International Journal of Speech-Language Pathology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/iasl20

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To cite this article: Leenke van Haaften, Sanne Diepeveen, Hayo Terband, Bert De Swart, Lenie Van Den Engel-Hoek & Ben Maassen (2021) Maximum repetition rate in a large cross-sectional sample of typically developing Dutch-speaking children, International Journal of Speech-Language Pathology, 23:5, 508-518, DOI: 10.1080/17549507.2020.1865458

To link to this article: https://doi.org/10.1080/17549507.2020.1865458

Published online: 19 Feb 2021.

International Journal of Speech-Language Pathology, 2021; 23: 508–518

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Maximum repetition rate in a large cross-sectional sample of typically developing Dutch-speaking children

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Abstract

Purpose: The current study aims to provide normative data for the maximum repetition rate (MRR) development of Dutch-speaking children based on a large cross-sectional study using a standardised protocol.
Method: A group of 1014 typically developing children aged 3;0 to 6;11 years performed the MRR task of the Computer Articulation Instrument (CAI). The number of syllables per second was calculated for mono-, bi-, and trisyllabic sequences (MRR-pa, MRR-ta, MRR-ka, MRR-pata, MRR-taka, MRR-pataka). A two-way mixed ANOVA was conducted to compare the effects of age and gender on MRR scores in different MRR sequences.
Result: The data analysis showed that overall MRR scores were affected by age group, gender and MRR sequence. For all MRR sequences the MRR increased significantly with age. MRR-pa was the fastest sequence, followed by respectively MRR-ta, MRR-pata, MRR-taka, MRR-ka and MRR-pataka. Overall MRR scores were higher for boys than for girls, for all MRR sequences.
Conclusion: This study presents normative data of MRR of Dutch-speaking children aged 3;0 to 6;11 years. These norms might be useful in clinical practice to differentiate children with speech sound disorders from typically developing children. More research on this topic is necessary. It is also suggested to collect normative data for other individual languages, using the same protocol.

Keywords: *maximum repetition rate; diadochokinesis; speech development; motor speech; normative data; children*

Introduction

Maximum repetition rate (MRR), or *diadochokinesis*, involves alternating motion rate tasks comprising speech like syllables (Kent, 2015). MRR is one of the most commonly used oral-motor assessments in clinical practice (Icht & Ben-David, 2014; Williams & Stackhouse, 2000). It is suggested as an important part of a test battery to differentiate between various speech disorders (Diepeveen, Van Haaften, Terband, De Swart, & Maassen, 2019; Maassen & Terband, 2015; Terband, Maassen, & Maas, 2019). However, there is also still a debate about the clinical value of the MRR. A higher-faster-farther approach might not be a good assessment because in speech speed is not a necessary skill (Ziegler et al., 2019). Although this is the case, MRR can play a role in diagnosing underlying articulomotor planning and programming problems (Maassen & Terband, 2015; Rvachew et al., 2005; Van Haaften, Diepeveen, Terband et al., 2019). MRR is therefore often used in the assessment of children with a suspicion of a motor speech disorder (MSD) and/or childhood apraxia of speech (CAS) (Murray, McCabe, Heard, & Ballard, 2015; Thoonen, Maassen, Gabreels, & Schreuder, 1999), and it has been used in the characterisation of speech language phenotypes (e.g. Peter et al., 2017; Peter, Matsushita, & Raskind, 2012; Turner et al., 2015). To be able to interpret the results of the MRR adequately, it must be part of a set of speech tasks. By comparing the results of the MRR task with the results of other tasks (i.e. picture naming, nonword repetition) a complete speech profile can be obtained. The results of the MRR should not be used solely to

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ISSN print/ISSN online © 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
Published by Taylor & Francis
DOI: 10.1080/17549507.2020.1865458

diagnose children with speech sound disorders, because many children with SSD show similar behavioural symptoms in speech. The traditional way of diagnosing children with SSD might not be sufficient, because the different levels involved in speech influence each other (Namasivayam et al., 2019). The underlying processes involved in speech production are lemma access, word form selection, phonological encoding, speech motor planning and programming, and speech motor execution (Terband et al., 2019). Insight into the deficits that might be the underlying causes of an SSD, requires an extensive analysis of a child's performance on a range of speech tasks that reflect different underlying processes. A study of our research group (Van Haaften, Diepeveen, Van den Engel-Hoek et al., 2019) showed the distinctive function of four different speech tasks of a new speech production test battery for children: the Computer Articulation Instrument (CAI). The CAI contains the tasks picture naming, nonword imitation, word and nonword repetition and MRR. Factor analyses were conducted based on the assumption that clusters of selected parameters would reflect different aspects of speech production, either within or across tasks. Factor analyses revealed five meaningful factors: all picture-naming parameters (PN), the segmental parameters of nonword imitation (NWI-Seg), the syllabic structure parameters of nonword imitation (NWI-Syll), (non)word repetition consistency (PWV), and all MRR parameters. Each task reflects different aspects of speech production. Furthermore, the construct validity was underlined by the weak correlations between CAI factor scores, indicating the independent contribution of each factor to the speech profile. In another study with 41 children (age 3;0 to 6;4; 26 boys and 15 girls) with SSD data were collected from the four tasks of the CAI. The children were categorised in two groups, moderate or a severe SSD indicated by their speech-language pathologist (SLP). Results indicated a significant difference between the two groups for picture naming, nonword imitation (segmental and syllable structure) and the bisyllabic and trisyllabic MRR factor (Van Haaften, Diepeveen, Terband et al., 2019). The findings of these two studies suggest that the MRR should be part of the diagnostic process. Normative data of MRR is essential to differentiate children with delayed or disordered speech development from typically developing children. The availability of these data is important for SLPs to make clinical decisions.

Several studies have investigated MRR in typically developing children. The overall conclusion, across languages, is that MRR increases with age. Contrasting results were found in studies investigating gender differences and differences between specific MRR sequences. Some studies found differences between boys and girls (Modolo, Berretin-Felix, Genaro, & Brasolotto, 2011) or between MRR sequences (Blech, 2010; Prathanee, Thanaviratananich, & Pongjanyakul, 2003), while other studies found no differences between gender (Fletcher, 1972; Icht & Ben-David, 2015; Wong, Allegro, Tirado, Chadha, & Campisi, 2011; Zamani, Rezai, & Garmatani, 2017) or MRR sequence (Rvachew, Ohberg, & Savage, 2006; Thoonen, Maassen, Wit, Gabreels, & Schreuder, 1996). However, considerable methodological differences exist between the studies, with different methods of data collection and different scoring methods of MRR. Several studies used a time-by-count procedure (the time needed to repeat a certain number of syllables) (Blech, 2010; Fletcher, 1972; Prathanee et al., 2003; Rvachew et al., 2006; Thoonen et al., 1999; Thoonen et al., 1996; Yaruss & Logan, 2002; Zamani et al., 2017), while in other studies a procedure of count-by-time was used (the number of syllables repeated in a certain amount of time) (Henry, 1990; Icht & Ben-David, 2015; Juste et al., 2012; Modolo et al., 2011; Robbins & Klee, 1987). Because of these methodological differences, the normative data is difficult to compare. To reduce these differences, a standardised protocol is proposed in a study by Diepeveen et al. (2019). In this protocol, it is suggested that MRR should not be assessed in children under the age of 3 years. The maximum age up to seven years has been chosen, because previous research has shown that speech sound development continues up to seven years (Priester and Goorhuis-Brouwer, 2013). Monosyllabic sequences and bi- and trisyllabic sequences should be described as separate outcome measures and if children cannot produce the monosyllabic sequences, the bi- and trisyllabic sequences should not be administered. Nonsense syllabic sequences are used instead of real words as MRR is supposed to measure motor speech abilities rather than linguistic skills (Williams & Stackhouse, 2000). The measurement procedure follows the time-by-count principle. The data indicates that children do not have to be encouraged to perform series of at least ten syllables, but that series of five syllables is sufficient for a reliable and valid calculation of the MRR (Diepeveen et al., 2019). After exclusion of the first and last syllable, the mean rate is then based on the duration of at least three syllables.

Most of the MRR studies in typically developing children are based on a small number of children and relatively limited age ranges (Blech, 2010; Prathanee et al., 2003; Rvachew et al., 2006; Thoonen et al., 1999; Thoonen et al., 1996; Wong et al., 2011; Yaruss & Logan, 2002). As typically developing children show progress in speech motor skills as they grow older, normative data are required for consecutive age groups. Therefore, the aim of the present study is to provide normative data for the MRR development of Dutch-speaking children aged 3;0 to 6;11 years based on a large cross-sectional study using the standardised protocol by Diepeveen et al. (2019). Differences between age groups, gender and MRR sequences are described.

Table I. Sample composition: numbers of children per age group, broken down by gender.

Age group (years;months)	Total number of children	M_{age}	Gender (*n*) Boys	Girls
3;0-3;3	68	3;01	32	36
3;4-3;7	65	3;05	34	31
3;8-3;11	86	3;08	46	40
4;0-4;3	77	4;01	42	35
4;4-4;7	90	4;05	48	42
4;8-4;11	93	4;08	43	50
5;0-5;3	103	5;01	54	49
5;4-5;7	111	5;05	61	50
5;8-5;11	104	5;08	55	49
6;0-6;5	108	6;02	63	45
6;6-6;11	109	6;07	53	56
Grand total	1014		531	483
% sample	100		52.4	47.6

Method

Participants

The 1014 participants of this study participated in a large normative study in the context of the development of a new speech production test battery in Dutch: the Computer Articulation Instrument (CAI; Maassen et al., 2019; Van Haaften, Diepeveen, Van den Engel-Hoek et al., 2019). The CAI consists of four tasks: (1) picture naming, (2) nonword imitation, (3) word and nonword repetition, and (4) maximum repetition rate (MRR) task. The data of the MRR task was used for the current study. Between January 2008 and April 2015, typically developing Dutch-speaking children aged between 2;0 and 7;0 were recruited via nurseries ($n = 47$) and mainstream primary schools ($n = 71$) in the Netherlands. Inclusion criteria were no hearing loss and Dutch being the spoken language at the nursery or primary school. The sample was representative for gender, geographic region and degree of urbanisation (Van Haaften, Diepeveen, Van den Engel-Hoek et al., 2019). The parents or caregivers were asked to fill out a questionnaire containing questions about hearing problems, speech and language development, developmental problems and whether the child is seen by an SLP. Children were excluded if they had developmental problems that could influence the speech performance. See Maassen et al. (2019) and Van Haaften, Diepeveen, Van den Engel-Hoek et al. (2019) for detailed information on sample characteristics and data collection. As Diepeveen et al. (2019) concluded that the MRR protocol of the CAI is applicable for children of 3 years and older, this study only used the data of children aged between 3;0 and 7;0, divided in 11 age groups. Table I shows the number of children per MRR sequence per age group and gender.

Ethical considerations

The research ethics committee of the Radboud University Nijmegen Medical Centre stated that this study does not fall within the remit of the Medical Research Involving Human Subjects Act (WMO). Therefore, this study can be carried out (in the Netherlands) without an approval by an accredited research ethics committee. The study was conducted according to the ethical principles and guidelines in the Netherlands. For example, informed consent was obtained from all parents or caregivers.

Procedure

In the CAI project 14 SLPs administrated the test for the younger children (2 to 4 years of age) and 110 SLP students (working in pairs) assessed the older children (4 to 7 years of age). All assessors were trained in the administration of the MRR task by the first two authors. The assessment took place at the child's nursery or primary school in a quiet room. The CAI was administered using a computer laptop and the acoustic signal (minimum of 44.1 Hz; 16 bits) was automatically stored on the computer's hard disc. The child and SLP or SLP student were seated side by side in front of the computer. Both wore a headset, or a speaker and microphone were used. Testing took approximately 30 minutes for all the tasks of the CAI. The administration of the MRR task took about five to ten minutes per child.

MRR administration

For the administration of the MRR task the CAI uses the protocol described by Diepeveen et al. (2019). This protocol was developed based on previous studies in the Dutch language (Thoonen et al., 1999; Thoonen et al., 1996; Wit, Maassen, Gabreels, & Thoonen, 1993). Instructions were given by the CAI computer program to maximise standardisation. During the task children are required to reproduce pre-recorded sequences on one single breath: first three monosyllabic sequences (/papa./, /tata./ and /kaka./), followed by one trisyllabic sequence (/pataka … /) and finally two bisyllabic sequences (/pata./ and /taka./). It was not possible to change the order of sequences; the computer program was fixed.

First, the children were asked to repeat a short sequence of three syllables (e.g. /papapa/) in a normal speaking rate after an audio model. Second, children were asked to repeat a longer sequence of six syllables in a normal rate (e.g. /papapapapapa/). The third

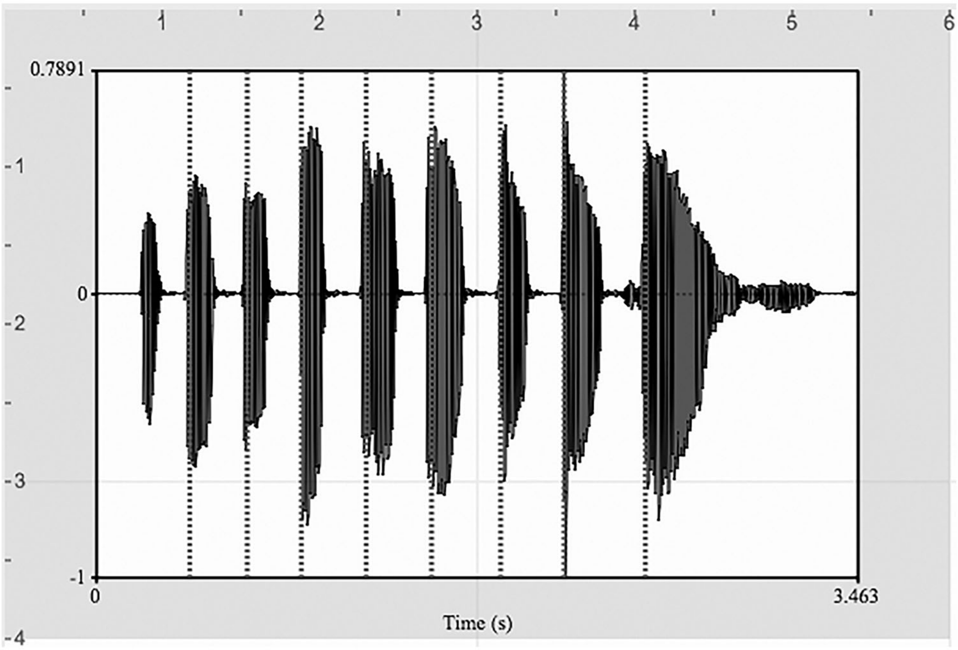

Figure 1. Example of the analysis with the Praat-script of one of the maximum repetition rate sequences.

instruction included imitation of a sequence of 12 syllables at a faster speech rate after an audio example. Finally, the children were asked to produce the syllable sequences as fast as possible, without an audio model. The CAI allows a maximum of three attempts per sequence.

MRR analysis

Six SLP students of HAN University of Applied Sciences and three SLPs analysed the mono-, tri- and bi-syllabic sequences according to the analysis protocol for calculating the MRR proposed by Diepeveen et al. (2019). They were trained by one of the first authors (SD) and practiced with one sample before analysing the other samples. Since the program stores all tasks and all trials of a child in one recording, the recordings were spliced into fragments per trial manually with Praat software, version 6.0.21 (Boersma & Weenink, 2016). First the administrator determined if the sequence was pronounced correctly. The sequence was correct when the syllables were pronounced fluently in succession and had no articulation errors, allowing for dialect variances. The test administrator analysed the attempts the child has produced upon the last two instructions, calculated the syllables per second and recorded this in the database. The audio-recordings, each containing just one attempt of one sequence, were analysed with the help of a customised Praat-script (developed by one of the authors; HT). The script detected and marked syllable onsets by localising the noise burst of the voiceless plosives. The first and the last syllable were excluded because speakers often produce the first syllable with a longer duration and higher intensity (Thoonen et al., 1996) and the last syllable is also often lengthened (Ackermann, Hertrich, & Hehr, 1995). Before extracting the number of syllables, syllable durations and MRR score, the marked syllable onsets were depicted in the waveform and inspected visually and any errors in the number of syllables indicated by the script were corrected manually. Figure 1 gives an example of one of the sequences with the markers. Only sequences with a remaining minimum of three syllables, after exclusion of the first and last syllable, were included in the analysis. In 30% of the cases, the script could not detect syllable onsets correctly. These samples were analysed manually to determine the number of syllables and the duration of the sequence; administrators used both visual examination of the waveform and playback of the audio recording. In the pilot study for our MRR-protocol, we studied the reliability ($n = 126$) between the computer script and the manually analysed recordings. The intraclass correlation coefficients (ICCs) were sufficient to good: /pa/= .79; /ta/= .90; /ka/= .85; /pataka/= .74; /pata/= .79; /taka/= .76. MRR score was calculated by dividing the number of syllables of the sequence by the duration of the sequence (syll/s). Eventually, number of syllables, duration time, and MRR score were merged in SPSS, version 24 for Windows (SPSS Inc., Chicago, IL, USA). The fastest correctly produced series of syllables, based on the number of syllables, is used for analysis.

Not all children completed all MRR sequences for reasons of shyness or inattentiveness. Furthermore, in some cases the audio files were damaged due to technical problems or background noise that prevented recognising the individual syllables. In this case, the recordings were excluded from the sample. Table II shows the number of children from whom an analysable MRR sequence was collected.

Table II. Descriptive statistics (means and standard deviations) of the maximum repetition rate (MRR) score (syll/s) per age group and gender, broken down by MRR sequence.

			MRR sequence					
Gender	Age group		MRR-pa	MRR-ta	MRR-ka	MRR-pataka	MRR-pata	MRR-taka
Total	3;0–3;3	*n*	37	37	37	37	37	37
		M	3.95	3.91	3.66	3.40	4.01	3.81
		SD	0.59	0.56	0.46	0.55	0.88	0.78
	3;4–3;7	*n*	38	38	38	38	38	38
		M	4.06	4.06	3.76	3.54	3.99	4.08
		SD	0.50	0.51	0.57	0.83	0.60	0.82
	3;8–3;11	*n*	51	51	51	51	51	51
		M	4.15	4.11	3.84	3.74	4.03	4.07
		SD	0.52	0.67	0.53	0.87	0.79	0.83
	4;0–4;3	*n*	60	60	60	60	60	60
		M	4.27	4.17	4.00	3.82	4.35	4.25
		SD	0.57	0.61	0.54	0.73	0.90	0.78
	4;4–4;7	*n*	77	77	77	77	77	77
		M	4.59	4.40	4.14	3.88	4.41	4.38
		SD	0.51	0.57	0.54	0.82	0.76	0.74
	4;8–4;11	*n*	77	77	77	77	77	77
		M	4.55	4.42	4.20	3.93	4.49	4.47
		SD	0.67	0.62	0.56	0.90	0.97	0.83
	5;0–5;3	*n*	87	87	87	87	87	87
		M	4.64	4.40	4.33	4.04	4.49	4.36
		SD	0.54	0.59	0.48	0.79	0.70	0.84
	5;4–5;7	*n*	97	97	97	97	97	97
		M	4.82	4.69	4.37	4.14	4.68	4.53
		SD	0.55	0.54	0.46	0.83	0.72	0.57
	5;8–5;11	*n*	94	94	94	94	94	94
		M	4.83	4.70	4.45	4.35	4.55	4.70
		SD	0.62	0.62	0.47	0.89	0.84	0.80
	6;0–6;5	*n*	99	99	99	99	99	99
		M	4.96	4.87	4.48	4.37	4.86	4.64
		SD	0.51	0.66	0.49	0.96	0.91	0.72
	6;6–6;11	*n*	103	103	103	103	103	103
		M	5.03	4.92	4.63	4.51	4.80	4.96
		SD	0.56	0.59	0.56	0.86	0.83	0.78
	Total	*n*	820	820	820	820	820	820
		M	4.64	4.52	4.26	4.07	4.51	4.48
		SD	0.64	0.67	0.58	0.90	0.86	0.81
Boys	3;0–3;3	*n*	18	18	18	18	18	18
		M	3.95	3.86	3.63	3.28	4.14	3.57
		SD	0.56	0.62	0.52	0.68	1.06	0.78
	3;4–3;7	*n*	21	21	21	21	21	21
		M	4.24	4.18	3.87	3.58	4.23	4.24
		SD	0.48	0.47	0.66	0.64	0.53	0.84
	3;8–3;11	*n*	28	28	28	28	28	28
		M	4.27	4.22	3.90	3.90	4.14	4.21
		SD	0.45	0.76	0.53	1.00	0.82	0.93
	4;0–4;3	*n*	33	33	33	33	33	33
		M	4.36	4.31	4.03	4.00	4.52	4.19
		SD	0.51	0.66	0.60	0.73	0.96	0.89
	4;4–4;7	*n*	38	38	38	38	38	38
		M	4.64	4.39	4.29	3.83	4.45	4.35
		SD	0.49	0.59	0.57	0.77	0.92	0.73
	4;8–4;11	*n*	37	37	37	37	37	37
		M	4.51	4.51	4.18	3.94	4.50	4.46
		SD	0.75	0.58	0.64	1.03	1.03	0.95
	5;0–5;3	*n*	44	44	44	44	44	44
		M	4.68	4.49	4.34	4.04	4.65	4.44
		SD	0.59	0.71	0.47	0.77	0.71	0.97
	5;4–5;7	*n*	56	56	56	56	56	56
		M	4.80	4.68	4.30	4.26	4.66	4.48
		SD	0.55	0.57	0.47	0.94	0.74	0.57
	5;8–5;11	*n*	52	52	52	52	52	52
		M	4.90	4.76	4.46	4.39	4.55	4.69
		SD	0.72	0.62	0.53	0.90	0.80	0.84
	6;0–6;5	*n*	57	57	57	57	57	57
		M	4.94	4.96	4.55	4.43	4.92	4.71
		SD	0.50	0.72	0.5	1.11	0.95	0.80
	6;6–6;11	*n*	51	51	51	51	51	51
		M	5.21	4.98	4.62	4.53	4.98	5.02
		SD	0.63	0.59	0.59	0.86	0.92	0.83
	Total	*n*	435	435	435	435	435	435
		M	4.70	4.59	4.29	4.13	4.60	4.49
		SD	0.66	0.70	0.60	0.94	0.89	0.87
Girls	3;0–3;3	*n*	19	19	19	19	19	19
		M	3.95	3.97	3.69	3.51	3.89	4.03
		SD	0.63	0.49	0.40	0.38	0.69	0.72
	3;4–3;7	*n*	17	17	17	17	17	17
		M	3.84	3.91	3.61	3.49	3.69	3.88
		SD	0.44	0.54	0.41	1.04	0.55	0.77
	3;8–3;11	*n*	23	23	23	23	23	23
		M	4.02	3.98	3.75	3.54	3.90	3.89
		SD	0.57	0.54	0.53	0.65	0.75	0.67

(*Continued*)

Table II. (*Continued*).

Gender	Age group		MRR sequence					
			MRR-pa	MRR-ta	MRR-ka	MRR-pataka	MRR-pata	MRR-taka
	4;0–4;3	*n*	27	27	27	27	27	27
		M	4.17	3.97	3.97	3.61	4.15	4.32
		SD	0.63	0.51	0.46	0.68	0.81	0.62
	4;4–4;7	*n*	39	39	39	39	39	39
		M	4.54	4.41	4.00	3.92	4.36	4.42
		SD	0.52	0.56	0.47	0.88	0.57	0.76
	4;8–4;11	*n*	40	40	40	40	40	40
		M	4.59	4.34	4.22	3.92	4.48	4.48
		SD	0.60	0.65	0.49	0.79	0.92	0.71
	5;0–5;3	*n*	43	43	43	43	43	43
		M	4.60	4.30	4.31	4.04	4.33	4.28
		SD	0.48	0.44	0.49	0.83	0.65	0.68
	5;4–5;7	*n*	41	41	41	41	41	41
		M	4.85	4.69	4.47	3.98	4.72	4.59
		SD	0.54	0.51	0.43	0.63	0.70	0.56
	5;8–5;11	*n*	42	42	42	42	42	42
		M	4.74	4.61	4.45	4.29	4.54	4.71
		SD	0.46	0.61	0.39	0.88	0.89	0.76
	6;0–6;5	*n*	42	42	42	42	42	42
		M	4.99	4.74	4.38	4.30	4.79	4.54
		SD	0.52	0.57	0.43	0.71	0.86	0.61
	6;6–6;11	*n*	52	52	52	52	52	52
		M	4.86	4.86	4.64	4.50	4.63	4.91
		SD	0.43	0.60	0.54	0.87	0.69	0.72
	Total	*n*	385	385	385	385	385	385
		M	4.58	4.44	4.23	4.02	4.42	4.46
		SD	0.62	0.63	0.55	0.84	0.80	0.74

Note. *n*: number of children from whom an MRR sequence was analysed; *M*: mean of the MRR score (syll/s); *SD*: standard deviation of the mean MRR score (syll/s); MRR-pa: number of syllables per second of sequence /pa/; MRR-ta: number of syllables per second of sequence /ta/; MRR-ka: number of syllables per second of sequence /ka/; MRR-pataka: number of syllables per second of sequence /pataka/; MRR-pata: number of syllables per second of sequence /pata/; MRR-taka: number of syllables per second of sequence /taka/.

Reliability

Interrater and test-retest reliability of the MRR scores (syll/s) were examined and described by Van Haaften, Diepeveen, Van den Engel-Hoek et al. (2019). In this study, typically developing children aged between 2;0 and 7;0 were included. To measure interrater reliability the audio recordings of 103 children were randomly selected and scored by 33 raters. Their MRR scores were compared with those of one independent rater. A total of 107 children were randomly selected for the test-retest reliability study; these children were examined twice within three months by the same administrator. Two raters scored the audio recording of the initial test and retest, with the same rater scoring the tests of the same child. Interrater reliability, calculated with interclass correlation coefficient (ICC), was good for the monosyllabic sequences /pa/ (ICC 0.81) and /ka/ (ICC 0.83) and sufficient for /ta/ (ICC 0.77). The interrater reliability for the bisyllabic and trisyllabic items was insufficient, with ICCs ranging from 0.41 to 0.62. Especially the younger children (i.e. the 2- to 3-year-olds) had difficulties performing the bisyllabic and trisyllabic items, whereas a large number of children were not able to perform the task at all. The data of children who failed to perform the task were not included in the reliability study; had we included whether the attempts were successful or not, the ICC might have been higher. Another factor that might have influenced the low interrater reliability is that judging whether the sequences of the bisyllabic and trisyllabic items were produced correctly is more difficult than it is for the monosyllabic items because the younger children made more errors of pronunciation (Van Haaften, Diepeveen, Van den Engel-Hoek et al., 2019). To measure interrater reliability the audio recordings of 103 children were randomly selected and scored by 33 raters. Their scores were compared to those of one independent rater. The calculation of ICC involves dividing the between-speaker variability by the total variability (similar to ANOVA). The total variability can be modelled as consisting of the between-speaker variability (BV) plus the within-speaker variability, or – in case of a reliability study – error variance (EV). This implies that the higher number of raters in our study as compared to comparable studies, could have caused more variation between ratings of the same speaker (higher value of EV) and this results in a lower ICC. At the same time, however, because we used this number of raters ($n = 33$), our study may be a good reflection of the professional field, with the ICCs we obtained being representative of clinical practice.

Test-retest reliability was sufficient for /pa/ (ICC 0.70) and insufficient for the other sequences, with ICCs ranging from 0.18 to 0.60. Reasons for these low scores could be the rapid development of the younger children during the interval between test and retest or a test-retest training effect. Based on these results, and the results of the study of Diepeveen et al. (2019), the younger children aged between 2;0 and 3;0 were not included in the current study. Further details and interpretations of the reliability study are discussed in Van Haaften, Diepeveen, Van den Engel-Hoek et al. (2019).

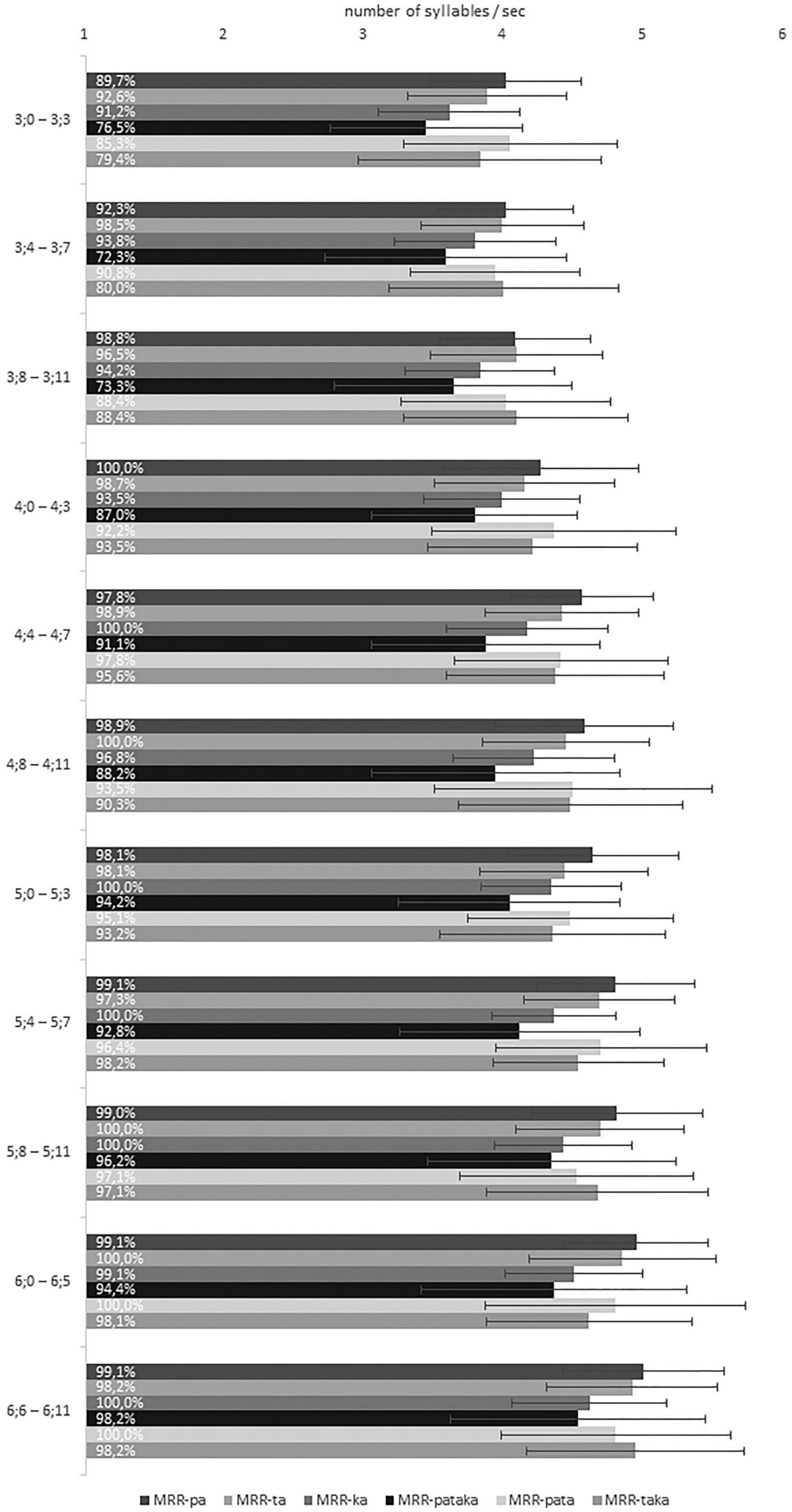

Figure 2. Mean number of syllables / second per age group and per sequence. The percentage of children able to perform the task (in relation to the total number of children of the respective age group) are shown at the beginning of the bars.

Statistical analysis

To compare the effects of age and gender on MRR scores in different MRR sequences, and to test the hypotheses that there is a difference between the six MRR sequences and between boys and girls for the 11 age groups, a two-way mixed ANOVA was conducted. MRR score (syll/s) was the dependent variable, MRR sequence was the within-subject factor with six levels (MRR-pa, MRR-ta, MRR-ka, MRR-pataka, MRR-pata, MRR-taka), and there were two between-subject factors: age group (11 age groups) and gender (2 levels: boys and girls). Mauchly's test of Sphericity was conducted to test the hypothesis that the variances of differences between conditions are equal. Bonferroni correction was applied for post hoc comparisons. Statistical analyses were performed using SPSS version 20 for Windows (SPSS Inc., Chicago, IL, USA).

Result

The results of the mean number of syllables/second per age group and per sequence are presented in Figure 2. The percentage of children (in relation to the total number of children of the respective age group) who could perform the sequence correctly (fluently in succession; no articulation errors, allowing for dialect variances) is shown at the beginning of the bars.

The mean and standard deviations of each MRR sequence are depicted by age group and gender in Table II, showing data of children who could perform all the six sequences correctly. Mauchly's test indicated that the assumption of sphericity was violated [χ^2 (14) = 521.6, $p < .001$], therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .85$).

The two way mixed ANOVA revealed a significant effect of the within-subject factor "MRR sequence" ($F(4.24, 3382.89) = 100.16$, $p < .001$, effect size or partial $\eta^2 = .112$), which means that the MRR scores were significantly different for the MRR sequences. Post hoc analyses showed that the difference between mean MRR scores was significant for most of the pairwise comparisons, but was not significant between MRR-ta and the bi-sylabic sequences MRR-pata ($p = 1.000$) and MRR-taka ($p = 1.000$), nor between MRR-pata and MRR-taka ($p = 1.000$). The fastest sequence is MRR-pa ($M = 4.64$, $SD = 0.64$) and the slowest sequence is MRR-pataka ($M = 4.07$, $SD = 0.90$), see Table II.

The effect of between-subject factor "age group" was also significant ($F(10, 798) = 29.96$, $p < .001$, effect size or partial $\eta^2 = .273$). The number of syllables per second increased with age for all MRR sequences. As shown in Table II, MRR sequences increased on average with 1.02 syllables per second from the youngest to the oldest age group.

The statistical analysis also yielded a significant effect of the between-subject factor "gender" on overall MRR scores ($F(1, 798) = 9.49$, $p = .002$, effect size or partial $\eta^2 = .012$). As shown in Table II, MRR scores were higher for boys than for girls for all MRR sequences.

No significant interaction was found between "MRR sequence" and "age group" ($F(42.39, 3382.89) = 1.181$, $p = .196$, effect size or partial $\eta^2 = .015$), "MRR sequence" and "gender" ($F(4.24, 3382.89) = 2.172$, $p = .066$, effect size or partial $\eta^2 = .003$), "age group" and "gender" ($F(10, 798) = .876$, $p = .555$, effect size or partial $\eta^2 = .011$), or "MRR sequence" and "age group" and "gender" ($F(42.39, 3382.89) = 1.069$, $p = .351$, effect size or partial $\eta^2 = .013$).

Discussion

This study presents normative data of MRR from a large population of Dutch-speaking children aged 3;0 to 6;11 years. Tight ranges of age groups were used to be able to examine the relationship between age and MRR score. A cross-sectional study was performed, using a standardised protocol (Diepeveen et al., 2019). This protocol was used for both the administration of the MRR task and the analysis of the MRR scores. Effects of age, MRR sequence and gender were investigated.

Effect of age on MRR scores

For all MRR sequences the number of syllables per second increased significantly and monotonously with age. No interaction was found between MRR sequence and age group. The MRR score of all sequences was about 1 syllable per second faster for the oldest age group when compared with the youngest age groups. These results are in accordance with the findings in previous studies (Henry, 1990; Icht & Ben-David, 2015; Juste et al., 2012; Modolo et al., 2011; Prathanee et al., 2003; Robbins & Klee, 1987; Zamani et al., 2017). Thus, MRR score increases with age, which is likely to be caused by maturation of the speech motor system (Kent, Kent, & Rosenbek, 1987). Our study included children from 3;0 to 6;11 years of age. Fletcher (1972) found an increase of MRR score in a study with 48 children between the ages of 6;0 and 13;0 years. Wong et al. (2011) demonstrated that MRR score still increases up to the age of 18 years. Between 18 and 60 years of age, Knuijt, Kalf, Van Engelen, Geurts, and de Swart (2019) found stable MRR scores, with a decrease in maximum number of syllables per second from 60 years of age. To conclude, the increase in MRR score seen in the current study in children aged 3 to 7 years is in line with the results of other studies in older children and with studies in adults.

Effect of MRR sequences on MRR scores

The present results show that at the group level typically developing children produce the monosyllabic sequence MRR-ta slower than MRR-pa, and MRR-ka was slower than MRR-pa and MRR-ta. This is in agreement to similar studies with children (Kent et al., 1987; Prathanee et al., 2003; Robbins & Klee, 1987; Rvachew et al., 2006; Thoonen et al., 1996) and adults (Knuijt et al., 2019; Padovani, Gielow, & Behlau, 2009). The production of velar sounds takes longer than the production of alveolar and lip sounds. This might be due to the involvement of physiological factors. The production of /ka/ requires movement of the tongue dorsum, which has a larger mass than the tongue tip, required for pronouncing /ta/; larger inertia of the larger mass, might be (part of) the explanation. The difference in speed between MRR-pa and MRR-ta, with MRR-ta being slower, could be explained by an earlier neurological maturation of jaw and lip movements as compared to tongue tip movements. Lip and jaw movements stabilise earlier in speech motor control development as compared to tongue movement (Terband, Maassen, Van Lieshout, & Nijland, 2011; Terband, Van Brenk, Van Lieshout, Nijland, & Maassen, 2009).

Taken all MRR sequences into account, our results show that MRR-pataka is the slowest sequence, which is probably due to the fact that the motor program of trisyllabic sequences is more complex than mono- or bisyllabic sequences (Wright et al., 2009). Furthermore, it can also be due to physiological aspects as described above. However, contradictory results are described in previous studies. In the studies of Rvachew et al. (2006) and Thoonen et al. (1996) the monosyllabic sequences were slower than the trisyllabic sequences, whereas several other studies found that in their population the MRR-pataka was slower than the monosyllabic sequences (Blech, 2010; Modolo et al., 2011; Wong et al., 2011). Differences in these outcomes are probably due to the use of different protocols. In addition to other studies, our study also investigated the MRR rate of bisyllabic sequences. The mean MRR rate of both bisyllabic sequences was similar to MRR-ta, and thus faster than the production of the monosyllabic sequence MRR-ka. Also, no previous studies have described normative data of MRR scores based on such a large representative sample as in our study. To summarise, the data of our study shows influences from *physiological factors*; larger movement inertia of the tongue body as compared to the tongue tip (i.e. MRR-ta > MRR-ka); from *neurological maturation*; jaw and lips movements stabilise earlier than tongue tip and tongue body movements (i.e. MRR-pa > MRR-ta and MRR-ka):, and *sequence complexity*; sequencing is more complex when more different units must be produced (i.e. MRR monosyllabic sequences > MRR bisyllabic sequences > MRR trisyllabic sequences). How these three factors (physiological factors, neurological maturation and sequence complexity) interact will have to be investigated further.

Gender differences

For all MRR sequences, overall rates were higher for boys than for girls. Prathanee et al. (2003) also found significant higher MRR scores for boys than for girls for /pə/, /tə/, /kə/, and /pə-tə/. Modolo et al. (2011) described older children and found for the 8-year-old children that boys performed faster on /pa/ and girls performed faster on /ta/ and /ka/. For the 9-year-old children these results were different; girls were overall faster than boys. At the age of 10 years girls were still faster than boys, except for the sequences /pataka/. However, other studies (Fletcher, 1972; Henry, 1990; Icht & Ben-David, 2015; Robbins & Klee, 1987; Wong et al., 2011; Zamani et al., 2017) found no differences between the performance of boys and girls in similar age ranges as our study. Our findings suggest that at the level of motor speech tasks, less taxing on linguistic skills, boys outperform girls. This is in contrast with studies that found boys showing a slower maturation of the speech motor development (Smith & Zelaznik, 2004), and in contrast with studies concluding that phonological accuracy measures of girls are better than that of boys (Dodd, Holm, Hua, & Crosbie, 2003). However, the results of this study should be interpreted with care; the sample is large, yet the effect size is small (Pek & Flora, 2018). Further research is needed.

Clinical implications and future perspectives

Despite of the ongoing debate on the clinical value of MRR, it has been suggested to have an important function in the assessment of children with MSD, and especially in children with CAS (Murray et al., 2015). Children with MSD show difficulties on MRR tasks when compared to typically developing children, more specifically with the speed(ing up) (Henry, 1990; Thoonen et al., 1996; Wit et al., 1993) and with the sequencing of different speech sounds (Henry, 1990; Thoonen et al., 1996). The studies of Thoonen (1999; 1996) indicate that monosyllabic MRR sequences differentiate children with spastic dysarthria from children with CAS and typically developing children. In addition, MRR can contribute to a first step in differential diagnosis between different types of speech sound disorders (SSD), and especially between different types of MSD. MRR offers insight into possible underlying motor execution impairments (Terband et al., 2019), and is thereby a potential added value in describing a complete speech profile. With only tasks like picture naming and nonword imitation it is not possible to distuingish a speech motor execution impairment from problems in lemma acces, word form selection, and phonological encoding (Van Haaften, Diepeveen, Terband et al., 2019).

In this protocol, articulation errors were not included in the analysis. As a result, there are missing values in the norm dataset. However, we consider the remaining data as sufficient to draw conclusions. Studies are currently being conducted to collect MRR data from children with SSD. With the normative data presented in this study and MRR data from children with SSD, clinicians will be able to distinguish typically developing children from children with SSD.

The present study is the largest available study using a standardised administration procedure for the age range 3;0 to 6;11 years. However, the test-retest of the norm group shows a low score for the bi- and tri-syllabic sequences. This is related to a test-retest effect; children were significantly faster on the second test moment because they know what they are expected (Diepeveen et al., 2019). The normative data of our study is based on a large and representative sample of only Dutch-speaking children. Therefore, the clinical usability of our data in other languages must be discussed. Icht and Ben-David (2014) demonstrated that MRR score is influenced by language differences. They found significant differences in adults in MRR scores between English, Portuguese, Farsi and Greek-speaking persons, with the mean MRR in the Portuguese and Greek sample being faster than the mean MRR in the English sample and the mean MRR in Farsi being slower than in English. Prathanee et al. (2003) found differences in speech rate on an MRR task between English-speaking and Thai-speaking children. They therefore suggest using the norm data of English with English-speaking children and the Thai norms for children who speak Thai. They suggest that the shorter height, and coinciding smaller lung volume, of Thai children when compared to Western children, influences the slower MRR score of Thai children. However, we hypothesise that this explanation is not plausible, since lung volume is related mainly to length of sequence (Pennington et al., 2006) and not to speed of the articulation. Furthermore, Diepeveen et al. (2019) showed that length of sequence is independent of rate. The described language differences can be a possible explanation for the differences found between the results of the present study and other studies, besides differences in sample size and sample representativeness. For example, in the English language the voiceless stops (/p, t, k/) are aspirated in syllable initial position, whereas in Dutch these stops are not aspirated. These findings suggest that reference norms cannot be generalised across languages. In addition, in the past different protocols were used for measuring MRR score (time-by-count or count-by-time measures), making it even more difficult to compare normative data between languages (Diepeveen et al., 2019). We suggest to use this protocol for MRR studies in children for further studies in other languages.

Declaration of interest

No potential conflict of interest was reported by the author(s).

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