024)	.174 (.017)	.206 (.015)
	3 bps	.168 (.011)	.164 (.011)	.153 (.013)	.145 (.014)	.166 (.007)	.168 (.008)	.153 (.010)	.162 (.015)	.168 (.017)	.164 (.010)	.155 (.011)	.152 (.009)
	3.5 bps	.142 (.009)	.140 (.008)	.134 (.010)	.132 (.009)	.144 (.011)	.144 (.010)	.136 (.012)	.141 (.016)	.142 (.007)	.140 (.006)	.131 (.015)	.129 (.014)
	4 bps	.120 (.011)	.120 (.011)	.116 (.014)	.115 (.011)	.124 (.012)	.125 (.012)	.121 (.013)	.124 (.013)	.120 (.009)	.120 (.006)	.112 (.015)	.112 (.015)
AMP	Slow	8.05 (3.57)	7.99 (3.51)	8.01 (4.25)	7.85 (4.13)	9.10 (4.93)	9.22 (4.81)	11.4 (5.60)	11.5 (5.67)	9.73 (5.13)	9.71 (5.11)	13.7 (7.60)	13.5 (7.58)
	Hab	8.51 (4.02)	8.51 (4.09)	8.00 (3.32)	8.02 (3.29)	9.71 (3.84)	9.96 (3.90)	10.8 (3.98)	10.9 (3.94)	8.97 (5.17)	9.36 (5.23)	13.5 (7.34)	13.4 (7.31)
	Fast	9.02 (3.37)	9.02 (3.42)	7.98 (4.32)	7.96 (4.26)	7.83 (3.14)	8.09 (3.33)	7.24 (2.49)	7.48 (2.57)	9.00 (5.08)	9.09 (5.04)	10.7 (6.14)	10.7 (5.91)
	2 bps	8.12 (3.71)	8.16 (3.79)	9.56 (5.39)	9.54 (5.59)	8.60 (3.82)	8.73 (3.94)	9.25 (3.02)	9.30 (3.05)	10.1 (5.21)	10.0 (5.16)	12.8 (7.66)	12.9 (7.61)
	2.5 bps	8.35 (3.77)	8.46 (3.77)	8.40 (3.99)	8.25 (3.85)	7.45 (2.70)	7.70 (2.83)	8.79 (3.29)	9.04 (3.27)	8.96 (4.15)	9.07 (4.26)	10.7 (4.80)	10.8 (4.79)
	3 bps	8.28 (3.83)	8.30 (3.77)	7.50 (4.01)	7.59 (3.96)	7.47 (3.23)	7.70 (3.42)	8.89 (3.75)	9.26 (3.93)	7.94 (4.35)	8.09 (5.32)	10.7 (5.01)	10.7 (5.08)
	3.5 bps	7.82 (3.07)	7.77 (2.99)	7.23 (2.95)	7.15 (2.86)	6.63 (3.12)	6.92 (3.22)	8.96 (4.65)	9.15 (4.55)	10.1 (3.83)	9.98 (3.79)	10.2 (4.92)	10.2 (5.07)
	4 bps	7.42 (2.69)	7.45 (2.69)	6.59 (2.53)	6.63 (2.59)	6.24 (2.37)	6.45 (2.42)	7.19 (2.15)	7.36 (2.20)	8.13 (4.06)	8.20 (4.12)	7.81 (3.87)	7.90 (3.92)
VEL	Slow	73.1 (30.4)	47.7 (21.7)	71.0 (36.0)	56.8 (43.3)	75.7 (31.8)	62.9 (33.3)	98.7 (47.0)	56.9 (24.2)	82.2 (39.5)	71.6 (27.7)	121.8 (78.6)	64.5 (43.7)
	Hab	75.1 (30.5)	72.2 (39.2)	74.5 (33.3)	61.5 (26.5)	82.3 (29.2)	81.2 (35.8)	96.7 (35.4)	68.5 (17.0)	85.2 (45.3)	81.8 (37.5)	122.6 (73.3)	87.2 (49.2)
	Fast	88.8 (39.5)	90.0 (43.2)	98.3 (51.7)	97.6 (47.4)	83.0 (28.1)	85.8 (31.1)	78.4 (27.2)	83.9 (21.2)	93.3 (49.8)	96.2 (53.3)	126.0 (60.9)	126.1 (57.5)
	2 bps	69.0 (30.7)	64.7 (31.9)	98.3 (68.9)	82.3 (77.7)	74.4 (28.7)	62.5 (22.7)	84.8 (32.8)	58.1 (21.3)	88.6 (44.6)	77.4 (39.0)	118.7 (75.4)	85.4 (57.5)
	2.5 bps	73.9 (34.0)	76.0 (39.4)	88.8 (54.3)	88.8 (47.3)	68.1 (23.5)	69.3 (26.3)	90.7 (42.1)	77.3 (33.3)	77.3 (32.4)	79.3 (32.5)	107.7 (62.3)	98.3 (60.2)
	3 bps	80.8 (41.5)	82.7 (41.5)	82.6 (49.2)	86.3 (48.5)	74.9 (30.5)	76.6 (33.5)	94.1 (42.0)	90.7 (40.0)	76.3 (36.9)	81.1 (43.3)	111.9 (58.6)	112.8 (56.7)
	3.5 bps	87.7 (39.5)	88.7 (38.8)	84.9 (35.4)	85.9 34.2)	72.4 (33.0)	76.3 (34.3)	108.7 (70.0)	106.3 (67.0)	107.7 (38.8)	109.0 (41.8)	123.0 (66.1)	124.6 (66.7)
	4 bps	98.2 (41.2)	99.2 (41.3)	92.0 (44.0)	93.5 (44.3)	78.4 (28.0)	80.9 (28.9)	92.2 (23.9)	92.6 (23.7)	102.8 (52.3)	104.0 (52.7)	106.8 (50.6)	108.4 (50.8)
CSTI	Slow	9.32 (4,17)		13.9 (7.35)		13.9 (12.4)		8.65 (3.23)		11.6 (5.92)		9.01 (3.99)	
	Hab	10.8 (4.81)		8.64 (4.62)		9.29 (6.98)		7.72 (3.35)		12.9 (12.9)		10.5 (8.73)	
	Fast	5.50 (1.94)		6.66 (4.46)		6.82 (4.59)		5.37 (2.90)		6.37 (3.33)		5.00 (3.37)	
	2 bps	8.82 (2.36)		12.1 (9.32)		11.1 (8.54)		6.81 (2.14)		10.2 (5.98)		8.46 (7.24)	
	2.5 bps	5.88 (2.15)		6.50 (2.29)		10.0 (6.22)		5.35 (1.09)		9.53 (6.96)		6.10 (2.46)	
	3 bps	6.24 (2.46)		5.95 (1.89)		8.24 (5.53)		4.70 (2.08)		10.7 (9.81)		6.24 (7.69)	
	3.5 bps	4.34 (1.55)		5.74 (2.63)		6.24 (2.98)		4.98 (1.56)		6.06 (2.69)		3.84 (1.48)	
	4 bps	5.24 (0.65)		7.07 (4.28)		6.09 (2.86)		4.71 (2.80)		6.90 (6.15)		5.04 (2.77)	

Kinematic data

The means of the kinematic variables are displayed in figure 1. Statistical analyses of the kinematic variables duration, peak velocity, amplitude, and cSTI were calculated separately for pacing condition (self-paced and metronome paced) and task (/pa/, /sa/

and /ta/). The sections below summarise the results for each kinematic variable in turn.

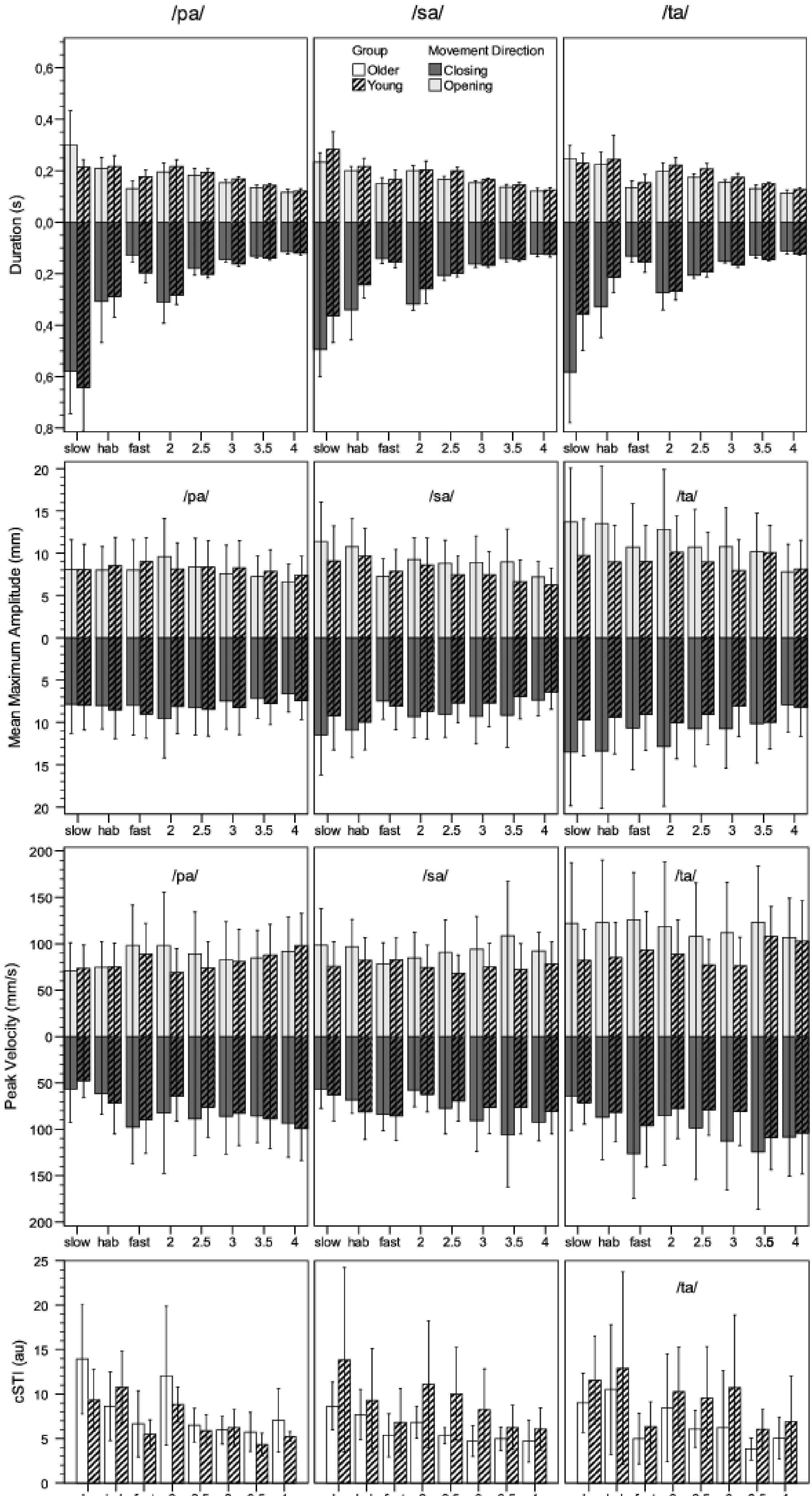
/pa/
/sa/
/ta/
Group
Older
Young
Movement Direction
Closing
Opening
Duration (s)
Mean Maximum Amplitude (mm)
Peak Velocity (mm/s)
cSTI (au)
slow
hab
fast
2
2.5
3
3.5
4

Figure 1. Mean duration, maximum amplitude, peak velocity and csti with 95% confidence intervals of articulator opening and closing movements for the young and older groups in both pacing conditions. Results are shown separately for speech task.

Duration

For all syllable repetition tasks and both pacing conditions, the main effect of group on duration of articulatory movements was non-significant. The main effects of rate were all significant; metronome condition /pa/ [$F(4,135.82) = 122.2$, $p < .001$], /sa/ [$F(4,41.55) = 185.9$, $p < .001$], /ta/ [$F(4,41.16) = 154.0$, $p < .001$], and self-paced condition /pa/ [$F(2,27.33) = 52.45$, $p < .001$], /sa/ [$F(2,20.25) = 68.30$, $p < .001$], /ta/ [$F(2,24.13) = 43.25$, $p < .001$]. The effects of direction were also all significant; metronome condition /pa/ [$F(1,25.56) = 15.76$, $p = .001$], /sa/ [$F(1,32.56) = 57.59$, $p < .001$], and /ta/ [$F(1,32.89) = 11.39$, $p = .002$], and self-paced condition /pa/ [$F(1,41.26) = 48.87$, $p < .001$], /sa/ [$F(1,25.38) = 38.25$, $p < 0.001$], /ta/ [$F(1,30.19) = 24.04$, $p < .001$]. Across groups, durations were effectively reduced with increasing syllable repetition rate, and closing durations were longer than opening durations. A significant group by rate effect was present in the self-paced condition of /ta/ [$F(2,24.13) = 4.74$, $p = .018$, but no clear pattern was present. Significant interaction effects of group by direction were present for /sa/ and /ta/ in the metronome condition: [$F(1,32.56) = 15.23$, $p < .001$] and [$F(1,32.89) = 5.36$, $p = .027$], and the self-paced condition: [$F(1,25.38) = 13.75$, $p = .001$] and [$F(1,30.19) = 9.57$, $p = .004$], showing that the overall difference of opening movements being longer than closing movements, were larger in older compared to younger adults. There were significant interaction effects of rate by direction in the metronome conditions in all tasks: /pa/ [$F(4,40.89) = 6.31$, $p < .001$], /sa/ [$F(4,49.70) = 12.06$, $p < .001$], /ta/ [$F(4,45.98) =$

4.74, p = .003] and in all self-paced conditions: /pa/ [F 2,30.20) = 23.36, p <.001], /sa/ [F(2,24.34) = 20.92, p < .001], /ta/ [F(2,28.10) = 13.30, p < .001], indicating that the difference in duration between closing and opening movements decreased with increasing syllable repetition rate. Significant three-way interaction effects of group by rate by direction were present in the metronome condition in /sa/ [F(4,49.70) = 4.57, p = .003] and /ta/ [F(4,45.98) = 2.86, p = .034] and the self-paced condition of /sa/ [F(2,24.34) = 5.75, p = .009] and /ta/ [F(2,28.10) = 5.06, p = .013], indicating that, especially at slower syllable repetition rates, the older adults showed a larger difference in duration between closing and opening movements, compared to younger adults.

<u>Movement Amplitude</u>

The analysis showed no significant main effects of group. Significant main effects of rate were found in the metronome condition of /sa/ [F(4,16.01) = 3.14, p = .014], and /ta/ [F(4,15.65) = 7.38, p = .002], as well as in the self-paced condition of /sa/ [F(2,16.00) = 8.19, p = .004]. Significant effects of direction were also found in the metronome condition of /sa/ [F(1,16.00) = 57.90, p < .001], and /ta/ [F(1,16.08) = 6.69, p = .020], and in the self-paced condition of /sa/ [F(1,16.00) = 25.91, p < .001]. In these cases, an increase in rate was associated with a decrease in movement range, and the mean amplitude of closing movements was larger compared to opening movements. The group by rate interaction effect was significant in the metronome condition of /ta/ [F(4,15.65) = 5.64, p = .005], and the rate by direction interaction was significant in the metronome condition of /sa/ [F(4,16.00) = 12.14, p < .001], and the self-paced conditions of /pa/ F(2,16.00) = 4.25, p = 033] and /ta/ [F(2,15,59) = 4.41, p = .030], but inspection of the data did not reveal a clear pattern. An interaction effect of group by direction was present in the self-paced condition of /ta/: [F(1,14.80) = 9.71, p = .007], showing that the younger adults displayed slightly larger amplitudes of closing movements compared to opening movements, while the older adults displayed a slight reverse effect.

Peak Velocity

The results of the statistical analyses of peak velocity of articulatory movements revealed no significant main effect of group. The main effect of rate was significant in the metronome condition of /pa/: [F(4,16.00) = 7.43, p = .001], /sa,/: [F(4,16.00) = 4.32, p = .015], and /ta/[F(4,15.76) = 14.89, p < .001], and the self-paced condition of /pa/: F(2,16.00) = 11.91, p = .001], /sa/: [F(2,16.00) = 6.28, p = .010], and /ta/: [F(2,15.78) = 8.12, p = .004], showing that an increase in syllable repetition rate was associated with an increase in maximum velocity. A significant main effect of direction was present in the metronome condition of /sa/: [F1,16.00) = 14.22, p = .002] and /ta/: [F(1,15,47) = 5.58, p = .032], and in the self-paced condition of /pa/ [F(1,16.00) = 17.33, p = .001], /sa/ F(1,16.00) = 20.54, p < .001], and /ta/ [F(1,16.08) = 13.44, p = .002], indicating that the maximum velocity was higher in opening movements, compared to closing movements. This difference decreased with an increasing syllable repetition rate, indicated by significant rate by direction effects in the metronome condition of /sa/ [F(4,16.00) = 9.60, p < .001] and /ta/ [F(4,15.61) = 6.50, p = .003, and in the self-paced conditions of /pa/ [F(2,16.00) = 15.71, p < .001, /sa/ [F(2,16.00) = 12.26, p = .001], and /ta/ [F(2,15.58) = 9.34, p = .002]. A significant interaction effect of group by rate in the metronome condition of /ta/ [F(4,15.65) = 5.26, p = .007] did not reveal a clear pattern. Significant interaction effects of group by direction were present for /sa/ and /ta/ in the metronome condition: [F(1,16.00) = 11.18, p = .004] and [F(1,15.47) = 4.56, p = .049], and the self-paced condition: [F(1,16.00) = 10.27, p = .006] and [F(1,16.08) = 8.38, p = .011], showing that the overall differences of maximum velocities between opening and closing movements were larger in older adults compared to younger adults. Furthermore, a significant three-way interaction effect of group by rate by direction was observable in the metronome condition of /sa/ [F(4,16.00) = 3.33, p = .036], and the self-paced condition of /sa/ [F(2,16.00) = 5.10, p = .019], and /ta/ [F(2,15.58) = 3.71, p = .048], indicating that both the direction and the rate effects were only present in the older adults, whereas no such effects were present in the younger adults. These findings show that, especially at slower syllable repetition rates, the older adults showed a larger difference in peak velocity between closing and opening movements, compared to younger adults.

Cyclic Spatiotemporal Index

Statistical analysis of the cSTI did not reveal differences between younger and older adults as evidenced by a non-significant group effect. A significant effect of rate was present in all tasks in the metronome condition: /pa/: [F(4,16.00) = 9.11, p < .001], /sa/: F(4,16.00) = 4.86, p = .009], /ta/: [F(4,16) = 4.20, p = .016], and all tasks in the self-paced condition: /pa/: [F(2,16.00) = 19.23, p < .001], /sa/: [F(2,16.00) = 4.17, p = .035], and /ta/: [F(2,16.00) = 12.35, p < .001], indicating that cSTI decreased with increasing syllable repetition rate. A significant interaction effect of group by rate was present in the self-paced condition of /pa/ [F(2,16.00) = 13.33, p < .001] and the metronome paced condition of /sa/ [F(4,16.00) = 3.12, p = .045], but further group comparisons revealed no clear pattern.

Discussion

In this study, the influence of syllable repetition rate on articulation movements of younger and older adults was investigated with the aim of assessing the effects of aging on the kinematic characteristics and stability of articulation movements produced at different syllable repetition rates. The results showed that older adults were able to repeat syllables as fast as younger adults (or even faster) when stimulated (by instruction or external metronome cues) to do so. These findings suggest that possible physiological changes to speech systems associated with aging are minimally disruptive (see also [7]). Alternatively, older adults have acquired effective compensatory behaviours for possible physiological changes, at least in the case of the relatively simple syllable repetition tasks used in this study.

The kinematic results confirm a close relation between syllable repetition rate and movement duration as found in earlier studies [6,8,9,11]. Since both groups showed overall longer durations in closing movements compared to opening movements, and closing durations were proportionally more reduced with increasing rate, it can be concluded that the increase in rate was primarily achieved by actively reducing the closing duration. When producing the alveolar constrictions associated with /sa/ and /ta/ at slower rates, the older adults made a larger differentiation between closing and opening movements, compared to the younger adults, suggesting that for the tongue tip, older adults control articulation differently at slow rates than younger adults. In contrast, Goozee et al. [11] reported longer durations of opening movements compared to closing movements. This difference could be due to the use of different stimuli and the methods through which changes in syllable repetition rate were induced.

With respect to the amplitude of articulatory movements, the younger and older adults reduced tongue movement amplitude with increasing speech rate in both pacing conditions for /sa/ and in the self-paced condition of /ta/. During these speech tasks closing movements were larger than opening movements. This asymmetry suggests that speakers increased or decreased their speech rate during trial repetitions [17]. However, since tongue tip movements were not corrected for jaw movements, it cannot be ruled out that jaw movements contributed to the results found, and should be confirmed in future research.

An increase in syllable repetition rate is usually associated with an increase in peak velocity [17]. The current study corroborates these findings. In most tasks, both age groups showed lower velocities during closing movements compared to opening movements. During the production of the alveolar constrictions of /sa/ in both pacing conditions and for /ta/ in the self-paced condition, the group of older adults showed a significantly larger difference in peak velocity between closing and opening movements, and this effect was most notably present in the slower rates, mimicking the effects found for movement duration.

How can the current kinematic findings be explained in the absence of speed or stability limitations? In experimental tasks where capacities have to be distributed across articulation rate and stability, speakers may focus on one or the other, depending on their skills and task priorities [11]. Contrary to our hypothesis, the results of the present study showed that older adults realized equal and faster syllable repetition rates compared to the young group, without changes in articulation stability. With increasing rates, movements made by older adults became more similar, in that the differences in duration and peak velocity between closing and opening movements decreased, mimicking the pattern typically displayed by the younger adults. Greater similarity between opening and closing movement sequences often reflects a more open loop or ballistic type of motor control [8,15]. Vice versa, the current findings that the older adults -but not the younger adults- increased the duration (and decreased peak velocity) of closing movements more than opening movements at slower rates can be interpreted as the result of a less ballistic mode of control. It has been demonstrated that slowing down articulation facilitates closed loop (feedback based) control, enabling the online detection of movement errors and subsequent computation and integration of corrections [22]. At faster rates, closed loop control is not possible, as corrective movements are ineffective for on-going speech sound sequences [23]. Based on the present results, we hypothesize that older adults may utilize a control strategy facilitating feedback control of tongue movements when speaking at a relatively slower rate. This might be linked to age-related changes in cognitive processing during speech and/or structural changes in the speech production system. For example, several studies suggested that aging is related to a decrease in general oral sensory function [24,25]. Specifically, Weismer and Liss [1] suggested an age-related decrease in proprioception for active tongue movements based on their findings that older adults were less able to judge the required durations and velocities of lifting the tongue in executing speech tasks. If indeed with increasing age the quality of somatosensory information of (especially) tongue movements decreases, this could force older adults to adapt control strategies, in particular with a stronger reliance on closed loop control. We speculate that for older speakers, the stronger slowing down of closing movements may compensate for a reduced quality of sensory information, enabling the use of closed loop control and allowing a more extensive processing. If this were true, kinematic differences with respect to duration and peak velocity of closing movements between older and younger speakers would disappear when speakers are forced to use a more open loop control through a paradigm that masks auditory feedback (through noise) and (part of) proprioceptive feedback (through tendon vibration), possibly at the cost of a reduced articulatory stability for older speakers. These apparent age-related differences in speech motor control as a function of self-paced and externally timed repetition rates are in line with earlier studies using syllable repetition experiments to study speech performance in clinical populations [e.g. 26], and can provide insight in limitations in speech production due to age and its relationship to potentially affected neural systems. Speech motor control reserve capacities in healthy aging speakers may mask speech problems, and only when additional disease processes affecting the oromotor control system appear (in particular dysarthria), a divergent speech output becomes more salient [26,27].

It should be noted that the interpretation of the data leading to our hypothesis is constrained in various aspects. To be able to fully investigate our predictions, future directions should be geared towards investigating movements of additional articulators, including the jaw and the tongue dorsum, as well as their relative role during articulation as a function of age. More natural speech stimuli could be used, and in addition to measuring articulatory stability by means of the cSTI or other speech variability measures, perceptual measurements should be included to further assess the role of speech intelligibility in age-related changes in speech motor control.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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