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

1 duration [9,10]. Goozee, Stephenson, Murdoch, Darnell, and Lapointe [11] assessed
2 age-related differences in speech kinematics and found that with increasing syllable
3 repetition rates, participants from all age groups reduced tongue movement distances
4 during consonant production, but the effect was significantly smaller in older adults
5 compared to younger adults. In addition, the older adults showed a trend towards a
6 relatively lower velocity and lower acceleration with increasing syllable repetition
7 rates. The authors hypothesized that the older adults might have used a compensatory
8 strategy in the face of reduced neuromuscular control in order to maintain articulatory
9 stability or speech accuracy. Alternatively, a possible age-related decrease in
10 proprioception of the tongue could lead to a decreased ability to judge tongue
11 distances, thus making it difficult for older adults to actively reduce distances while
12 increasing rate [11]. The experimental setup did not allow for definite conclusions,
13 since in the fast condition syllable repetition rates were self-chosen and realized
14 consistently slower in the group of older compared to younger adults. The question
15 thus remains whether the observed differences resulted from a limitation in speech
16 motor control (i.e., older individuals could not go any faster) or from differences in
17 effort (i.e., older individuals preferred not to go any faster). In fact, other studies
18 suggest that older adults prefer to monitor their speech production more carefully than
19 younger adults with the intent of maximizing speech intelligibility, naturalness and
20 accuracy, at the cost of rate [12].

21 The aim of the current study was to investigate the effects of aging on the
22 kinematic characteristics and stability of speech movements, addressing some of the
23 central, theoretically distinctive questions that arose from the previous studies by
24 using both a self- and a metronome-paced syllable repetition task, allowing to study
25 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

1 in the group of older adults had hearing aids, but reportedly used them only rarely.
2 Neither used their hearing aids during the experiments. Based on participants' self
3 reports and informal assessment during conversation prior to the recordings, the
4 hearing and speech of all participants was judged to be within normal ranges for
5 taking part in the study.

6

7 ***Instrumentation and procedures***

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

21

22 ***Tasks***

23 The participants were instructed to repeat a set of monosyllabic utterances in trials of
24 12 seconds. The syllables were made up in a CV format: /pa/, /sa/, and /ta/. The

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

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

24 ***Data analysis***

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

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

17 The Tailor Data Processing Program v1.3 (Carstens Medizinelektronik,
18 GmbH, Germany) and Matlab were used to analyze the data, following procedures
19 described in [15]. For the kinematic measurements of the lower lip, mandible
20 movement contributions were subtracted using a 2D based method that estimates a
21 jaw rotation component, which has been found to be more precise than a simple
22 subtraction procedure [16]. This method was not used for tongue tip movements since
23 it cannot not guarantee uniform results with respect to compensating tongue tip
24 movements for jaw contributions [15]. As tongue tip and jaw are only loosely coupled
25 [17], this would introduce extra, possibly serious, measurement artefacts [18]. An

1 automated peak-picking algorithm was used to identify and label maximum peak and
2 valley values of the articulatory movement signals using the cyclic spatiotemporal
3 index, or cSTI [17,19]. Peak assignment was manually corrected where necessary. For
4 each syllable repetition, the following kinematic parameters were analysed separately
5 for opening and closing movements of the tongue tip (for /sa/ and /ta/) and the lower
6 lip (for /pa/): movement duration (in sec), movement amplitude or displacement (in
7 mm), peak velocity (in mm/sec. Furthermore, the cyclic spatiotemporal index was
8 measured to assess variability of cyclic movement patterns of individual articulators.

10 ***Statistical analysis***

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

1

2 **Results**

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

16

17 ***Syllable repetition rates***

18 The means and standard deviations of the syllable repetition rates are displayed in
19 table 1. A significant effect of group on syllable repetition rate was absent in both
20 pacing conditions. A main effect of rate was present in the metronome condition [F
21 $(4, 224) = 721.7, p < .001$] and the self-paced condition [$F(2, 128) = 227.8, p < .001$];
22 both groups changed syllable repetition rates according to the syllable repetition rate
23 condition. A main effect of task was present in the self-paced condition [$F(2, 128) =$
24 $3.77, p = .026$]. Post-hoc analysis showed that syllable repetition rates of /ta/ were

1 faster compared to /pa/. Significant interaction effects of group by rate (metronome:
2 [F (4, 224) = 5.84, $p < .001$], self-paced: [F (2, 128) = 18.80, $p < .001$]) indicated that
3 the group of older adults had faster syllable repetition rates than the young
4 participants at 3, 3.5 and 4 bps in the metronome condition and in the fast rate task of
5 the self-paced condition pooled over the three syllables. A significant interaction
6 effect of group by task in the self-paced condition [F (2, 128) = 7.86, $p = .001$]
7 indicated that the older group was significantly faster during /ta/ pooled over the three
8 rate tasks.

9

10 Table 1. Means and standard deviations (in parentheses) of syllable repetition rates (in syllables per second) for younger and
11 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)

12

13

14 Table 2. Means and standard deviations (in parentheses) of kinematic parameters for younger and older adults, broken down by
15 task, movement direction and rate condition. DUR = duration, AMP = amplitude, VEL = peak velocity, CSTI = cyclic
16 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	.643	.301	.579	.284	.364	.233	.496	.214	.643	.246	.582
		(.034)	(.202)	(.158)	(.197)	(.082)	(.125)	(.044)	(.126)	(.045)	(.170)	(.061)	(.236)
	Hab	.216	.289	.209	.307	.216	.243	.199	.341	.215	.289	.224	.329
		(.052)	(.096)	(.051)	(.192)	(.038)	(.064)	(.019)	(.139)	(.110)	(.071)	(.059)	(.142)
	Fast	.178	.196	.130	.129	.165	.157	.150	.141	.178	.196	.135	.133
		(.049)	(.030)	(.036)	(.032)	(.045)	(.025)	(.028)	(.024)	(.038)	(.048)	(.031)	(.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)
		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)
	Hab	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)
		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)
		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 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)
		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)
	3.5 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)
		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)
	4 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)
		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)
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)
		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)
	Hab	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)
		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)
		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 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)
		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)
	3.5 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)
		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)
	4 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)
		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)
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)	

1

2 ***Kinematic data***

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

- 1 and $/t_a/$). The sections below summarise the results for each kinematic variable in
- 2 turn.

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

4

5 Duration

6 For all syllable repetition tasks and both pacing conditions, the main effect of group
7 on duration of articulatory movements was non-significant. The main effects of rate
8 were all significant; metronome condition /pa/ [$F(4,135.82) = 122.2, p < .001$], /sa/
9 [$F(4,41.55) = 185.9, p < .001$], /ta/ [$F(4,41.16) = 154.0, p < .001$], and self-paced
10 condition /pa/ [$F(2,27.33) = 52.45, p < .001$], /sa/ [$F(2,20.25) = 68.30, p < .001$], /ta/
11 [$F(2,24.13) = 43.25, p < .001$]. The effects of direction were also all significant;
12 metronome condition /pa/ [$F(1,25.56) = 15.76, p = .001$], /sa/ [$F(1,32.56) = 57.59, p <$
13 $.001$], and /ta/ [$F(1,32.89) = 11.39, p = .002$], and self-paced condition /pa/
14 [$F(1,41.26) = 48.87, p < .001$], /sa/ [$F(1,25.38) = 38.25, p < 0.001$], /ta/ [$F(1,30.19) =$
15 $24.04, p < .001$]. Across groups, durations were effectively reduced with increasing
16 syllable repetition rate, and closing durations were longer than opening durations. A
17 significant group by rate effect was present in the self-paced condition of /ta/
18 [$F(2,24.13) = 4.74, p = .018$], but no clear pattern was present. Significant interaction
19 effects of group by direction were present for /sa/ and /ta/ in the metronome
20 condition: [$F(1,32.56) = 15.23, p < .001$] and [$F(1,32.89) = 5.36, p = .027$], and the
21 self-paced condition: [$F(1,25.38) = 13.75, p = .001$] and [$F(1,30.19) = 9.57, p = .004$],
22 showing that the overall difference of opening movements being longer than closing
23 movements, were larger in older compared to younger adults. There were significant
24 interaction effects of rate by direction in the metronome conditions in all tasks: /pa/
25 [$F(4,40.89) = 6.31, p < .001$], /sa/ [$F(4,49.70) = 12.06, p < .001$], /ta/ [$F(4,45.98) =$

1 4.74, $p = .003$] and in all self-paced conditions: /pa/ [$F(2,30.20) = 23.36$, $p < .001$], /sa/
2 [$F(2,24.34) = 20.92$, $p < .001$], /ta/ [$F(2,28.10) = 13.30$, $p < .001$], indicating that the
3 difference in duration between closing and opening movements decreased with
4 increasing syllable repetition rate. Significant three-way interaction effects of group
5 by rate by direction were present in the metronome condition in /sa/ [$F(4,49.70) =$
6 4.57, $p = .003$] and /ta/ [$F(4,45.98) = 2.86$, $p = .034$] and the self-paced condition of
7 /sa/ [$F(2,24.34) = 5.75$, $p = .009$] and /ta/ [$F(2,28.10) = 5.06$, $p = .013$], indicating
8 that, especially at slower syllable repetition rates, the older adults showed a larger
9 difference in duration between closing and opening movements, compared to younger
10 adults.

11

12 Movement Amplitude

13 The analysis showed no significant main effects of group. Significant main effects of
14 rate were found in the metronome condition of /sa/ [$F(4,16.01) = 3.14$, $p = .014$], and
15 /ta/ [$F(4,15.65) = 7.38$, $p = .002$], as well as in the self-paced condition of /sa/
16 [$F(2,16.00) = 8.19$, $p = .004$]. Significant effects of direction were also found in the
17 metronome condition of /sa/ [$F(1,16.00) = 57.90$, $p < .001$], and /ta/ [$F(1,16.08) =$
18 6.69, $p = .020$], and in the self-paced condition of /sa/ [$F(1,16.00) = 25.91$, $p < .001$].
19 In these cases, an increase in rate was associated with a decrease in movement range,
20 and the mean amplitude of closing movements was larger compared to opening
21 movements. The group by rate interaction effect was significant in the metronome
22 condition of /ta/ [$F(4,15.65) = 5.64$, $p = .005$], and the rate by direction interaction
23 was significant in the metronome condition of /sa/ [$F(4,16.00) = 12.14$, $p < .001$], and
24 the self-paced conditions of /pa/ [$F(2,16.00) = 4.25$, $p = .033$] and /ta/ [$F(2,15.59) =$
25 4.41, $p = .030$], but inspection of the data did not reveal a clear pattern. An interaction

1 effect of group by direction was present in the self-paced condition of /ta/: [F(1,14.80)
2 = 9.71, $p = .007$], showing that the younger adults displayed slightly larger amplitudes
3 of closing movements compared to opening movements, while the older adults
4 displayed a slight reverse effect.

5

6 Peak Velocity

7 The results of the statistical analyses of peak velocity of articulatory movements
8 revealed no significant main effect of group. The main effect of rate was significant in
9 the metronome condition of /pa/: [F(4,16.00) = 7.43, $p = .001$], /sa/: [F(4,16.00) =
10 4.32, $p = .015$], and /ta/[F(4,15.76) = 14.89, $p < .001$], and the self-paced condition of
11 /pa/: F(2,16.00) = 11.91, $p = .001$], /sa/: [F(2,16.00) = 6.28, $p = .010$], and /ta/:
12 [F(2,15.78) = 8.12, $p = .004$], showing that an increase in syllable repetition rate was
13 associated with an increase in maximum velocity. A significant main effect of
14 direction was present in the metronome condition of /sa/: [F(1,16.00) = 14.22, $p =$
15 .002] and /ta/: [F(1,15.47) = 5.58, $p = .032$], and in the self-paced condition of /pa/
16 [F(1,16.00) = 17.33, $p = .001$], /sa/ F(1,16.00) = 20.54, $p < .001$], and /ta/ [F(1,16.08)
17 = 13.44, $p = .002$], indicating that the maximum velocity was higher in opening
18 movements, compared to closing movements. This difference decreased with an
19 increasing syllable repetition rate, indicated by significant rate by direction effects in
20 the metronome condition of /sa/ [F(4,16.00) = 9.60, $p < .001$] and /ta/ [F(4,15.61) =
21 6.50, $p = .003$], and in the self-paced conditions of /pa/ [F(2,16.00) = 15.71, $p < .001$,
22 /sa/ [F(2,16.00) = 12.26, $p = .001$], and /ta/ [F(2,15.58) = 9.34, $p = .002$]. A
23 significant interaction effect of group by rate in the metronome condition of /ta/
24 [F(4,15.65) = 5.26, $p = .007$] did not reveal a clear pattern. Significant interaction
25 effects of group by direction were present for /sa/ and /ta/ in the metronome

1 condition: $[F(1,16.00) = 11.18, p = .004]$ and $[F(1,15.47) = 4.56, p = .049]$, and the
 2 self-paced condition: $[F(1,16.00) = 10.27, p = .006]$ and $[F(1,16.08) = 8.38, p = .011]$,
 3 showing that the overall differences of maximum velocities between opening and
 4 closing movements were larger in older adults compared to younger adults.
 5 Furthermore, a significant three-way interaction effect of group by rate by direction
 6 was observable in the metronome condition of /sa/ $[F(4,16.00) = 3.33, p = .036]$, and
 7 the self-paced condition of /sa/ $[F(2,16.00) = 5.10, p = .019]$, and /ta/ $[F(2,15.58) =$
 8 $3.71, p = .048]$, indicating that both the direction and the rate effects were only
 9 present in the older adults, whereas no such effects were present in the younger
 10 adults. These findings show that, especially at slower syllable repetition rates, the
 11 older adults showed a larger difference in peak velocity between closing and opening
 12 movements, compared to younger adults.

13

14 **Cyclic Spatiotemporal Index**

15 Statistical analysis of the cSTI did not reveal differences between younger and older
 16 adults as evidenced by a non-significant group effect. A significant effect of rate was
 17 present in all tasks in the metronome condition: /pa/: $[F(4,16.00) = 9.11, p < .001]$,
 18 /sa/: $F(4,16.00) = 4.86, p = .009]$, /ta/: $[F(4,16) = 4.20, p = .016]$, and all tasks in the
 19 self-paced condition: /pa/: $[F(2,16.00) = 19.23, p < .001]$, /sa/: $[F(2,16.00) = 4.17, p =$
 20 $.035]$, and /ta/: $[F(2,16.00) = 12.35, p < .001]$, indicating that cSTI decreased with
 21 increasing syllable repetition rate. A significant interaction effect of group by rate was
 22 present in the self-paced condition of /pa/ $[F(2,16.00) = 13.33, p < .001]$ and the
 23 metronome paced condition of /sa/ $[F(4,16.00) = 3.12, p = .045]$, but further group
 24 comparisons revealed no clear pattern.

1

2 **Discussion**

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

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

1 With respect to the amplitude of articulatory movements, the younger and
2 older adults reduced tongue movement amplitude with increasing speech rate in both
3 pacing conditions for /sa/ and in the self-paced condition of /ta/. During these speech
4 tasks closing movements were larger than opening movements. This asymmetry
5 suggests that speakers increased or decreased their speech rate during trial repetitions
6 [17]. However, since tongue tip movements were not corrected for jaw movements, it
7 cannot be ruled out that jaw movements contributed to the results found, and should
8 be confirmed in future research.

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

17 How can the current kinematic findings be explained in the absence of speed
18 or stability limitations? In experimental tasks where capacities have to be distributed
19 across articulation rate and stability, speakers may focus on one or the other,
20 depending on their skills and task priorities [11]. Contrary to our hypothesis, the
21 results of the present study showed that older adults realized equal and faster syllable
22 repetition rates compared to the young group, without changes in articulation stability.
23 With increasing rates, movements made by older adults became more similar, in that
24 the differences in duration and peak velocity between closing and opening movements
25 decreased, mimicking the pattern typically displayed by the younger adults. Greater

1 similarity between opening and closing movement sequences often reflects a more
2 open loop or ballistic type of motor control [8,15]. Vice versa, the current findings
3 that the older adults -but not the younger adults- increased the duration (and decreased
4 peak velocity) of closing movements more than opening movements at slower rates
5 can be interpreted as the result of a less ballistic mode of control. It has been
6 demonstrated that slowing down articulation facilitates closed loop (feedback based)
7 control, enabling the online detection of movement errors and subsequent
8 computation and integration of corrections [22]. At faster rates, closed loop control is
9 not possible, as corrective movements are ineffective for on-going speech sound
10 sequences [23]. Based on the present results, we hypothesize that older adults may
11 utilize a control strategy facilitating feedback control of tongue movements when
12 speaking at a relatively slower rate. This might be linked to age-related changes in
13 cognitive processing during speech and/or structural changes in the speech production
14 system. For example, several studies suggested that aging is related to a decrease in
15 general oral sensory function [24,25]. Specifically, Weismer and Liss [1] suggested
16 an age-related decrease in proprioception for active tongue movements based on their
17 findings that older adults were less able to judge the required durations and velocities
18 of lifting the tongue in executing speech tasks. If indeed with increasing age the
19 quality of somatosensory information of (especially) tongue movements decreases,
20 this could force older adults to adapt control strategies, in particular with a stronger
21 reliance on closed loop control. We speculate that for older speakers, the stronger
22 slowing down of closing movements may compensate for a reduced quality of
23 sensory information, enabling the use of closed loop control and allowing a more
24 extensive processing. If this were true, kinematic differences with respect to duration
25 and peak velocity of closing movements between older and younger speakers would

1 disappear when speakers are forced to use a more open loop control through a
2 paradigm that masks auditory feedback (through noise) and (part of) proprioceptive
3 feedback (through tendon vibration), possibly at the cost of a reduced articulatory
4 stability for older speakers. These apparent age-related differences in speech motor
5 control as a function of self-paced and externally timed repetition rates are in line
6 with earlier studies using syllable repetition experiments to study speech performance
7 in clinical populations [e.g. 26], and can provide insight in limitations in speech
8 production due to age and its relationship to potentially affected neural systems.
9 Speech motor control reserve capacities in healthy aging speakers may mask speech
10 problems, and only when additional disease processes affecting the oromotor control
11 system appear (in particular dysarthria), a divergent speech output becomes more
12 salient [26,27].

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

21

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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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