Title
Geminated Liquids in Japanese: A production study

Author
Morimoto, Maho

Publication Date
2020

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

GEMINATED LIQUIDS IN JAPANESE: A PRODUCTION STUDY

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

LINGUISTICS

by

Maho Morimoto

March 2020

The Dissertation of Maho Morimoto
is approved:

Grant McGuire, Chair

Jaye Padgett

Ryan Bennett

Quentin Williams
Acting Vice Provost and Dean of Graduate Studies

Contents

List of Figures **vi**

List of Tables **ix**

Abstract **xvi**

Dedication **xviii**

Acknowledgments **xix**

1 Introduction **1**
- 1.1 Introduction 1
- 1.2 Japanese phonology 2
  - 1.2.1 Vowel and consonant inventories 2
  - 1.2.2 Morpheme classes and lexical domains 2
  - 1.2.3 Geminates in Japanese 3
  - 1.2.4 Liquid consonant in Japanese 6
- 1.3 Geminated liquids in Japanese 11
  - 1.3.1 Avoidance of geminated liquids 11
  - 1.3.2 Appearance of geminated liquids 13
  - 1.3.3 Issues in geminated liquids 15
- 1.4 Outline of the dissertation 17

2 Acoustic Characteristics of Geminated Liquids in Japanese **18**
- 2.1 Introduction 18
  - 2.1.1 Acoustic characteristics of liquids 19
  - 2.1.2 Acoustic characteristics of geminates 21
- 2.2 Method 24
  - 2.2.1 Subjects 24
  - 2.2.2 Speech materials 25
  - 2.2.3 Procedure 28
  - 2.2.4 Measurements 29

2.3 Durational results & discussion 30
2.3.1 Consonant duration 30
2.3.2 Preceding vowel duration 34
2.3.3 Following vowel duration 37
2.3.4 VCV duration 40
2.3.5 Discussion 42
2.4 Non-durational results & discussion 43
2.4.1 Intensity on the consonants 43
2.4.2 Formant frequencies on liquids 48
2.4.3 Laryngeal activity 50
2.5 Discussion & summary 53

3 Articulatory Characteristics of Geminated Liquids in Japanese 54
3.1 Introduction 54
3.1.1 Articulatory characteristics of liquids 55
3.1.2 Articulatory studies of liquids in Japanese 58
3.1.3 Articulatory characteristics of geminates 65
3.1.4 Articulatory studies of geminates in Japanese 69
3.2 Method 71
3.2.1 Subjects 73
3.2.2 Speech materials 73
3.2.3 Procedure 73
3.2.4 Measurements 76
3.3 Durational results 80
3.3.1 Gesture duration 80
3.3.2 Plateau duration 83
3.3.3 Gestural duration vs. acoustic duration 86
3.3.4 Summary 90
3.4 Positional results 91
3.4.1 TT position at TT maximal constriction point 91
3.4.2 TB position at TT maximal constriction point 96
3.4.3 TD backness at TT maximal constriction point 102
3.5 Lateralization and tongue curling 104
3.5.1 Lateralization at TT maximal constriction point 104
3.5.2 Tongue curling at TT maximal constriction point 108
3.6 Trajectory results 111
3.6.1 Temporal dynamics of lateralization and tongue curling 112
3.6.2 Temporal dynamics of TT and TB rising gestures 115
3.6.3 Temporal dynamics of TD backing gestures 118
3.6.4 Relative timings of gestures 119
3.7 Discussion & summary 120

4 Conclusion **122**
4.1 Summary of the results 122
4.2 Implications and future research 123

A Supplemental Materials: Acoustic **127**
A.1 Mixed effects models of C2 duration per subject 127
A.2 Mixed effects models of V1 duration per subject 130
A.3 Mixed effects models of V2 duration per subject 133
A.4 Mixed effects models of VCV duration per subject 135
A.5 Mixed effects models of C2 amplitude per subject 138
A.6 Word duration 141
A.7 Mixed effects models of Word duration per subject 143

B Supplemental Materials: Articulatory **147**
B.1 Mixed effects models of TT gestural duration per subject 147
B.2 Mixed effects models of TT plateau duration per subject 150
B.3 Mixed effects models of TT height per subject 153
B.4 Mixed effects models of TT backness per subject 156
B.5 Mixed effects models of TB height per subject 158
B.6 Mixed effects models of TB backness per subject 161
B.7 Mixed effects models of TD backness per subject 164
B.8 Mixed effects models of lateralization per subject 166
B.9 Mixed effects models of tongue curling per subject 169
B.10 TT horizontal trajectories per subject (restricted data) 172
B.11 TB horizontal trajectories per subject (restricted data) 173
B.12 Resting position for each subject 174
B.13 Sensor configuration at TT maximal constriction of liquids 176

References **177**

List of Figures

1.1 Waveforms and spectrograms for consonant length contrast in Japanese 4
1.2 Phonological representation of consonant length contrast in Japanese . . 5
1.3 Gestural possibilities for geminated liquids 17

2.1 C2 acoustic duration per consonant 31
2.2 C2 acoustic duration of liquids per subject 33
2.3 V1 duration per consonant 35
2.4 V1 duration for liquids per subject 36
2.5 V2 duration per consonant 38
2.6 V2 duration for liquids per subject 39
2.7 VCV duration per consonant 40
2.8 VCV duration for liquids per subject 42
2.9 C2 RMS amplitude per consonant 44
2.10 C2 RMS amplitude for liquids per subject 45
2.11 Sample spectrograms for each subject 47
2.12 C2 formant frequencies for liquids per subject 50
2.13 Sample spectrograms from S5 52
2.14 Gestural possibilities for geminated liquids, updated 53

3.1 Sensor position 75
3.2 Sample gestural tracking interface for singleton /t/ 77
3.3 Gestural landmarks 77
3.4 Lateralization for each side of the tongue 79

3.5 C2 gestural duration per consonant 81
3.6 C2 gestural duration for liquids per subject 83
3.7 C2 plateau duration per consonant 84
3.8 C2 plateau duration for liquids per subject 86
3.9 C2 acoustic, gestural, and plateau durations 87
3.10 Relationship between acoustic and gestural durations per subject 88
3.11 Distribution of acoustic vs. gestural durations from S5 89
3.12 SSANOVA: TT vertical movement trajectories from S5 and S8 90
3.13 TT height at TT maximal constriction point per consonant 92
3.14 TT height at TT maximal constriction point per subject 93
3.15 TT backness at TT maximal constriction point per consonant 94
3.16 TT backness at TT maximal constriction point per subject 96
3.17 TB height at TT maximal constriction point per consonant 97
3.18 TB height at TT maximal constriction point per subject 99
3.19 TB backness at TT maximal constriction point per consonant 100
3.20 TB backness at TT maximal constriction point per subject 101
3.21 TD backness at TT maximal constriction point per consonant 102
3.22 TD backness at TT maximal constriction point per subject 104
3.23 Lateralization per consonant 105
3.24 Lateralization per subject 107
3.25 Tongue curling per consonant 108
3.26 Tongue curling per subject 110
3.27 SSANOVA: singleton lateralization 113
3.28 SSANOVA: geminate lateralization 113
3.29 SSANOVA: singleton tongue curling 114
3.30 SSANOVA: geminate tongue curling 115
3.31 SSANOVA: singleton TT vertical movement 116
3.32 SSANOVA: geminate TT vertical movement 116
3.33 SSANOVA: singleton TB vertical movement 117
3.34 SSANOVA: geminate TB vertical movement 117
3.35 SSANOVA: singleton TD horizontal movement 118

3.36 SSANOVA: geminate TD horizontal movement 118
3.37 SSANOVA: liquid gestures for VCV region in S2 and S6 119
3.38 Gestural possibilities for geminated liquids, repeated 120
3.39 Gestural possibilities for geminated liquids, repeated again 121

A.1 Word duration per consonant 141
A.2 Word duration for liquids per subject 143

B.1 SSANOVA: singleton TT horizontal movement 172
B.2 SSANOVA: geminate TT horizontal movement 172
B.3 SSANOVA: singleton TB horizontal movement 173
B.4 SSANOVA: geminate TB horizontal movement 173
B.5 Sensor configuration at resting position for each subject 174
B.6 Sensor configuration for geminated liquids for each subject 176

List of Tables

1.1 Japanese vowel inventory 2
1.2 Japanese consonant inventory 2
1.3 Basic consonant length contrast in Japanese 4
1.4 Avoidance of liquid gemination in adverbs 11
1.5 Avoidance of liquid gemination in loanwords 12
1.6 Geminate types and occurrences across languages 13
1.7 Liquid geminates in loanwords 14
1.8 Geminated liquids in emphatic expressions 15

2.1 Speaker gender, age, and language background 25
2.2 Speech materials 27
2.3 Number of productions subject to acoustic analysis 29
2.4 Mean C2 duration and GSR per consonant 31
2.5 Mixed effects model of C2 duration 32
2.6 Mean C2 duration and GSR for liquids by subject 33
2.7 Mean V1 duration and GSR per consonant 34
2.8 Mixed effects model of V1 duration 35
2.9 Mean V1 durations and GSR for liquids by subject 36
2.10 Mean V2 duration and GSR per consonant 37
2.11 Mixed effects model of V2 duration 38
2.12 Mean V2 duration and GSR for liquids by subject 39
2.13 Mean VCV duration and GSR per consonant 40
2.14 Mixed effects model of VCV duration 41

2.15 Mean VCV duration and GSR for liquids by subject 41
2.16 Mean RMS amplitude on C2 per consonant 44
2.17 Mixed effects model of RMS amplitude 44
2.18 Mean RMS amplitude of C2 for liquids per subject. 45
2.19 Mean RMS amplitude of liquids per subject for each third 48
2.20 Mean F1, F2, and F3 on the mid-third portion of liquids by subject . . . 49
2.21 Number of laryngealized productions for each consonant 51
2.22 Number of laryngealized productions for each subject 51

3.1 Linguo-palatal contact patterns for /r/ in Onishi (1987) 61
3.2 Linguo-palatal contact patterns for /r/ in Kawahara and Matsui (2017) . 62
3.3 Number of productions subject to articulatory analysis 73
3.4 Labels and placement of the sensors 74
3.5 Raw lateralization index for each subject 79
3.6 Mean gestural duration and GSR per consonant 80
3.7 Mixed effects model of TT gestural duration 82
3.8 Mean gestural duration and GSR for liquids by subject 82
3.9 Mean plateau duration and GSR per consonant 83
3.10 Mixed effects model of TT plateau duration 85
3.11 Mean plateau duration and GSR for liquids by subject 85
3.12 Correlation coefficients for acoustic duration and gestural duration . . . 87
3.13 Mean TT height per consonant 91
3.14 Mixed effects model of TT height 92
3.15 Mean TT backness per consonant 94
3.16 Mixed effects model of TT backness 95
3.17 Mean TB height per consonant 97
3.18 Mixed effects model of TB height 98
3.19 Mean TB backness per subject 100
3.20 Mixed effects model of TB backness 101
3.21 Mean TD backness per subject 102
3.22 Mixed effects model of TD backness 103

3.23 Mean TD backness and GSR for liquids by subject 103
3.24 Lateralization per consonant 105
3.25 Mixed effects model of lateralization 106
3.26 Lateralization for liquids by subject 107
3.27 Tongue curling per consonant 108
3.28 Mixed effects model of tongue curling 109
3.29 Tongue curling for liquids by subject 110
3.30 Restricted data set for trajectory analysis 111

A.1 Mixed effects model of S1 C2 duration 127
A.2 Mixed effects model of S2 C2 duration 128
A.3 Mixed effects model of S3 C2 duration 128
A.4 Mixed effects model of S4 C2 duration 128
A.5 Mixed effects model of S5 C2 duration 129
A.6 Mixed effects model of S6 C2 duration 129
A.7 Mixed effects model of S7 C2 duration 129
A.8 Mixed effects model of S8 C2 duration 130
A.9 Mixed effects model of S1 V1 duration 130
A.10 Mixed effects model of S2 V1 duration 130
A.11 Mixed effects model of S3 V1 duration 131
A.12 Mixed effects model of S4 V1 duration 131
A.13 Mixed effects model of S5 V1 duration 131
A.14 Mixed effects model of S6 V1 duration 132
A.15 Mixed effects model of S7 V1 duration 132
A.16 Mixed effects model of S8 V1 duration 132
A.17 Mixed effects model of S1 V2 duration 133
A.18 Mixed effects model of S2 V2 duration 133
A.19 Mixed effects model of S3 V2 duration 133
A.20 Mixed effects model of S4 V2 duration 134
A.21 Mixed effects model of S5 V2 duration 134
A.22 Mixed effects model of S6 V2 duration 134

A.23 Mixed effects model of S7 V2 duration 135
A.24 Mixed effects model of S8 V2 duration 135
A.25 Mixed effects model of S1 VCV duration 135
A.26 Mixed effects model of S2 VCV duration 136
A.27 Mixed effects model of S3 VCV duration 136
A.28 Mixed effects model of S4 VCV duration 136
A.29 Mixed effects model of S5 VCV duration 137
A.30 Mixed effects model of S6 VCV duration 137
A.31 Mixed effects model of S7 VCV duration 137
A.32 Mixed effects model of S8 VCV duration 138
A.33 Mixed effects model of S1 C2 amplitude 138
A.34 Mixed effects model of S2 C2 amplitude 138
A.35 Mixed effects model of S3 C2 amplitude 139
A.36 Mixed effects model of S4 C2 amplitude 139
A.37 Mixed effects model of S5 C2 amplitude 139
A.38 Mixed effects model of S6 C2 amplitude 140
A.39 Mixed effects model of S7 C2 amplitude 140
A.40 Mixed effects model of S8 C2 amplitude 140
A.41 Mean Word duration and GSR per consonant 141
A.42 Mixed effects model of Word duration 142
A.43 Word duration and GSR of word for liquids by subject 142
A.44 Mixed effects model of S1 Word duration 143
A.45 Mixed effects model of S2 Word duration 144
A.46 Mixed effects model of S3 Word duration 144
A.47 Mixed effects model of S4 Word duration 144
A.48 Mixed effects model of S5 Word duration 145
A.49 Mixed effects model of S6 Word duration 145
A.50 Mixed effects model of S7 Word duration 145
A.51 Mixed effects model of S8 Word duration 146

B.1 Mixed effects model of S1 TT gestural duration 147

B.2 Mixed effects model of S2 TT gestural duration 148
B.3 Mixed effects model of S3 TT gestural duration 148
B.4 Mixed effects model of S4 TT gestural duration 148
B.5 Mixed effects model of S5 TT gestural duration 149
B.6 Mixed effects model of S6 TT gestural duration 149
B.7 Mixed effects model of S7 TT gestural duration 149
B.8 Mixed effects model of S8 TT gestural duration 150
B.9 Mixed effects model of S1 TT plateau duration 150
B.10 Mixed effects model of S2 TT plateau duration 151
B.11 Mixed effects model of S3 TT plateau duration 151
B.12 Mixed effects model of S4 TT plateau duration 151
B.13 Mixed effects model of S5 TT plateau duration 152
B.14 Mixed effects model of S6 TT plateau duration 152
B.15 Mixed effects model of S7 TT plateau duration 152
B.16 Mixed effects model of S8 TT plateau duration 153
B.17 Mixed effects model of S1 TT height 153
B.18 Mixed effects model of S2 TT height 153
B.19 Mixed effects model of S3 TT height 154
B.20 Mixed effects model of S4 TT height 154
B.21 Mixed effects model of S5 TT height 154
B.22 Mixed effects model of S6 TT height 155
B.23 Mixed effects model of S7 TT height 155
B.24 Mixed effects model of S8 TT height 155
B.25 Mixed effects model of S1 TT backness 156
B.26 Mixed effects model of S2 TT backness 156
B.27 Mixed effects model of S3 TT backness 156
B.28 Mixed effects model of S4 TT backness 157
B.29 Mixed effects model of S5 TT backness 157
B.30 Mixed effects model of S6 TT backness 157
B.31 Mixed effects model of S7 TT backness 158
B.32 Mixed effects model of S8 TT backness 158

B.33 Mixed effects model of S1 TB height 158
B.34 Mixed effects model of S2 TB height 159
B.35 Mixed effects model of S3 TB height 159
B.36 Mixed effects model of S4 TB height 159
B.37 Mixed effects model of S5 TB height 160
B.38 Mixed effects model of S6 TB height 160
B.39 Mixed effects model of S7 TB height 160
B.40 Mixed effects model of S8 TB height 161
B.41 Mixed effects model of S1 TB backness 161
B.42 Mixed effects model of S2 TB backness 161
B.43 Mixed effects model of S3 TB backness 162
B.44 Mixed effects model of S4 TB backness 162
B.45 Mixed effects model of S5 TB backness 162
B.46 Mixed effects model of S6 TB backness 163
B.47 Mixed effects model of S7 TB backness 163
B.48 Mixed effects model of S8 TB backness 163
B.49 Mixed effects model of S1 TD backness 164
B.50 Mixed effects model of S2 TD backness 164
B.51 Mixed effects model of S3 TD backness 164
B.52 Mixed effects model of S4 TD backness 165
B.53 Mixed effects model of S5 TD backness 165
B.54 Mixed effects model of S6 TD backness 165
B.55 Mixed effects model of S7 TD backness 166
B.56 Mixed effects model of S8 TD backness 166
B.57 Mixed effects model of S1 lateralization 166
B.58 Mixed effects model of S2 lateralization 167
B.59 Mixed effects model of S3 lateralization 167
B.60 Mixed effects model of S4 lateralization 167
B.61 Mixed effects model of S5 lateralization 168
B.62 Mixed effects model of S6 lateralization 168
B.63 Mixed effects model of S7 lateralization 168

B.64 Mixed effects model of S8 lateralization 169
B.65 Mixed effects model of S1 tongue curling 169
B.66 Mixed effects model of S2 tongue curling 169
B.67 Mixed effects model of S3 tongue curling 170
B.68 Mixed effects model of S4 tongue curling 170
B.69 Mixed effects model of S5 tongue curling 170
B.70 Mixed effects model of S6 tongue curling 171
B.71 Mixed effects model of S7 tongue curling 171
B.72 Mixed effects model of S8 tongue curling 171

Abstract

Geminated Liquids in Japanese: A production study

by

Maho Morimoto

While the Japanese language makes use of consonant length contrast abundantly, liquid geminates are disfavored. The status of geminated liquids in Japanese is marginal, only appearing in particular loanwords and through emphatic gemination. However, to the extent that they are attested, geminated liquids in Japanese offer a unique window into the abstract representation of geminates and liquids in general.

The foremost goal of this dissertation is to fill the gap in the literature by providing a detailed documentation of the production of geminated liquids in Japanese. Based on the results of an experiment using EMA (electromagnetic articulography), I report the acoustic and articulatory characteristics of geminated liquids in Japanese, focusing on the variability and similarity across productions.

The acoustic results indicate that while the local durational correlates for geminated liquids are quite variable, their durational contrast with singletons is strikingly robust and similar to that of more established geminates at a global level. Furthermore, while the non-durational acoustic correlates exhibit a wide range of inter- and intra-speaker variability, all the productions of geminated liquids demonstrate prolonged duration and high sonority in one way or another.

The articulatory results suggest that liquids in Japanese are gesturally complex, as has been pointed out for other languages. Singleton and geminate liquids can be characterized with a rising tongue tip gesture and relatively retracted tongue body. Otherwise, speakers use variable strategies to produce liquids, with lateral and retroflex flavors. Results also show that liquids take up a lateral flavor of production in high-vowel environments, consistent with previous claims that rhotics are incompatible with palatalization. They also show that speakers and productions vary in terms of the gestural timing to lengthen liquids, suggesting multiple gestural strategies for the process of gemination.

The acoustic and articulatory variability demonstrated in the results are consistent with the view that Japanese liquid /r/ is highly underspecified. An alternative explanation appealing to the marginal status of geminated liquids is discussed. The acoustic and articulatory results, taken together, also suggest that the production of geminates may be governed by acoustic targets rather than a universal gestural target shared by all speakers.

Dedicated to Misty & Molly

Acknowledgments

Graduate school marked a formative era for me in many respects, and I owe it to many wonderful people and amazing communities. I am especially grateful to my advisor, Grant McGuire, for encouraging me, guiding me, and trusting me throughout this long and difficult journey. Most importantly, he taught me how to step back and then move forward when I was in an analysis paralysis (often times without knowing that I was in one). I would also like to express my sincere gratitude to my committee members, Jaye Padgett and Ryan Bennett, for their support and insights. Every meeting with Jaye was an opportunity for me to re-examine my assumptions and to gain momentum for writing, and every meeting with Ryan was a luxurious moment throwing ideas at what little results I got at the time, always bringing home much more than I brought into his office. I am also grateful to the three of them for being incredibly accommodating of my defense schedule, during the chaotic time of a wildcat strike and a pandemic.

The experiment presented in this dissertation would not have been possible without the help of my collaborator, Tatsuya Kitamura at Konan University. I would also like to thank Mafuyu Kitahara at Sophia University for kindly letting me use his lab facilities, Yukiko Nota at ATR-Promotions Inc. for handling the technical aspects of the experiment, Lester Ochura and Shiho Morimoto for additional assistance, and my participants for putting up with the rather onerous procedure.

I cannot thank enough the UCSC Linguistics Department, for generously supporting me throughout my graduate career and providing me with a nexus of mentors and role models that I will look up to for the rest of my life. My heartfelt thanks to Junko Ito and Armin Mester for their continuous support and for letting me be friends with Misty and Molly; to Pranav Anand and Maziar Toosarvandani for all the learning experiences that took place around fieldwork, Nido de Lenguas, and WLMA; to many other faculty members whom I learned from through the courses, meetings, TA-ships, reading groups, and potluck conversations – especially, many thanks to Jorge Hankamer, Sandy Chung, and Jim McCloskey, for their kind words and encouragement at difficult times; and to the staff, Ashley Hardisty, Maria Zimmer, Matt MacLeod, Logan Roberts, and Gwyn Vandevere, for their exceptional kindness and efficacy.

I am eternally indebted to my cohort for helping me navigate through the linguistics coursework and life in California. Jenny Bellik, Kelsey Kraus, Jason Ostrove, Deniz Rudin, and Filippa Lindahl, because of you all, I survived the first two years and stuck around nearly five more years than I originally envisioned. I would also like to thank many current and former linggrads who helped me become who I am today, to whom I did not get a chance to say proper thank you and goodbye in person as a result of social distancing – which at first was because of dissertation-writing, but now because of COVID-19. In particular, many thanks to Anie Thompson, Anna Greenwood, Clara Sherley-Appel, and Hitomi Hirayama for being excellent role models; to Jed Pizarro-Guevara for the numerous R tips and food trips, and to Kelsey Sasaki for being my banda buddy.

I would also like to thank the UCSC Language and Applied Linguistics Department and everyone in the Japanese language program, for the teaching opportunities and training. And from the same department, many thanks to Stephanie Lain and Mark Amengual for the time we spent in LIP reading group and their valuable input. My sincere gratitude also goes to Fe Silva-Robles and Senderos, for her friendship and guidance, and for introducing me to amazing communities in Santa Cruz and in Oaxaca.

Finally, thanks to my family, who were always cheering for me and yet pretty chill about my endeavor – especially to my parents, for their unconditional love and support; to my grandmothers, who cared for me across the ocean these past years, and to my grandfathers, caring for me across another kind of boundary. And last but not least, much gratitude to my partner Nico Fernandez, for his incredible patience, support, and love.

Chapter 1

Introduction

1.1 Introduction

Despite the fact that consonant length contrast is attested in many languages across the world, their phonetic and phonological nature are not entirely understood (Kubozono, 2017, *inter alia*). Similarly, while liquid consonants are quite ubiquitous in the world's languages, the essence of the phonological category of liquids and their phonetic characteristics has long been under debate. Japanese is an exceptionally well described language considering its size (Anand, Chung, & Wagers, 2011), but the phonetics of geminated liquids have not been documented in much detail. In this dissertation, I provide the first detailed acoustic and articulatory description and analysis of geminated liquids in Japanese, with the foremost goal of documenting the acoustic and articulatory characteristics of geminated liquids in Japanese, and to discuss the insights they provide into the general process of gemination and the representation of liquids.

1.2 Japanese phonology

1.2.1 Vowel and consonant inventories

Table 1.1 and Table 1.2 show the vowel and consonant inventories of Japanese (Vance, 2008; Labrune, 2012; Tsujimura, 2014). In this dissertation, the high back unrounded vowel [ɯ] will be indicated as [u] for simplicity. Japanese has one liquid consonant phoneme, which will be transcribed as /r/ unless otherwise noted. As will be explained in later sections, however, the phonetic realization of Japanese liquid phoneme varies considerably.

Table 1.1: Japanese vowel inventory.

	−Back	+Back
+High	i	u
	e	o
+Low	a	

Table 1.2: Japanese consonant inventory.

	Labial	Alveolar	Alveo-palatal	Palatal	Velar	Uvular	Glottal
Plosives	p b	t d			k g		
Affricates		ʦ ʣ	ʧ ʤ				
Fricatives	ɸ	s z	ʃ ʒ	ç			h
Nasals	m	n			ŋ	ɴ	
Liquids		r					
Glides				j	w		

1.2.2 Morpheme classes and lexical domains

There are four morpheme classes in Modern Japanese: Yamato, Sino-Japanese, Foreign, and Mimetic (Itô & Mester, 1993a, 2003). Yamato refers to the native stratum of the vocabulary, while Sino-Japanese vocabulary refers to roots originating from Chinese. The Foreign stratum covers loanwords from various sources, and Mimetic stratum covers the sound-symbolic items expressing various aspects of the activity involved, which are basically manner adverbs (McCawley, 1968; Itô & Mester, 1993a). These four strata are known to be distinct lexical domains in Japanese, subject to stratum-dependent phonological restrictions. For example, while the Yamato stratum is subject to *rendaku* and Lyman's law, none of the other strata are (Itô & Mester, 1993a, and citations therein). There are also segments that are only allowed in particular stratum.

The Foreign strata is assumed to have a gradient structure, as the degree to which they are subject to the phonological constraints vary depending on how nativized they are, or how integrated they are into the phonological system.

What is interesting about the Mimetic stratum is that while it is "native" in basic origin (in that they were not borrowed from Chinese or English), it is entitled to the violation of many of the constraints that are inviolable in the other stratum.[1] The morpheme class of Mimetic constitutes an exception to the gradient core-periphery nature of the Japanese lexicon, where the phonology is more conservative for native vocabulary, and less so for less integrated vocabulary (cf. J. L. Smith, 2018).

1.2.3 Geminates in Japanese

Consonant length is contrastive in Japanese, as exemplified in Table 1.3. Figure 1.1 illustrates the difference in constriction duration between *kata* and *katta*, where the obstruction of the air for geminate [tt] is about twice as long as for singleton [t]. Geminates in Japanese have traditionally been analyzed as coda obstruent often represented as the moraic phoneme /Q/, usually followed by an obstruent that is the onset of a syllable (Kawagoe, 2015; Vance, 2008, and citations therein). The coda obstruents are called *sokuon*, and are orthographically represented with the small or lowercase version of the

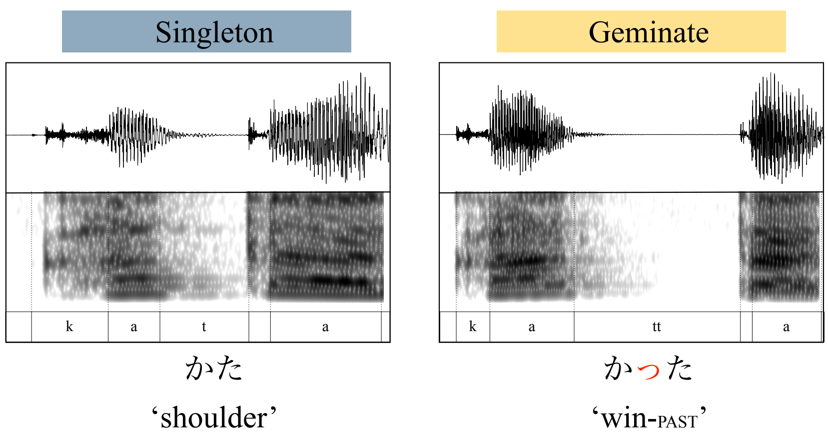
[1]For the characteristics of emphatic morphology in general, see Zwicky and Pullum (1987); Akita (2008); Akita and Dingemanse (2019).

kana syllabary for [tsu] (red letter in Figure 1.1).[2]

Table 1.3: Basic consonant length contrast in Japanese.

Singleton		Geminate	
supai	'spy'	*suppai*	'sour'
kata	'mold'	*katta*	'bought'
haka	'grave'	*hakka*	'ignition'
jisoo	'free-running'	*jissoo*	'actual running'
ishi	'willpower'	*isshi*	'an arrow'
ichi	'one'	*icchi*	'agreement'
kana	'syllabary'	*kanna*	'plane'
sama	'manner'	*samma*	'saury'

Figure 1.1: Waveforms and spectrograms for [kata] 'shoulder' and [katta] 'won' in Japanese.



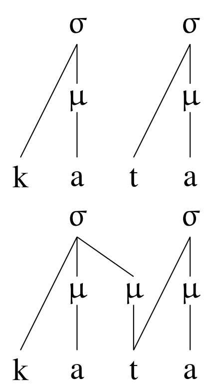
The phoneme /Q/ is quite peculiar in that it can only occur in syllable-final position, always followed by another consonant, and in that it takes on the phonetic characteristics of the following consonant (i.e., lacks its own specification for place of articulation; Kawagoe, 2015).

In the meantime, modern view of geminates involves the linking of the geminate

[2]For nasal geminates, a coda nasal or *hatsuon*, often represented as /N/ and transcribed with a distinct kana symbol, is followed by a nasal onset.

segment to a mora (Hyman, 1985; McCarthy & Prince, 1996; Hayes, 1989; Itô & Mester, 1993b), as illustrated in Figure 1.2 (bottom). Under this view, geminate segment is a consonant that is linked to coda and onset positions at the same time. This representation accounts for the peculiarities mentioned above, as well as the moraic status of geminates.

Figure 1.2: Phonological representation of [kata] 'shoulder' (top) and [katta] 'won' (bottom) in Japanese.



In Japanese, voiceless obstruents and nasals are the most common geminates. They are the only types of consonants that contrast in length in the Yamato and Sino-Japanese vocabularies in the lexicon (Itô & Mester, 1995a, 1995b, 1999). Previous work on Japanese geminates largely pertains to voiceless obstruents. Studies on nasal geminates are rather limited, and tend to be conducted under the topic of moraic nasal rather than geminate per se.

Compared to voiceless obstruent geminates, voiced obstruent and approximant geminates are much more restricted in terms of distribution, and phonetic investigation of these geminates is relatively new. Geminated voiced stops appear in Japanese loanwords from English such as *baggu* 'bag' or *beddo* 'bed' (see Kubozono, Itô, & Mester, 2009; Itô, Kubozono, & Mester, 2017, for the gemination process in loanwords), and have recently drawn special attention as native speakers of Japanese are found to partially or entirely devoice them in production (Kawahara, 2016, *inter alia*). Work on geminated voiced stops has also encouraged the documentation of non-Tokyo varieties of Japanese which contrast consonant length in voiced obstruents. On the other hand, geminated voiced fricatives and affricates are not studied as extensively (Kawahara, 2015b), and phonetic investigation of approximant geminates constitute a gap in the literature. This reflects the cross-linguistic dispreference against sonorant geminates, assumed to reflect their perceptual difficulty (Kawahara & Pangilinan, 2017).

1.2.4 Liquid consonant in Japanese

Japanese has only one liquid phoneme /r/. As Mester and Itô (1989) emphasized, it is coronal and does not stand in contrast with another liquid consonant in terms of place of articulation. While the Japanese liquid consonant is most commonly characterized as apico-alveolar tap (e.g., Hattori, 1984), its phonetic realization is highly variable, sometimes crossing the lateral/rhotic boundary (Tsuzuki & Lee, 1992; Akamatsu, 1997; Vance, 2008; T. Arai, 2013b; Tsujimura, 2014; Labrune, 2014; Kawahara & Matsui, 2017; Katz, Mehta, & Wood, 2018). Variability in the realizations of Japanese /r/ has been documented at mainly two levels: as socio-linguistic variation, and as free or phonetic variation.[3]

Socio-linguistic variants Perhaps the most conspicuous of all socio-linguistic variants would be the apico-alveolar trill. The pronunciation is associated with virility and masculinity (Matsuno, 1971), boorishness (Kawakami, 1977), or toughness (Vance, 2008, citing Akamatsu 2000 *Japanese Phonology*, which I don't have). It is also thought to be popular among male speakers in Tokyo region (Labrune, 2014), and specifically, the Edo dialect (*beranmee* variety) of Japanese spoken in the central Tokyo

[3]Individual differences are mostly considered to be idiosyncratic at this point, though some researchers express the possibility of differences based on physiological differences such as palate shape or tongue size.

Shitamachi area (Hattori, 1984). In the meantime, many speakers find this pronunciation difficult, or are unable to produce it (Vance, 2008).

Three socially marked realizations of /r/, including the trill, are discussed in Matsuno (1971), along with their socio-linguistic values. The voiced lateral allophone [l], whose production can be more front than the alveolar ridge (but rarely dental), common among children, while singing Western tunes, and often produced with lip-spreading; trilled [r], appearing in the singing of traditional pentatonic tunes, in addition to certain register and regional dialects; and retroflex continuant [ɹ], used in traditional performing arts and singing such as Kabuki, Noh, Joruri, etc. The socio-linguistic values associated with each of these variations are, respectively, childishness, virility or masculinity, and unnaturalness (when used in normal speech). He maintains that voiced alveolar tap/flap [ɾ] is the neutral, typical production of /r/, though he also notes that it can be produced with a "longer and more complete closure somewhat like the English [d]."

On the other hand, Labrune (2014) claims that the apico-alveolar lateral [l] and retroflex lateral [ɭ] are common among young women, although the sources do not necessarily support this (Onishi, 1987; Tsuzuki & Lee, 1992).[4] Finally, Hattori (1951) notes that some dialects employ a voiced retroflex fricative articulation of /r/.

Other variants The descriptions of the basic phonetic variants are quite diverse. In his phonemic description of standard Japanese, Bloch (1950, pp.108; 101; 114) lists [r] (short voiced alveolar flap) and [l] (short voiced alveolar lateral flap) as being in free variation, noting that the environments for [r] subsume that of [l], but not vice-versa. Specifically, [r] appears before /e, a, o, u/, word-initially, and after /i, e, a, o, u, n/, while [l] appears before /e, o/, but also word-initially and after /i, e, a, o, u/. In addition, [*r*] (short voiced alveolar flap, palatalized) appears before /i, y/, as well as word-initially,

[4]Sudo, Kiritani, and Yoshioka (1982) found that the young, female speaker produced more lateral patterns compared to the older, male speaker. However, they only had two subjects.

after /i, e, a, o, u/, and palatalized coda nasal (coda nasal that is preceded by /i/). He also notes that laterals are much less common than the flaps, and many individuals just do not produce them. The lack of post-nasal position as common context for a lateral production is at odds with Akamatsu (1997), reviewed below.

Hattori (1951, pp. 129–130) points out that the place of articulation varies depending on the following vowel, from posterior to anterior in the following order: /ro, ra, re, ru, ri/, with palatalization for /ri/. He also notes that there are speakers who articulate all of /r/ as plosives, and speakers who articulate some of them (e.g., /re, ro, ra/) as laterals.

Kawakami (1977) describes /r/ as usually a flap, with a [d]-like variant. He emphasizes the primacy of the movement away from the alveolar ridge rather than the movement toward the alveolar ridge, which allows him to consider the [d]-like variant also as a type of flap: in the [d]-like variant, the tongue tip is lightly rested at the alveolar ridge prior to the abrupt pulling-away movement. He also notes that some speakers use laterals instead of flaps, in front of [a, e, o].

A very detailed description of /r/ was provided decades later in Akamatsu (1997, pp. 105–116).[5] He identifies two main non-palatalized variants of Japanese /r/: voiced non-palatalized apico-alveolar tap, and voiced non-palatalized apico-alveolar lateral. According to his description, the latter variant is most common after [n], as in /kanro/ 'honeydew.' The closure is formed at the upper front teeth-ridge with the tongue tip (though he notes that the blade of the tongue may often also contribute to the closure at the upper front teeth-ridge), while both rims of the tongue are lowered not to touch the upper side of the teeth-ridge (he notes that the lateral airstream is symmetrical, unlike English lateral sounds where only one side of the tongue may be lowered).He also notes that after [n], a voiced apico-alveolar lateral tap [l̆] may also occur. The

[5]As far as I know, there is no explanation as to the methodology with which he obtained the descriptions of the phones in Japanese. He claims to be a native and continuous speaker of the standard variety of Japanese.

lateral production of /r/ following [n] is explained with the difficulty of producing [ɾ], whose articulation is unsustainable, after holding the apical constriction for [n]: "the sustained apico-alveolar closure is accompanied by the lowering of the soft palate (for [n]), and then the soft palate is raised while the apico-alveolar *closure* is shared by [n] and [l]." Akamatsu also clarifies that the lateral production of tap does not involve velarization as is often pointed out for English laterals. The articulation of the former variant, apico-alveolar tap, is prepared with the sides of the tongue raised and loosely contacting the rim of the teeth-ridge. Then, the tongue tip is raised, "poised" very close to the teeth-ridge, then shoots forward and downward to lightly hit the teeth-ridge, in a ballistic movement. This articulation is common before [a, e, o, u]; it becomes palatalized before [i], and a slightly different variant occurs in post-pausal environment. The variant is described as follows: at the outset of the consonant, the tongue tip is already lightly rested at the teeth-ridge and the sides of the tongue are also in contact with the sides of the teeth-ridge. Then, the tongue tip is "made to be blown downwards by the outgoing air." He notes that the acoustic effect of this variant is indeed different from the other one. He maintains that the articulation is still ballistic, and can still be considered as a tap. This variant is apparently the one that the other researchers pointed out to be like a weak plosive, or a weak [d], though he does not think it is actually [d] based on perceptual impression as well as articulatory differences (mainly a durational one). In response to some researchers' claim that [l] can occur in post-pausal contexts, he thinks it is rather an apico-alveolar lateral tap (also mentioned above as the post-nasal variant). Crucially, the apico-alveolar lateral tap and this post-pausal variant are articulatorily distinct as to whether the sides of the tongue are lowered or not. Finally, he emphasizes that each of these variants are not exclusively and systematically employed in the respective context by Japanese speakers, though knowing the general patterns might benefit learners of the language.

The illustration of Japanese sounds through IPA by Okada (1999) is somewhat unorthodox, as he maintains post-alveolar (rather than retroflex) [ɖ] to be the typical production of /r/. He also notes that /r/ in initial position is produced with slight affrication [ɖʴ]. [ɾ] is suggested as a frequent variant intervocalically, and post-alveolar [ɭ] in all positions.

T. Arai (2013b), through his search for an explanation as to why the pronunciation of Japanese /r/ is difficult for children to learn, illustrates the phonetic variability found in adults' production. Possible realization of /r/ includes: [d] (alveolar plosive) and [ɖ] (retroflex plosive), where the latter is common word-initially while the former is more of a speech error; [ɾ] (alveolar flap) and [ɽ] (retroflex flap) which are typical production intervocalically; [ɹ] (alveolar approximant) which lacks closure period; [l] (alveolar lateral approximant) and [ɭ] (retroflex lateral approximant), whose duration can be relatively long due to the sustainability of the apical contact; and [ɺ] (alveolar lateral flap), whose duration is relatively short compared to the earlier two variants. T. Arai (2013b, 2013a) also note that the sequence of /ri/ is particularly difficult for children, often becoming a plosive or a lateral.

Labrune (2014) presents the large phonetic variability of /r/ to support its phonologically unspecified status. In her view, the apico-alveolar lateral [l] and retroflex lateral [ɭ] are common before palatalized vowels (Onishi, 1987; Tsuzuki & Lee, 1992). The voiced plosive [d] is presented as common word-initially in certain dialects and child speech, but can also occur word-medially. The retroflex flap [ɽ] is common word-initially before /u/, or intervocalically when the surrounding vowels are identical (Tsuzuki & Lee, 1992). Lateral fricative [lʒ] is common before high vowels.

In addition to the description of the basic variants of /r/, some scholars made note of the palatalized variant [ɾʲ]. /r/ and /rʲ/ are in fact contrastive preceding /a, o, u/ (e.g., /raku/ 'ease' and /ryaku/ 'abbreviation'; /roku/ 'six' and /ryoku/ 'green'; there is something going on with /u/ that prevents us from seeing minimal pairs). Some scholars explicitly mention that /r/ is always palatalized preceding /i/ (Bloch, 1950; Akamatsu, 1997; Vance, 2008).

1.3 Geminated liquids in Japanese

1.3.1 Avoidance of geminated liquids

In light of K. C. Hall (2013)'s criteria, the length contrast in Japanese liquid qualifies as a marginal or intermediate contrast. Crucially, (a) the contrast is limited to specific strata in the lexicon; (b) there is talker-dependent variability in the distribution; and (c) the occurrence of the contrast is low in frequency. In Japanese, liquids are never geminated in Yamato or Sino-Japanese vocabularies, and tend to be avoided in other lexical classes as well. Table 1.4 shows an example of how liquid consonants resist gemination in a regular process. In the productive process of suffixation of adverbial -*ri* and gemination (Mester & Itô, 1989, and citations therein), forms with full or partial gemination (with a homorganic nasalized approximant) of liquids are unacceptable.

Table 1.4: Avoidance of liquid gemination in adverbs from Mester and Itô (1989).

Root	Adverb	
pata	*pattari*	'palpitating'
niko	*nikkori*	'smiling'
shina	*shinnari*	'supple'
shimi	*shimmiri*	'quiet'
shobo	*shoNbori*	'lonely'
uza	*uNzari*	'bored'
boya	*boNyari*	'vague'
fuwa	*fuNwari*	'light'
hura	*hurari* (*hurrari, *huNrari)	'swaying'

Another example of the avoidance of liquid gemination can be found in Japanese loanwords from English. Even when the consonant is in a prosodic position that qualifies for gemination, liquids appear to resist gemination (Table 1.5).

Table 1.5: Avoidance of liquid gemination in Japanese loanwords from English.

Source	Loan
bed	*beddo*
bell	*beru* (*berru)
pick	*pikku*
pill	*piru* (*pirru)
big	*biggu*
bill	*biru* (*birru)

Possible explanations for the avoidance of geminates include (a) featural underspecification of /r/, (b) violable constraints against geminated liquids, (c) perceptual difficulty, and (d) gestural incompatibility.

First, Mester and Itô (1989), mainly based on evidence from palatal prosody, *rendaku* and Lyman's Law, argued that Japanese /r/ is underspecified for the place feature [coronal] and [voice]. [Coronal], for /r/ being the only liquid in the phoneme inventory without any place contrast, and [voice], for /r/ being a sonorant (Itô, Mester, & Padgett, 1995). By advocating for the underspecification of the features onto which other materials can dock onto, they predicted the ingeminability of /r/ in Japanese. Furthermore, the view that Japanese /r/ is deprived of some phonological features is consistent with the wide range of phonetic realizations of /r/ described above. The degree of (under)specification of /r/ has since been met with some debate, starting with Labrune (2014)'s proposal that /r/ is underlyingly completely underspecified, consisting solely of an empty root node, with features determining more specific production of the liquid such as [continuant], [lateral], [retroflex] acquired later in the derivation (Labrune, 2014). This view has been argued against by Kawahara (2015a) and Pellard (2016), considering the systematic exceptions to Labrune's generalizations, one of which was the productive presence of geminated liquids in certain contexts (cf. Schourup & Tamori, 1992)[6]. In order to account for the exceptions, analyses using violable constraints making reference to the markedness of /r/ and /rr/ (such as */rr/) are called for, which can only be done with commitment to at least some degree of specification for the liquid consonant (Kurisu, 2014; Kawahara, 2015a).

On a slightly different note, it has been globally observed that certain types of consonants tend to have length contrast while others do not. In particular, liquid geminates are cross-linguistically rare. In the PHOIBLE data, of all geminates reported across languages, the most common type of consonants was plosives. We can see that the cross-linguistic frequency generally follows the sonority hierarchy (obstruents, nasals, liquids[7], and glides), as acknowledged before (Podesva, 2002, *et seq.*). Liquid geminates are suggested to be more confusable with their singleton counterparts, due to spectral continuity (Kawahara & Pangilinan, 2017).

Table 1.6: Geminate types and occurrences across languages.

Consonant type	Stop	Affricate	Fricative	Nasal stop	Nasal	Liquid	Glide	Total
Occurrence across languages	696	198	385	3	303	175	88	1848
Number of languages	112	73	105	1	108	97	53	159
Number of consonant entries	82	50	70	3	29	28	3	265

Finally, in the case of Japanese, the gestural incompatibility of liquids and gemination has been mentioned as well. For example, (Pellard, 2016) mentioned that there is “an inherent antagonism between the momentary nature of a tap like /r/ and gemination.” Kawahara (2015a), in a footnote, also expresses similar opinion.

1.3.2 Appearance of geminated liquids

In the meantime, geminated liquids can appear in loanwords from foreign languages that have length contrast for liquids themselves, such as Italian or Arabic (Tanaka, 2007;

[6]Note that Labrune (2014) also clearly noted the exceptions as mimetic lexicon and certain Western borrowings.

[7]I did not include lateral fricatives in the liquid category.

Kawahara, 2015a), as shown in Table 1.7 below. It should be noted, however, that the adaptation of words with geminated liquids shows some optionality. For example, both *rimoncherro* and *rimonchero* are available as adaptation of 'limoncello'.

Table 1.7: Liquid geminates in Japanese loanwords from Italian and Arabic.

Source (language)	Loan
limoncello (Italian)	*rimoncherro*
tortelli (Italian)	*toruterri*
Allah (Arabic)	*arra:*

Furthermore, liquids can be geminated through emphatic gemination (Aizawa, 1985; Kawahara, 2002; Kurisu, 2014; Kawahara & Braver, 2014). Emphatic gemination is a consonant lengthening process to express emphasis or intensification, and allows for otherwise prohibited geminates in the language. Emphatic gemination usually takes place on adjectives, adverbs, and mimetics (reduplicative and suffixed; Kurisu, 2014), but also on verbs and nouns (Aizawa, 1985). Examples are shown in Table 1.8. Emphatic geminates are unusual in that they allow for non-binary contrast: while most consonant length contrast in Japanese is short vs. long, additional emphasis can be expressed by adding more duration (Aizawa, 1985; Kawahara & Braver, 2014). According to Kawahara and Braver (2014), emphatic geminates may have up to six-way contrast depending on the speaker. It is also special because it can manifest word-initially or word-finally. As in the loanwords, these emphatic forms also show some optionality. For example, emphatic form of *dorodoro* can be either *dorrodoro* or *doroddoro* (Kurisu, 2014).

Table 1.8: Geminated liquids in emphatic expressions from Kurisu (2014) and Kawahara (2015a).

Category	Singleton (regular)		Geminate (emphatic)	
mimetic	*paripari*	'crunchy'	*parripari*	'very crunchy'
mimetic	*dorodoro*	'muddy'	*dorrodoro*	'very muddy'
mimetic	*guragura*	'unsteady'	*gurragura*	'very unsteady'
adjective	*karui*	'light'	*karrui*	'very light'
adjective	*zurui*	'cunning'	*zurrui*	'very cunning'
adjective	*hiroi*	'spacious'	*hirroi*	'very spacious'

1.3.3 Issues in geminated liquids

1.3.3.1 Issues related to the representation of liquids

While the marginal status of geminated liquids in Japanese is undeniable, they are systematically available in certain lexical strata. However, compared to geminated liquids in Italian, for example, in which /ll/ is simply a lateral with prolonged constriction duration, predicting the realization of geminated liquids in Japanese is not straightforward. Especially, there is an apparent incompatibility between the very short nature of Japanese liquids, and the usual implementation of gemination, which is to lengthen the constriction of the consonant.

The above concern is particularly real in a model of gemination in which the lengthening of the consonant occurs based on a fairly rich representation of /r/, already endowed with the feature [tap]. Resolving the conflict between the featurally specified momentary nature of the consonant and lengthening due to gemination would be problematic. Cross-linguistically, introducing a trill as the geminate counterpart of a tap is an option (e.g. Inouye, 1995; Payne, 2005), while it phonetically involves more than just increased constriction duration. Additionally, trill in Japanese is a sociolinguistically marked variant of the singleton /r/, often associated with toughness (Vance, 2008), and it is unlikely to be a normal candidate for /rr/.

Alternatively, the process of gemination may occur based on the underspecified representation of /r/. In this scenario, the momentary nature of /r/ may not have been acquired yet, and the "lengthened /r/" might be realized as long lateral or long rhotic approximant. Since laterals and retroflexes are also attested as variants of singleton /r/, elongating an underlying tap may not be what is happening necessarily. This scenario, however, is at odds with what Mester and Itô (1989) proposed in terms of the relationship between feature underspecification and ingeminability.

1.3.3.2 Issues related to the representation of geminates

Another issue that is relevant to an attempt at predicting what geminated liquids in Japanese might look like is the operation involved in gemination in general. In the frame of Articulatory Phonology (AP), in which articulatory gestures are the minimal units of speech (Browman & Goldstein, 1986, 1990, 1992a, 1992b; N. Hall, 2010), two kinds of questions have been addressed concerning the gestural representation of geminates. The first question is about how many distinct gestures it takes to produce a geminate, and the second one is about the temporal organization among the consonant and the surrounding vowels. Here, we consider the first question. Browman and Goldstein (1986) proposed two possibilities as to the gemination process in AP, whereby consonants can be either added (i.e. two partially overlapping gestures) or lengthened (i.e. a single, long gesture). Several studies addressed this issue, but the results are inconclusive. For example, Byrd (1995) concluded that English juncture geminates can be accounted for as gestural overlap based on EPG contact profiles.[8] For true geminates, Gafos (2002) presented constraints on gestural coordination to account for geminates separability and inseparability facts in Moroccan Colloquial Arabic, and proposed that a geminate is a single long gesture instead of two overlapping consonants.

[8]The paper's focus was whether it should be thought as a summation or blending of two gestures. She favored the blending process, as there was no evidence of consistently increased contact for geminates (cf. Munhall & Löfqvist, 1992; Kelso & Tuller, 1987).

In turn, Zeroual et al. (2015) investigated gestural coordination in Moroccan Arabic using EMA, and supported the hypothesis that geminate plosives can be analyzed as two identical consonants overlapping with each other.

Figure 1.3 represents the two possibilities for liquid geminates. In a way, geminated liquids in Japanese provide an interesting testing ground for these possibilities, as the realization of /r/ is not uniform. If geminates are overlapping two consonants (as in the right image in Figure 1.3), for example, it should be possible that the first liquid has a lateral flavor and the second has a retroflex flavor.

Figure 1.3: Gestural possibilities for geminated liquids. Left image represents a single long liquid; right image represents two partially overlapping liquids.

By investigating the acoustic and articulatory characteristics of geminated liquids in Japanese, the current dissertation aims to further explore the nature of the consonant as well as the process of gemination. To this end, we conducted a production experiment using EMA (electromagnetic articulography).

1.4 Outline of the dissertation

Chapter 2 provides an overview of previous studies on the acoustic characteristics of liquids and and geminates, and reports on the acoustic results from the production experiment. Chapter 3 provides an overview of previous studies on the articulatory characteristics of liquids and geminates, and reports on the articulatory results from the production experiment. Chapter 4 provides a general discussion given the results of the production experiment, and concludes.

Chapter 2

Acoustic Characteristics of Geminated Liquids in Japanese

2.1 Introduction

This chapter summarizes the previous research on the acoustic nature of liquids and geminates, and reports on the methodology and acoustic results of the production experiment. The primary purposes of the chapter are (a) to establish the *durational* correlates of geminated liquids in Japanese as compared with those of previously studied geminates, (b) to examine the *non-durational* correlates of geminated liquids as compared with those of previously studied geminates, and (c) to explore the non-durational correlates that are uniquely available for geminated liquids.

Subsections 2.1.1 and 2.1.2 provides an overview of previous studies, section 2.2 explains the methods of the experiment, and sections 2.3 and 2.4 report and discuss the durational and non-durational results, respectively. Section 2.5 summarizes the chapter.

2.1.1 Acoustic characteristics of liquids

While phonologists tend to agree that the class of liquid has some phonological validity (e.g. Walsh Dickey, 1997), it has been difficult to identify a phonetic property that is shared among the various liquid consonants across languages. Besides having well-defined formant structures, lateral and rhotic sonorants are quite different from each other (and within themselves) acoustically.

2.1.1.1 Laterals

The most frequent lateral sounds in the world are the voiced lateral approximants (Ladefoged & Maddieson, 1996). In many languages, these involve a tongue tip/blade rise towards the palate, with some opening behind. Trademarks for lateral approximants are lower F1 frequency and anti-formant near the F3 (Johnson, 2004). The anti-formant is also known to cause reduced amplitudes of all higher formants, and laterals have generally lower intensity compared to vowels.

For English lateral approximants, it has been pointed out that the prevocalic [l] ("clear l") and postvocalic [ɫ] ("dark l") have different acoustic signatures, reflecting the difference in the coordination of the articulatory gestures (Sproat & Fujimura, 1993) in each position. Prevocalic [l] has lower F1 and higher F2 compared to postvocalic [ɫ] (Narayanan, Alwan, & Haker, 1997; Kent & Read, 2002), as a result of a negative correlation between F1 and tongue tip height, as well as a positive correlation between F2 and tongue body retraction (Ying, Shaw, Kroos, & Best, 2012).

2.1.1.2 Rhotics

Rhotics include trills, tap/flaps, approximants, and fricatives (Ladefoged & Maddieson, 1996), which together form a group of "r-sounds" that are quite common in the world's languages: 76% of languages in UPSID are reported to include one or more rhotics (Maddieson, 1984). However, rhotic sounds vary in terms of manner and place of articulation, and it is especially difficult to find phonetic commonalities within the group (Lindau, 1985).

The most common rhotic sounds are the trills, made with the vibration of tongue-tip or tongue-blade (Ladefoged & Maddieson, 1996; McGowan, 1992). It is typical for these trills to involve two or three vibration periods. In Japanese, trill is a socially marked variant of /r/ (Vance, 2008).

While taps and flaps are often described as a "very rapid stop gesture" (e.g. Ladefoged & Johnson, 2006), they are acoustically quite different from stops. They tend to lack a stop burst at the closure release, as there is not as much buildup of air pressure (Derrick & Gick, 2011, and citations therein). In Japanese, liquids are most typically realized as apico-alveolar taps or flaps, and they are one of the shortest of all consonants in terms of inherent duration, lasting only about 20-30 ms (Han, 1962; T. Arai, 2013b). In the meantime, there is a wide range of variability in the realization of this consonant, including a plosive-like and approximant-like productions, and the formant frequencies vary accordingly (T. Arai, 2013b; Katz et al., 2018). For example, T. Arai (2013b) reports a lowered F1, raised F2, and lowered F3 for a retroflex flap variant.

Rhotic approximant [ɹ] is not as common as trills or taps/flaps cross-linguistically, but is relatively well-described as the American English /r/, whose articulation strategies are known to vary within and across speakers while achieving similar acoustic effects (Lindau, 1985; Delattre & Freeman, 1968; Alwan, Narayanan, & Haker, 1997). English voiced approximant is characterized by lowered F3 and F4 frequencies (Ladefoged & Johnson, 2006), resulting in a small F2-F3 separation (Espy-Wilson, 1992). These acoustic effects are achieved by curling up the tongue tip ("retroflex r"), or by raising the middle part of the tongue body ("bunched r").

2.1.2 Acoustic characteristics of geminates

Usually, geminates refer to long consonants that are distinctive from their short counterparts, or singletons.[1] They are also often described as "doubled consonants" (Davis, 2011). As noted by a few scholars, the precise nature of geminates has not been fully uncovered. Their phonetic implementation, phonological representation and behavior, as well as cross-linguistic variations have still much to be debated (Blevins, 2004; Ridouane, 2010; Kubozono, 2017, *inter alia*).

2.1.2.1 Consonant duration

Constriction duration is the most commonly reported correlate of geminate consonants, cross-linguistically.[2] It is usually reported in raw duration (often in milliseconds) and/or in the form of the ratio of the duration of singleton and geminate counterparts (we will call it Geminate-to-Singleton Ratio, or GSR). In this dissertation, we follow Kawahara (2015b) and the common practice in referring to the phonological contrast as "length" and the phonetic measures as "duration".

Generally, long stop consonants are about one and a half to three times longer than short consonants in terms of the acoustic closure (Lahiri & Hankamer, 1988; Ladefoged & Maddieson, 1996). In Japanese, the geminate-to-singleton ratio (GSR) of obstruent geminates is reported to be around 2-3, varying across manner and voicing of the obstruents (Kawahara, 2015b, and citations therein). For plosives, gemination results in prolonged duration of the obstruction of the air. For fricatives, gemination results in prolonged duration of the frication noise. For affricates, gemination results in the lengthening of the plosive portion rather than the fricative portion (Oba, Braun,

[1] Though there are languages that have a three-way contrast in consonant length (short, long, and extra-long; Blevins, 2004, p. 169).

[2] Especially for word-internal geminates. Word-initial geminates and word-final geminates are also attested and reported, not only in terms of phonetic durations but also in terms of non-durational correlates such as amplitude (e.g. Abramson, 2003; Ridouane, 2010).

& Handke, 2009).[3] For nasals, gemination results in the lengthening of the closure (Han, 1962). In previous durational reports on obstruent geminates, while the absolute durations for singleton and geminate consonants vary, the GSRs reported for each consonant are fairly steady across experiments and speech rates, where controlled (e.g. Hirata & Whiton, 2005).

In the meantime, it has been pointed out in other languages that there is an inverse relationship between singleton and geminate durations (Dmitrieva, 2017, p.37; Payne, 2005), whereby the duration of a geminate consonant whose singleton counterpart is shorter would be longer than the duration of a geminate consonant whose singleton counterpart is longer. For example, the GSR for fricatives in general would be smaller than the GSR for plosives because singleton fricatives are inherently longer compared to plosives. This tendency mostly holds in Campbell (1999), Kawahara (2015b), and T. Arai, Warner, and Greenberg (2007), in which durational contrasts for various consonant types were investigated. This leaves us with a prediction that GSR for Japanese liquid geminates would be large, given the momentary nature of a tap (cf. Beckman, 1982). In the corpus-based study by T. Arai et al. (2007), mean duration of singleton /r/ was reported to be 29.3 ms, shortest of all singleton consonants in the study.

2.1.2.2 Preceding vowel duration

Another commonly reported correlate of geminates is the preceding vowel duration, as there is a cross-linguistic tendency to shorten the vowels preceding geminates (Maddieson, 1985). However, in Japanese, vowels are characteristically longer before geminates compared to singletons, and in closed syllables in general (including syllables with moraic nasals), indicating that this is not a geminate-specific tendency.

[3] In Hungarian affricates reported in Pycha (2009), either the stop portion or the frication portion can be lengthened depending on the context. For the alveolar affricate [ts] in Japanese, the fricative portion was reported to be slightly shorter in geminates than in singletons, with some individual variability (Oba et al., 2009).

Previous studies vary as to the robustness of the preceding vowel lengthening effects, but they more or less agree that the effect is real (M. Arai & Kawagoe, 1998; Campbell, 1999; Fukui, 1978; Han, 1994; Hirata, 2007; Hirose & Ashby, 2007; Idemaru & Guion, 2008; Kawahara, 2006, 2013; Kawahara & Braver, 2014; Ofuka, 2003; Port, Dalby, & O'Dell, 1987; Kawahara, 2018; Maddieson, 1985; Port & Dalby, 1982; Oba et al., 2009; Kawahara, 2017; Aizawa, 1985).

While it is most likely that Japanese geminate liquids also involve lengthening of the preceding vowel, it is difficult to predict the size of the effect relative to the other types of consonants. We may predict that geminate liquids involve shorter preceding vowels compared to geminate stops or fricatives, based on the report that pre-geminate vowel lengthening effect is larger when the consonant is a voiceless stop (Idemaru & Guion, 2008). We can also predict that geminate liquids involve longer preceding vowels compared to other geminates, based on the report that for geminates with relatively shorter constriction duration, preceding vowels tend to be longer compared to geminates with longer constriction duration (Fukui, 1978).

Perceptually, listeners are thought to attend to both constriction duration and to the lengthening of preceding vowels to identify geminates in Japanese (but what exact cues listeners use to distinguish long consonants against the short ones are, overall, still unclear). Given the claim that approximant geminates are cross-linguistically avoided due to the perceptual difficulty of the constriction duration (Kawahara, 2007; Kawahara & Pangilinan, 2017), whether the lengthening of the preceding vowels of liquid geminates would be exaggerated is of particular interests. One may predict that since the constriction duration would be harder to perceive for geminate liquids, the preceding vowel lengthening may be exaggerated to compensate.

On the other hand, the vowel lengthening tendency could be due to some articulatory pressure (the possibility not being exclusive from the perceptual one). Takada

(1985) in Ofuka (2003) mention this possibility. The moraic nature of Japanese seems to be especially relevant when it comes to timing properties that are different from other languages (C. L. Smith, 1993, 1995; Maddieson, 1985; cf. Löfqvist, 2017).

2.1.2.3 Following vowel duration

There is more variability in phonetic results concerning the following vowel duration than for preceding vowel duration. For Japanese, Oba et al. (2009) report no clear difference between singleton and geminate regarding following vowel duration (the results predominantly depended on subjects). However, in many experiments, it is found that vowels tend to be shorter following geminates (Homma, 1981; Aizawa, 1985; Campbell, 1999; Han, 1994; Hirata, 2007; Idemaru & Guion, 2008; Ofuka, 2003). It is controversial whether following vowel duration is perceptually relevant to geminate-singleton discrimination (Kawahara, 2015b; Fukui, 1978).

2.2 Method

In order to investigate the acoustics of geminated liquids in Japanese, a production experiment was conducted. The core contribution of this section is that it provides a first quantitative acoustic analysis of geminated liquids in Japanese. The production data was collected at the same time as the articulatory data.[4]

2.2.1 Subjects

Eight native speakers of Tokyo Japanese (female=5) participated. Age of participants ranged from 19 to 28 and averaged 23.5. All of them lived in Japan at the time of the experiment. Participants were compensated for their participation. Instructions

[4]Please see the chapter 3 for a potential interference of the EMA sensors. However, results from other consonants than liquids suggest that the acoustic results are within the norm.

were provided in written and spoken Japanese, and a consent form written in Japanese was provided (the experimental protocol was approved by the IRB at UC Santa Cruz and Konan University). All of the participants self-identified as having normal speaking ability at the time of the experiment. Their age, gender, and language background were self-reported on a background questionnaire. The following table details the speakers' background.

Table 2.1: Gender, age, and language background or the speakers.

Subject	Gender	Age	Non-native languages
S1	M	23	English, French, Russian, German
S2	F	27	English
S3	F	23	English, French
S4	M	18	English
S5	F	24	English, Portuguese, Spanish
S6	M	28	English
S7	F	23	English, German, Russian
S8	F	22	English, Spanish

2.2.2 Speech materials

Stimuli for the main section were 39 Japanese mimetics in regular form (singleton condition) and emphatic form (geminate condition) as shown in Table 2, embedded in a carrier phrase "konnani <mimetic> nanowa hajimeteda (I've never experienced something so <mimetic>)". The carrier phrase allowed the sentences to be natural for either condition. All mimetics, in its regular form, had the structure of CVCVCVCV (we refer to the target consonant as C2, preceding vowel as V1, and following vowel as V2 hereafter). As seen in Table 2.2, emphasizing these mimetics usually involves geminating C2 (e.g. [gatagata]$\rightarrow$ [gattagata]). Target C2 were alveolar consonantal phonemes /t, d, r, n, s, z/. Paired with various vowels, the target sounds included their allophones as well: [t, tʃ, ts, d, s, ʃ, z (dz), n, n^j].[5] Effort was made to exhaust the surrounding vowel combinations, especially for the liquids. Items with symmetrical vowel contexts were prioritized over items with asymmetrical vowel contexts. Summary of the material is provided in the Table below.

The sentences were presented in Japanese orthography (in hiragana, size 42 points Hiragino Sans font), on an 9.7-inch tablet placed within about 1m from the participants. Each sentence appeared three times in randomized order. The material was displayed manually by the experimenter, using a remote controller (eProjector). In case of mispronunciations, participants were asked to read the sentence again.

[5]The current experiment was followed by a similar session in English, including English /ɹ/ and /l/. These are not discussed in this paper.

Table 2.2: Full speech material. Shaded items are not included in the acoustic or articulatory analyses.

#	Item ID	Regular	Emphasized	Cons	ConsType	Gloss
1	JR1	garagara	garragara	r	liquid	empty
2	JR2	girigiri	girrigiri	r	liquid	barely
3	JR3	guruguru	gurruguru	r	liquid	spinning
4	JR4	deredere	derredere	r	liquid	spoony
5	JR5	dorodoro	dorrodoro	r	liquid	gooey
6	JR6	wareware	warreware	r	liquid	split
7	JR7	garigari	garrigari	r	liquid	skinny
8	JR8	marumaru	marrumaru	r	liquid	rotund
9	JR9	meramera	merramera	r	liquid	flaring
10	JR10	beriberi	berriberi	r	liquid	peeled
11	JR11	berobero	berrobero	r	liquid	drunk
12	JR12	kirakira	kirrakira	r	liquid	shiny
13	JR13	kirekire	kirrekire	r	liquid	determined
14	JR14	girogiro	girrogiro	r	liquid	glaring
15	JR15	gorigori	gorrigori	r	liquid	hard
16	JR16	burabura	burrabura	r	liquid	dangling
17	JR17	burebure	burrebure	r	liquid	slurred
18	JR18	puripuri	purripuri	r	liquid	fresh
19	JR19	guroguro	gurroguro	r	liquid	grotesque
20	JT1	gatagata	gattagata	t	voiceless obs	rattling
21	JT2	gichigichi	gicchigichi	ch	voiceless obs	stuffed
22	JT3	gutsugutsu	guttsugutsu	ts	voiceless obs	boiling
23	JT4	gotegote	gottegote	t	voiceless obs	gaudy
24	JT5	gotogoto	gottogoto	t	voiceless obs	rumbling
25	JS1	gasagasa	gassagasa	s	voiceless fric	rustling
26	JS2	gishigishi	gisshigishi	sh	voiceless fric	squeaky
27	JS3	busubusu	bussubusu	s	voiceless fric	pronging
28	JS4	kosokoso	kossokoso	s	voiceless fric	sneaky
29	JZ1	mazemaze	mazzemaze	z	voiced fric	mixing
30	JD1	hidahida	hiddahida	d	voiced obs	pleated
31	JD2	hadehade	haddehade	d	voiced obs	flashy
32	JD3	gudaguda	guddaguda	d	voiced obs	lax
33	JD4	gudegude	guddegude	d	voiced obs	unmotivated
34	JD5	kudokudo	kuddokudo	d	voiced obs	pesky
35	JD6	odoodo	oddoodo	d	voiced obs	intimidated
36	JN1	shinashina	shinnashina	n	nasal	limp
37	JN2	funifuni	funnifuni	n/ny	nasal	downy
38	JN3	kunyukunyu	kunnyukunyu	ny	nasal	floppy
39	JN4	uneune	unnenune	n	nasal	windy

2.2.3 Procedure

Speech sound was recorded in a sound-proof room, using a Sony ECM-77B microphone, at 22.05 kHz. Electromagnetic Articulograph sensors were attached to the tongue of the speakers as articulatory data were collected simultaneously. After the sensors were affixed, participants were asked to read the experiment instruction aloud to get used to the articulation with the sensors. The first six trials were practice trials. Participants could take a break anytime during the experiment (not many participants did).

The acoustic signals were annotated using the Praat software (Boersma & Weenink, 2001). The onset and offset of the consonantal constriction were identified in the waveform and spectrogram display. While it was often difficult to determine the onset and offset of a liquid consonant due to its high sonorancy and formant effects on surrounding vowels, effort was made to measure the consonants from the offset of periodicity of V1 in the waveform to the onset of periodic cycle of V2, roughly following Idemaru and Guion-Anderson (2010). Measurement for voiced obstruent included the VOT. Acoustic measurements were obtained using the VoiceSauce software (Shue, Keating, Vicenik, & Yu, 2011) on MATLAB, and analysis was implemented using R (R Core Team, 2013). For statistical analyses, we used *lme4* package (Bates, Maechler, & Bolker, 2012) and *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017) on R to perform a linear mixed effects analysis of each measure. Phonological length (S or G) and consonant were entered as fixed effects. As random effects, we had intercepts for subjects and surrounding vowel environments,[6] as well as by-subject random slope for the effect of length. P-values were obtained through likelihood ratio tests. Models

[6] I realize this model might not be the best, as I do not include the effect of vowel environments as fixed effect. However, given the highly asymmetric and variant nature of this factor, I decided to have it as random effect for the modeling of the entire data. In the experiment, there are 20 different vowel environments (combination of preceding vowels and following vowels), half of which only apply to liquids.

based on individual speakers were also constructed, and are available in Appendix A.

Among the 10 consonant types included in the experiment, I examined the results for [t, d, r, n, s], eliminating the tokens with only one item. This amounted to a total of 1622 productions. Note that there is no results for [n] from one subject (S1).

Table 2.3: Number of productions subject to acoustic analysis.

Target consonant	Singleton productions	Geminate productions
t	73	72
d	145	144
r	459	458
n	62	65
s	72	72

2.2.4 Measurements

2.2.4.1 Durational measures

Results on C2 duration, V1 duration, and V2 duration are reported, keeping in mind the predictions that given previous research, C2 and V1 durations would be longer for geminates than singletons, and V2 duration would be shorter for geminates than singletons. In addition, VCV duration is reported, as it turns out that the total duration of C2, V1, and V2 are quite similar across consonant types. Similar effect can be observed for the word duration, which is available in Appendix A.

2.2.4.2 Non-durational measures

Results on the amplitude of the consonants and formant information on liquids, as well as auditory characteristics focusing on the laryngeal activities are reported. RMS (Root Mean Square) amplitudes averaged over the consonant were obtained using VoiceSauce, after standardization.

Formant values for each speaker are provided as well, keeping in mind that for

American liquids, drop in F1 (associated with tongue tip rise) and F2 (associated with tongue body retraction) for dark /l/ compared to clear /l/ are reported (Ying et al., 2012), and that retroflexion is often associated with drop in F3 (Moore, Shaw, Kawahara, & Arai, 2018; Dalston, 1975; Hagiwara, 1995).

Finally, for some of the productions, it was auditorily clear that a full glottal stop has been inserted at the beginning of the geminates, or that some weak laryngealization has occurred during the first part of the geminates. The productions were categorized into four categories (Glottal stop insertion, Weak laryngealization, Possibly, and None) by the author based on the auditory information. The category "Possibly" was created to label non-sonorant tokens that may be accompanied with laryngealization. The effect is usually masked with the lingual constriction, making it difficult to determine the presence of laryngealization.

2.3 Durational results & discussion

2.3.1 Consonant duration

2.3.1.1 Duration and ratio per consonant

For all consonants, there is a robust difference between the singletons and geminates, geminates being about twice to three times longer than singletons. The durational difference and the geminate-to-singleton ratio (GSR) are summarized in Table 2.4 and Figure 2.1. The best model of acoustic consonant duration includes an interaction between Length and Consonant, and the fixed effects coefficients are shown in Table 2.5. Overall, there is a main effect of Length ($\chi^2(1)=27.934$, $p<0.001$), lengthening C2 by about 67.65 ms $\pm$ 5.4 (standard error). There is also a main effect of Consonant ($\chi^2(4)=441.26$, $p<0.001$).

Table 2.4: Mean constriction duration (ms) and GSR per consonant. Standard deviation is provided in parenthesis (the GSR are calculated for each item and averaged within each consonant category). *n* for singletons and geminates are provided for each consonant.

Consonant (*n*)	Singleton	Geminate	GSR
t (73, 72)	70.03 ms (16.04)	137.65 ms (20.46)	1.97 (0.09)
d (145, 144)	49.78 ms (14.84)	128.25 ms (28.72)	2.62 (0.34)
r (459, 458)	32.29 ms (13.12)	101.38 ms (29.24)	3.17 (0.36)
n (62, 65)	46.29 ms (21.85)	116.20 ms (28.30)	2.72 (0.8)
s (72, 72)	64.50 ms (19.36)	131.74 ms (19.22)	2.06 (0.21)

Figure 2.1: Violin plots showing the mean durations per consonant and length. The overlaid box plots show the median and the interquartile range (25% and 75%). The width of each violin represent the probability for the value to occur at any value.

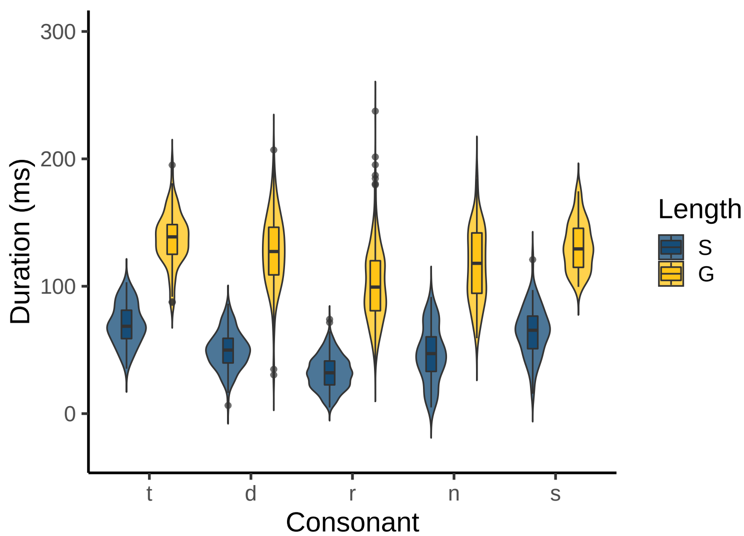


Table 2.5: Fixed effects coefficients table for the model of the acoustic consonant duration.

C2 duration $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	69.094	3.067	101.799	22.527	< 2e-16	***
LengthG	67.654	5.433	16.433	12.453	8.66e-10	***
Consonantd	-17.636	3.094	1030.165	-5.7	1.56e-08	***
Consonantr	-36.724	2.763	858.648	-13.29	< 2e-16	***
Consonantn	-20.189	3.75	1085.944	-5.384	8.91e-08	***
Consonants	-6.408	3.317	1505.207	-1.932	0.054	.
LengthG:Consonantd	10.961	3.833	1588.276	2.859	0.004	**
LengthG:Consonantr	1.116	3.367	1588.357	0.331	0.74	
LengthG:Consonantn	3.395	4.591	1591.927	0.74	0.46	
LengthG:Consonants	-0.336	4.432	1588.31	-0.076	0.94	

The average durations of the consonants show that singleton /r/ are very short (about 32 ms) compared to /t/ (about 70 ms), as expected. Singleton consonants are long in the order of [t > s > d > n > r], which is mostly consistent with Han (1962), who provides Japanese consonants grouped in terms of inherent singleton duration as [s, t > d, n > r] (excluding the consonants not considered in the current experiment). Voiceless obstruents are the longest, the voiced obstruents are less long, and the liquid is the shortest. The GSR of these consonants mirror the singleton duration, meeting the cross-linguistic expectation that consonant GSR inversely correlates with the duration of the singletons: [t < s < d < n < r]. Crucially, liquids have the shortest duration as singleton, and the largest GSR.

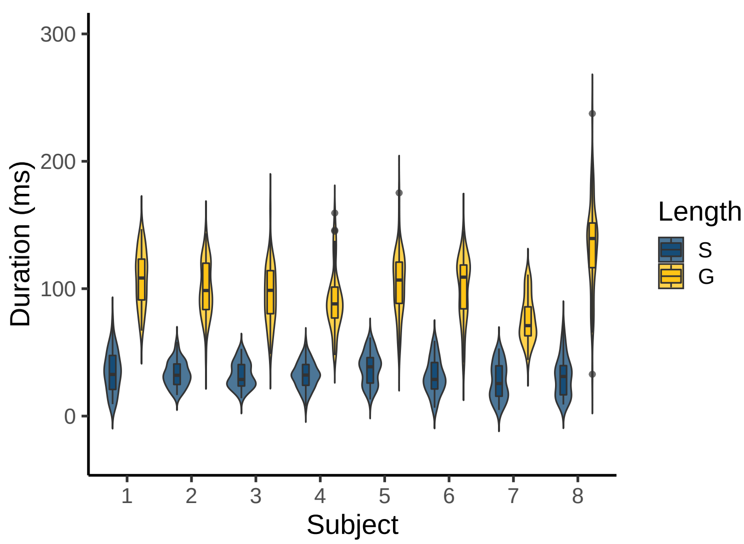
2.3.1.2 Duration and ratio for liquids

Table 2.6 and Figure 2.2 summarize the duration of liquid consonants per subject. While all subjects maintain clear durational contrast between singleton and geminate liquids, their GSR range from 2.95 (S5) to 4.86 (S8), showing considerable variation among the speakers. S8 stands out due to her within-speaker variability, especially when producing liquid geminates. Interestingly, as will be discussed in later section, S5 and S8 sometimes laryngealize their liquid geminates.

Table 2.6: Durations and GSR for liquids by subject. Standard deviation is provided in parenthesis (the GSR are calculated for each item and averaged within each subject). *n* for singletons and geminates are provided for each subject.

Subject	Singleton	Geminate	GSR
1 (54, 53)	34.94 ms (15.88)	108.21 ms (21.35)	3.43 (1.31)
2 (59, 57)	32.99 ms (9.92)	99.94 ms (21.05)	3.10 (0.61)
3 (57, 59)	32.18 ms (10.02)	95.03 ms (22.72)	3.10 (0.79)
4 (58, 57)	32.15 ms (10.27)	90.92 ms (24.25)	3.08 (1.21)
5 (57, 55)	37.28 ms (12.49)	104.20 ms (24.54)	2.95 (0.76)
6 (57, 57)	30.94 ms (13.58)	100.37 ms (24.49)	3.37 (0.70)
7 (58, 57)	27.28 ms (15.65)	76.08 ms (17.74)	3.10 (1.20)
8 (59, 63)	30.81 ms (12.21)	133.71 ms (36.29)	4.86 (1.96)

Figure 2.2: Acoustic duration of liquids per subject and length.



2.3.1.3 Summary

When asked to read some mimetic words with geminated liquids, speakers produce them with robust acoustic durational contrast. Geminated liquids are produced with about three times longer acoustic duration on average. The constriction duration of liquids vary depending on the speaker. While the singleton duration are fairly consistent (around 30 ms), the GSR vary from about 2 to 5 times depending on the speaker. The two extremes on this scale were S5 (smallest GSR) and S8 (largest GSR), who both produced some laryngealized tokens.

2.3.2 Preceding vowel duration

2.3.2.1 Duration and ratio per consonant

Vowels preceding geminates are characteristically longer compared to vowels preceding singletons, as expected. The duration of vowels preceding the target consonant for all consonant types is summarized in Table 2.7 and Figure 2.3. Again, the best model of the preceding vowel duration includes an interaction between Length and Consonant (Table 2.8). Overall, there is a main effect of Length ($\chi^2(1)$=23.71, p<0.001), lengthening the preceding vowel by about 19.14 ms $\pm$ 3.8 (standard error). There is also a main effect of Consonant ($\chi^2(4)$=115.4, p<0.001). The interaction between Length and Consonant shows that V1 duration for /r/ and /n/ are modulated by Length. While the durational differences across consonants in V1 are much less compared to C2, /r/ has the largest GSR, and longest average duration for geminates (about 100 ms).

Table 2.7: Mean preceding vowel duration and GSR (SD) per consonant.

Consonant	Singleton	Geminate	GSR
t	67.59 ms (16.38)	86.87 ms (20.5)	1.28 (0.07)
d	57.04 ms (23.39)	79.53 ms (24.34)	1.44 (0.17)
r	68.49 ms (20.46)	100.68 ms (25.71)	1.49 (0.19)
n	61.18 ms (22.17)	89.91 ms (27.43)	1.50 (0.24)
s	65.76 ms (17.98)	88.57 ms (18.38)	1.36 (0.06)

Figure 2.3: V1 duration per consonant and length.

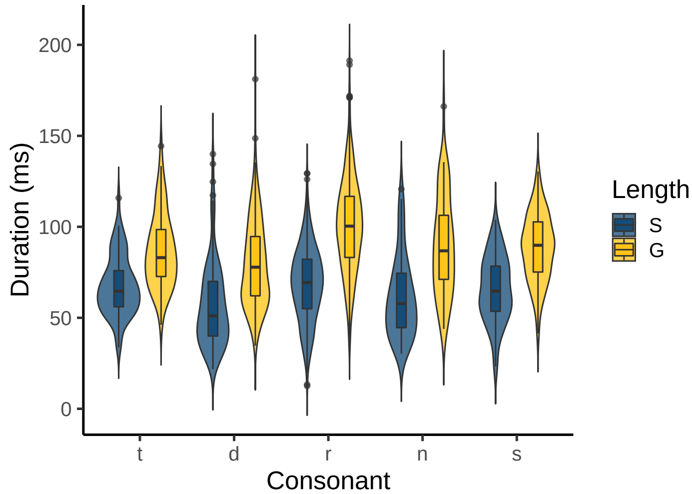


Table 2.8: Fixed effects coefficients table for the model of V1 duration.

V1 duration ∼ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	59.844	4.486	33.106	13.34	7.11e-15	***
LengthG	19.141	3.81	55.604	5.024	5.57e-06	***
Consonantd	1.367	3.236	1519.22	0.423	0.673	
Consonantr	9.096	2.916	1450.484	3.119	0.002	**
Consonantn	9.767	3.912	1541.8	2.497	0.013	*
Consonants	-1.244	3.395	1604.048	-0.366	0.714	
LengthG:Consonantd	3.394	3.862	1586.052	0.879	0.38	
LengthG:Consonantr	13.086	3.391	1586.104	3.859	0.0001	***
LengthG:Consonantn	10.157	4.624	1590.043	2.196	0.028	*
LengthG:Consonants	3.615	4.464	1586.067	0.81	0.418	

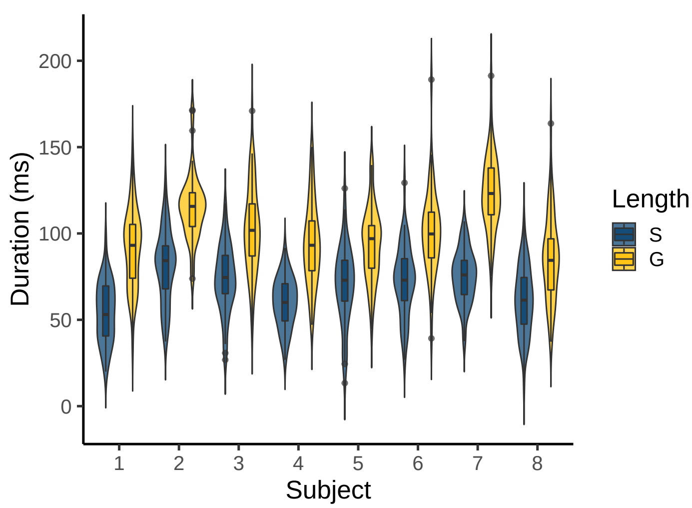
2.3.2.2 Duration and ratio for liquids

Compared to the constriction duration for geminated liquids, there are much less individual variability for the preceding vowels. Table 2.9 indicates that GSR is approximately between 1.4 to 1.7.

Table 2.9: V1 durations and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1	54.35 ms (17.25)	91.47 ms (22.45)	1.76 (0.44)
2	80.71 ms (20.89)	115.12 ms (18.91)	1.46 (0.27)
3	73.29 ms (19.34)	102.24 ms (25.2)	1.42 (0.32)
4	60.13 ms (14.33)	93.91 ms (23.84)	1.59 (0.25)
5	70.27 ms (22.7)	93.48 ms (20.93)	1.43 (0.46)
6	72.49 ms (20)	100.44 ms (23.93)	1.43 (0.3)
7	74.85 ms (15.12)	123.75 ms (21.44)	1.7 (0.36)
8	60.97 ms (19.42)	85.64 ms (25.09)	1.47 (0.37)

Figure 2.4: V1 duration for liquids per subject and length.



2.3.2.3 Summary

As expected from previous studies, preceding vowels are characteristically longer for geminates than in singletons, and liquids are no exception. There is no particularly remarkable individual differences either. However, V1 tends to be lengthened more before geminated liquids than in other consonants.

2.3.3 Following vowel duration

2.3.3.1 Duration and ratio per consonant

Against the expectation that vowels following geminates are shorter than vowels following singletons, consonants vary in terms of how their following vowels behave. The duration of vowels preceding the target consonant for all consonant types is summarized in Table 2.10 and Figure 2.5. The best model of the following vowel duration includes an interaction between Length and Consonant (Table 2.11).

First, the duration of V2 vary between singleton consonants, where V2 following voiced consonants (whose constriction durations are shorter than /t/) are longer than the ones following /t/. Second, V2 for obstruents (/t, d, s/) show a shortening tendency when following geminates. However, V2 for sonorants (/r, n/) have the opposite tendency, lengthening after geminates.

Table 2.10: Mean V2 duration and GSR (SD) per consonant.

Consonant	Singleton	Geminate	GSR
t	62.06 ms (16.03)	59.38 ms (13.89)	0.96 (0.02)
d	80.02 ms (18.1)	75.55 ms (18.78)	0.95 (0.09)
r	79.9 ms (19.94)	87.09 ms (19.71)	1.1 (0.09)
n	84.4 ms (18.65)	90.27 ms (18.98)	1.07 (0.05)
s	62.28 ms (23.95)	57.34 ms (13.46)	0.92 (0.07)

Figure 2.5: V2 duration per consonant and length.

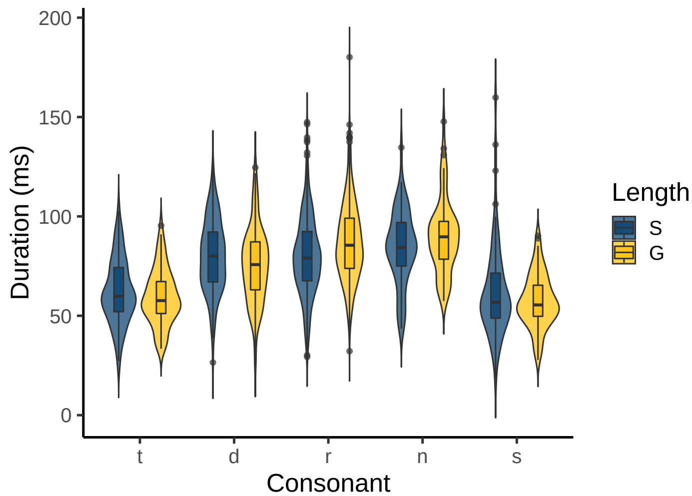


Table 2.11: Fixed effects coefficients table for the model of the following duration.

V2 duration ∼ Length * Consonant + (1 + Length ǀ Subj) + (1 ǀ VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> ǀtǀ)	
(Intercept)	58.719	3.481	40.252	16.866	< 2e-16	***
LengthG	-2.793	2.975	176.818	-0.939	0.349	
Consonantd	19.406	2.825	1368.219	6.869	9.77e-12	***
Consonantr	21.325	2.538	1238.462	8.401	< 2e-16	***
Consonantn	26.217	3.416	1412.717	7.674	3.09e-14	***
Consonants	1.059	2.983	1585.299	0.355	0.723	
LengthG:Consonantd	-1.843	3.409	1586.59	-0.54	0.589	
LengthG:Consonantr	10.038	2.994	1586.695	3.352	0.001	***
LengthG:Consonantn	8.267	4.078	1593.878	2.027	0.043	*
LengthG:Consonants	-2.157	3.942	1586.622	-0.547	0.584	

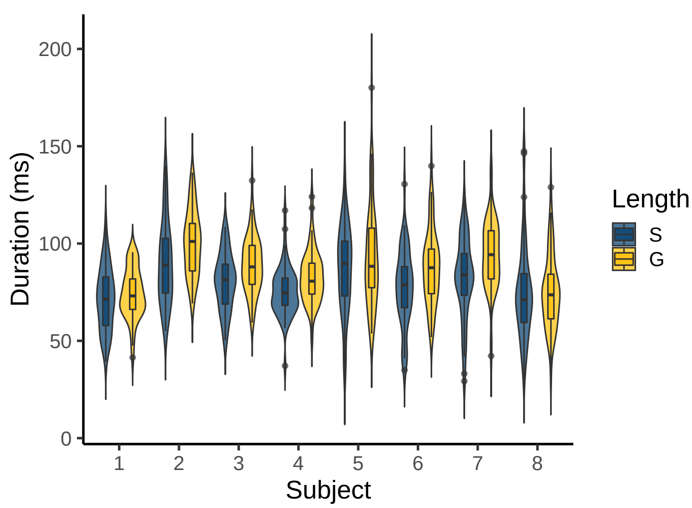
2.3.3.2 Duration and ratio for liquids

The duration of the vowels following liquids are again fairly consistent across speakers compared to C2 duration, and all speakers participate in the unexpected direction of the Length effect, slightly lengthening the following vowels.

Table 2.12: V2 durations and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1	71.63 ms (16.02)	74.14 ms (12.63)	1.06 (0.22)
2	89.94 ms (21.08)	100.47 ms (16.64)	1.14 (0.18)
3	80.33 ms (14.5)	89.04 ms (14.41)	1.12 (0.11)
4	75.47 ms (12.73)	82.85 ms (13.6)	1.11 (0.14)
5	87.05 ms (22)	93.47 ms (26.13)	1.14 (0.32)
6	77.33 ms (19.5)	87.93 ms (19.1)	1.16 (0.23)
7	82.14 ms (20.62)	94.3 ms (17.38)	1.21 (0.35)
8	74.77 ms (23.91)	75.01 ms (18.97)	1.05 (0.3)

Figure 2.6: V2 duration for liquids per subject and length.



2.3.3.3 Summary

Following vowels behave very differently depending on the consonant. There is a shortening tendency for obstruent geminates as expected, but not statistically significant. For sonorant geminates, there is a significant lengthening tendency.

2.3.4 VCV duration

2.3.4.1 Duration and ratio per consonant

As exemplified in Figure 2.7, VCV durations (and the GSR) are strikingly similar across consonants and length despite the differences in C2 durations. The best model of VCV duration (Table 2.14) shows that VCV duration for liquids is most greatly increased when geminated.

Table 2.13: Mean VCV duration (SD) and GSR per consonant.

Consonant	Singleton	Geminate	GSR
t	199.69 (27.14)	283.90 (27.39)	1.42 (0.01)
d	186.84 (32.32)	283.33 (33.31)	1.52 (0.07)
r	180.68 (26.25)	289.15 (28.37)	1.60 (0.09)
n	191.86 (37.64)	296.37 (36.40)	1.56 (0.11)
s	192.53 (32.89)	277.65 (27.80)	1.45 (0.04)

Figure 2.7: VCV duration per consonant and length.

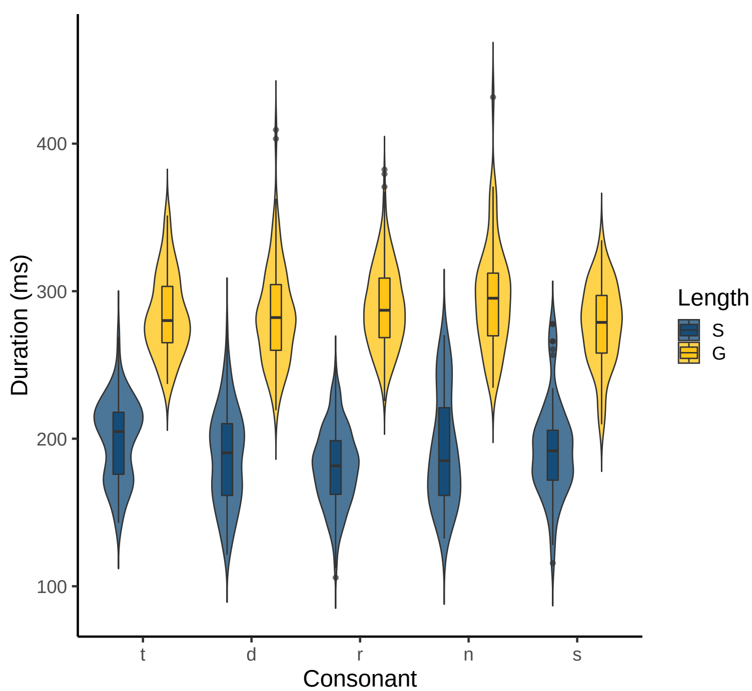


Table 2.14: Fixed effects coefficients table for the model of the VCV duration.

VCV duration $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	186.46	6.844	22.858	27.244	< 2e-16	***
LengthG	83.998	5.379	28.656	15.615	1.55e-15	***
Consonantd	4.772	4.008	1583.269	1.191	0.234	
Consonantr	-4.995	3.617	1555.736	-1.381	0.168	
Consonantn	18.016	4.842	1591.562	3.721	0.0002	***
Consonants	-6.281	4.188	1606.346	-1.5	0.134	
LengthG:Consonantd	12.527	4.748	1586.558	2.638	0.008	**
LengthG:Consonantr	24.233	4.17	1586.591	5.811	7.50e-09	***
LengthG:Consonantn	21.824	5.689	1588.54	3.836	0.0001	***
LengthG:Consonants	1.159	5.49	1586.564	0.211	0.833	

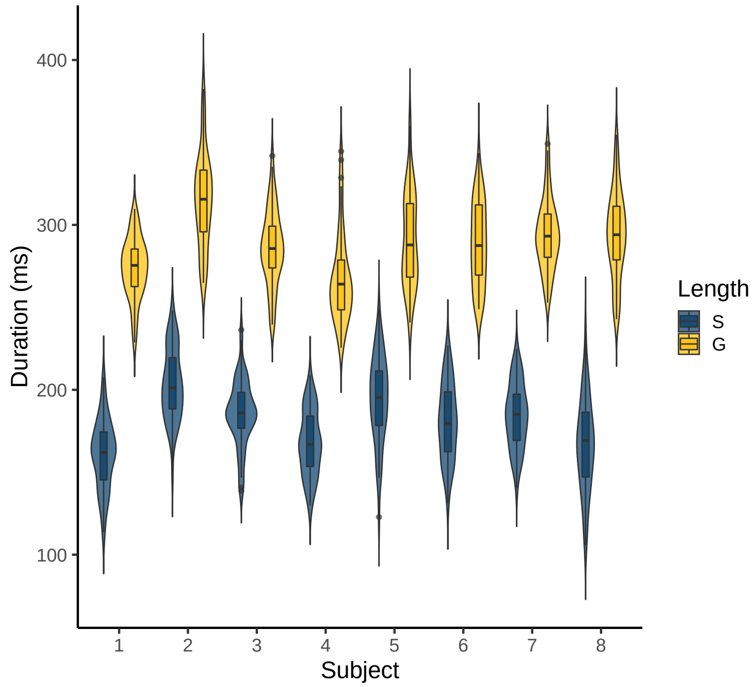
2.3.4.2 Duration and ratio for liquids

The durations of the VCV regions with target liquid consonants are quite uniform across speakers, as shown in Table 2.15 and Figure 2.8.

Table 2.15: VCV durations and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1	160.92 (20.72)	273.81 (18.37)	1.72 (0.16)
2	203.65 (21.72)	315.53 (28.59)	1.55 (0.12)
3	185.81 (19.96)	286.32 (23.20)	1.54 (0.08)
4	167.75 (19.61)	267.68 (27.29)	1.61 (0.16)
5	194.60 (26.04)	291.15 (28.50)	1.52 (0.12)
6	180.76 (23.09)	288.75 (25.17)	1.61 (0.16)
7	184.27 (19.69)	294.13 (21.75)	1.60 (0.12)
8	166.56 (27.65)	294.37 (26.46)	1.79 (0.20)

Figure 2.8: VCV duration for liquids per subject and length.



2.3.5 Discussion

For both C2 and V1 durations, the results confirmed previous research on obstruent geminates that gemination results in increased durations, and clarified that the same is true for liquid geminates. They also showed that constriction durations in liquid geminates vary per individuals, ranging from twice to almost five times longer than singletons. V1 lengthening was most robust in geminated liquids compared to other consonants, lengthening about 13 ms. This tendency was more consistent among speakers compared to constriction durations. V2 results were less consistent across consonants: obstruent geminates showed slight shortening (expected direction given previous research on Japanese geminates, but not significant), while sonorant geminates showed lengthening (expected direction given previous research on geminates in other languages such as Italian, and significant). Again, the individual variability in V2 lengthening was moderate compared to the variability in constriction durations.

The robust lengthening of C2 and V1 durations in liquids can be seen as "exaggeration of cue" for gemination, especially given the previously claimed perceptibility hardship of length contrast in liquids. By the same token, one could argue that V2 duration is not an important cue for gemination for listeners to pay attention to, given the disparity in our data.

From a slightly different perspective, the profuse lengthening of C2, V1, and V2 for geminated liquids, contributes to a stretched VCV duration (the duration between the onset of V1 and the offset V2), and more globally, to a stretched word duration (see Appendix A). The absolute durations of the VCV region with geminates were strikingly similar across consonants, the GSR for VCV region ranging from 1.42 to 1.60.

2.4 Non-durational results & discussion

2.4.1 Intensity on the consonants

2.4.1.1 Intensity per consonants

Overall, singletons have greater energy than geminates (averaged over the consonant; $\chi^2(1)=18.203$, $p<0.001$). The amplitude vary significantly among the consonants ($\chi^2(4)=721.3$, $p<0.001$), mostly depending on whether the consonant is voiced or voiceless (the RMS amplitude is 0 when there is no voicing). The best model of RMS amplitude at the mid-third portion of the consonant includes an interaction between Length and Consonant (Table 2.17). Intensity on voiced consonants are significantly reduced when geminated.

Table 2.16: RMS amplitude and GSR (SD) on C2 per consonant.

Consonant	Singleton	Geminate	GSR
t	0.16 (0.14)	0.06 (0.05)	0.41 (0.09)
d	0.38 (0.31)	0.15 (0.11)	0.38 (0.06)
r	0.65 (0.32)	0.33 (0.23)	0.52 (0.07)
n	0.73 (0.33)	0.58 (0.32)	0.80 (0.06)
s	0.16 (0.22)	0.06 (0.07)	0.38 (0.04)

Figure 2.9: RMS amplitude per consonant and length.

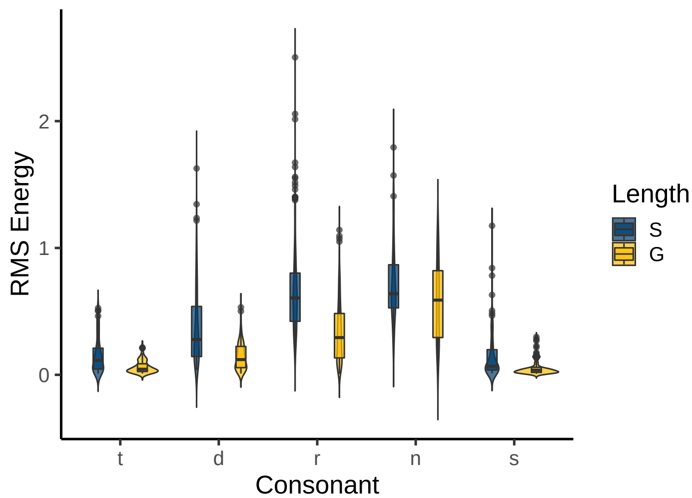


Table 2.17: Fixed effects coefficients table for the model of the RMS amplitude averaged over the consonant.

C2 RMS ∼ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.137	0.079	10.461	1.725	0.114	
LengthG	-0.095	0.04	31.201	-2.385	0.023	*
Consonantd	0.226	0.03	1371.563	7.527	9.37e-14	***
Consonantr	0.518	0.027	1242.872	19.246	< 2e-16	***
Consonantn	0.586	0.036	1414.23	16.169	< 2e-16	***
Consonants	0.008	0.032	1585.459	0.244	0.807	
LengthG:Consonantd	-0.145	0.036	1586.559	-4.013	6.29e-05	***
LengthG:Consonantr	-0.224	0.032	1586.63	-7.058	2.51e-12	***
LengthG:Consonantn	-0.073	0.043	1590.726	-1.698	0.09	.
LengthG:Consonants	-0.01	0.042	1586.572	-0.245	0.807	

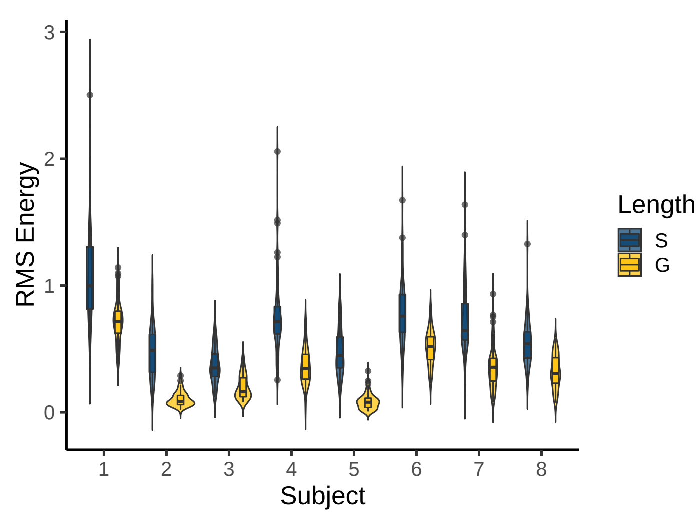
2.4.1.2 Intensity of liquids per subject

All the speakers share the tendency, and the reduction in amplitude for geminated liquids is significant for everyone except for S8. Similar reduction is present for /n/ in S2, S3, and S5 but not for others (S1 did not produce any /n/ tokens). However, speakers vary considerably in terms of the amplitude on liquids, short or long. The variability in singleton liquids is at least consistent with the previous reports that their manners of articulation vary, and seems to point to similar behavior for geminated liquids as well. The variability in the ratio also points to variable relationship between singleton articulation and geminate articulation in each speaker.

Table 2.18: Mean RMS amplitude of C2 for liquids per subject.

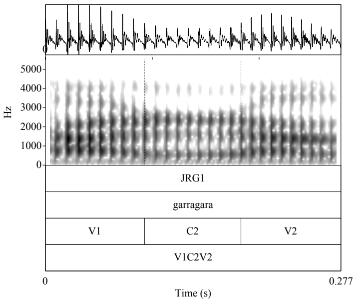
Subject	Singleton	Geminate	GSR
1	1.08 (0.36)	0.72 (0.18)	0.69 (0.12)
2	0.47 (0.2)	0.1 (0.06)	0.23 (0.09)
3	0.37 (0.14)	0.2 (0.1)	0.54 (0.17)
4	0.76 (0.31)	0.37 (0.14)	0.51 (0.14)
5	0.47 (0.18)	0.09 (0.07)	0.19 (0.11)
6	0.79 (0.26)	0.51 (0.13)	0.68 (0.19)
7	0.74 (0.27)	0.36 (0.18)	0.55 (0.31)
8	0.55 (0.18)	0.32 (0.13)	0.59 (0.16)

Figure 2.10: RMS amplitude for liquids per subject and length.

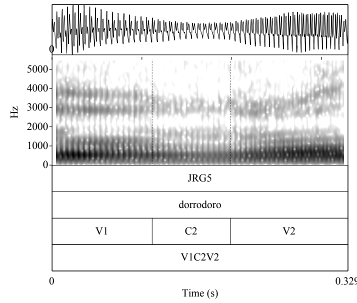


Among the speakers, S1's geminated liquids are as loud as the average singleton liquids. Otherwise, most of the amplitude on geminated liquids are as low as geminated /n/ or singleton /d/. However, most of the geminated liquid productions maintain the sonorant quality with clear formant structures, except for the tokens with glottal stop insertion (which mostly come from S5) discussed in later section, and some low-amplitude productions from S2. Figure 2.11 presents some spectrograms of representative geminated liquids (VCV region) from each speakers, showing that they are fully voiced throughout, supporting formant structures.

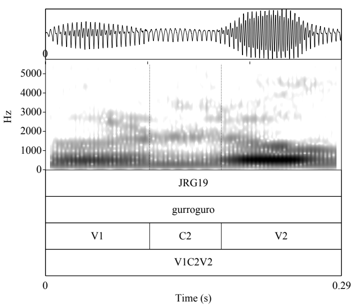
Figure 2.11: Sample spectrograms for each subject.



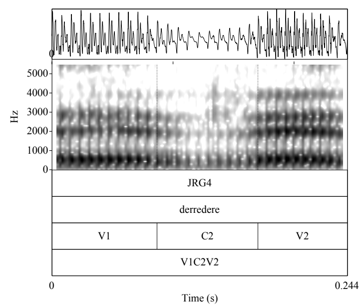
(a) S1



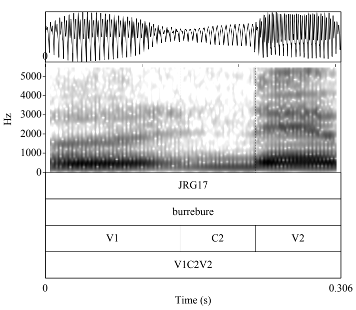
(b) S2



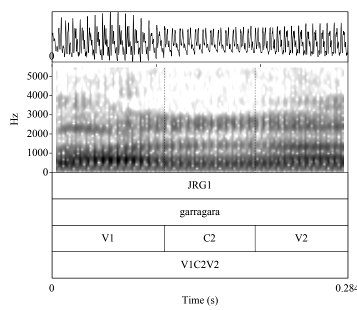
(c) S3



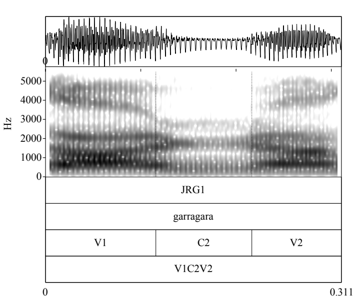
(d) S4



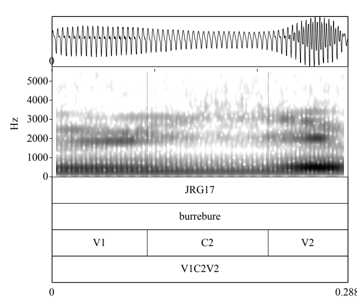
(e) S5



(f) S6



(g) S7



(h) S8

The following table summarizes the amplitude on the consonant at the first, second, and last third of the consonant duration. It shows that S5 has extremely low amplitude up to the mid-third, but the last part of the geminated liquids has an increased amplitude (this goes hand in hand with the results in section 2.4.3). S2 (and S3) never produced geminated liquids that contained glottal stops, but they have relatively low amplitude.

Table 2.19: Mean RMS amplitude of liquids per speaker: first third, mid-third, and last third.

	First third of C2		Mid-third of C2		Last third of C2	
Subject	Singleton	Geminate	Singleton	Geminate	Singleton	Geminate
1	1.01 (0.35)	0.75 (0.2)	1.02 (0.38)	0.6 (0.18)	1.19 (0.41)	0.8 (0.25)
2	0.45 (0.18)	0.12 (0.07)	0.45 (0.21)	0.09 (0.06)	0.51 (0.23)	0.11 (0.06)
3	0.35 (0.14)	0.23 (0.12)	0.36 (0.15)	0.17 (0.09)	0.41 (0.16)	0.2 (0.11)
4	0.69 (0.3)	0.42 (0.19)	0.71 (0.32)	0.27 (0.15)	0.88 (0.34)	0.41 (0.16)
5	0.47 (0.18)	0.06 (0.08)	0.46 (0.19)	0.06 (0.07)	0.48 (0.2)	0.15 (0.09)
6	0.8 (0.27)	0.56 (0.12)	0.78 (0.27)	0.47 (0.14)	0.78 (0.25)	0.52 (0.19)
7	0.74 (0.26)	0.44 (0.24)	0.73 (0.3)	0.33 (0.17)	0.74 (0.28)	0.32 (0.17)
8	0.55 (0.17)	0.38 (0.19)	0.55 (0.21)	0.29 (0.14)	0.56 (0.22)	0.29 (0.13)

2.4.1.3 Summary

Singletons are generally louder than geminates, and amplitude on liquids consonants show a lot of individual variability. Speakers vary considerably in terms of how loud their geminated liquids are, and also in terms of how quiet they are relative to their singleton liquids. The liquid geminates are largely sonorants, with voicing throughout (unless interrupted by a glottal stop), and there is some within- and across-subject variability as to how much formant structures are detectable.

2.4.2 Formant frequencies on liquids

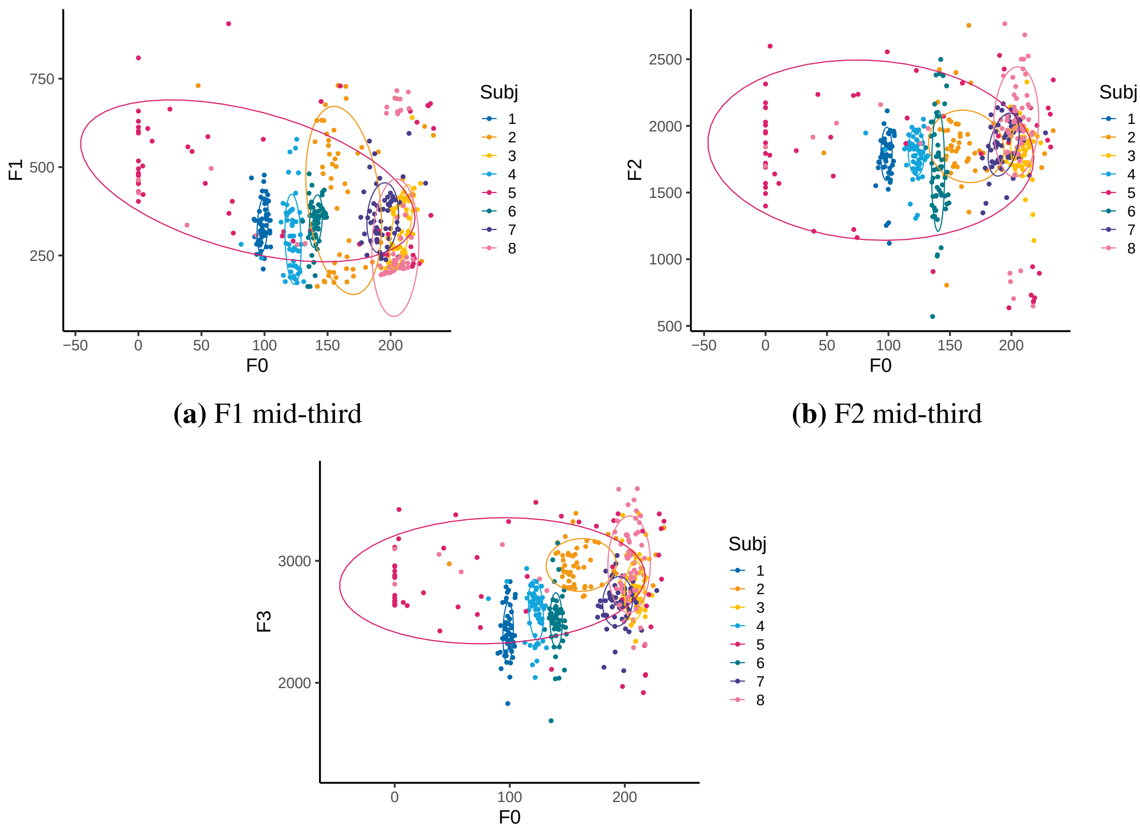
Table 2.20 below summarizes the frequency values for F1, F2, and F3, per length and subject. It should be noted that formant values in S2 and S5 (and sometimes S8) are not as reliable as in other speakers due to the absence of voicing or very low amplitude.

Table 2.20: Mean F1, F2, and F3 frequencies (SD) on the mid-third portion of liquids by subject.

Subject	Singleton F1	Gem F1	Singleton F2	Gem F2	Singleton F3	Gem F3
1	442.4 (85.51)	339.5 (60.18)	1681.92 (224.38)	1765.04 (183.01)	2341.91(325.6)	2411.57 (198.17)
2	480.69 (138.5)	409.6 (189.93)	1632.93 (508.88)	1855.14 (266.09)	2850.77 (298.44)	2986.47 (188.87)
3	444.74 (88.91)	338.87 (94.98)	1833.94 (222.7)	1810.67 (179.25)	2693.93 (217.56)	2777.05 (204.2)
4	441.52 (92.41)	304.07 (99.2)	1725.01 (210.83)	1791.97 (149.66)	2406.34 (300.67)	2579.12 (195.22)
5	466.72 (153.69)	475.13 (168.93)	1616.17 (695.23)	1764.17 (525.37)	2732.78 (474.92)	2825.34 (396.93)
6	424.58 (74.82)	343.18 (64.13)	1724.7 (472.13)	1671.05 (366.2)	2557.21 (277.03)	2503.94 (221.42)
7	439.04 (65.35)	362.51 (81.67)	1790.24 (303.53)	1851.57 (182.19)	2599.97 (325.73)	2651.67 (176.15)
8	375.88 (152.87)	328.93 (175.54)	1950.2 (433)	1964.07 (413.77)	2768.69 (334.89)	2968.78 (291.83)

F1 tends to reduce for geminates for most speakers, which is consistent with two lines of previous research. First, geminates are reported to have a tighter or higher constriction, so decrease in F1 frequency may be pointing to an higher tongue tip location. Second, F1 is reported to drop for dark /l/ compared to light /l/ in English, so geminated liquids in Japanese, if lateral, may have a darker flavor rather than a lighter flavor. The exception is S5, whose F1 frequency is rising for geminates (however, note that formant tracking in S5 may not be reliable due to the laryngeal activities, see section 2.4.3 below). Speakers vary as to the direction of F2 in geminates: S1, S2, S4, S5, S7, and S8 have an increasing trend, pointing to tongue body retraction, while S3 and S6 have a decreasing tendency. F2 has been falsified to correlate inversely with tongue body anteriority for English laterals, against the prediction based on vowels (Ying et al., 2012), such that for laterals, decrease in F2 indicates tongue advancement. In our data, most subject show increase in F2, indicating tongue retraction. The general tendency for F3 is to increase when geminated, except for S6. This could mean that in general, singletons have more retroflex flavor compared to geminates. Considering the individual differences in F0 (Figure 2.12), F3 in geminated liquids for S3 and S7 are particularly low.

Figure 2.12: C2 formant frequencies for liquids per subject.



(a) F1 mid-third

(b) F2 mid-third

(c) F3 mid-third

2.4.2.1 Summary

The formant profile of geminated liquids provides evidence for different flavors of liquids across speakers and consonant length.

2.4.3 Laryngeal activity

Auditory information (and later, tongue tip gestural information) suggest that there is no trilled productions, as expected. However, they also reveal that some of the productions include laryngeal activities of varying degrees (insertion of a glottal stop, voicing with weak laryngealization, possible laryngealization masked with consonant constriction, and none detected).

First, there is no audible laryngealization, weak or strong, for singletons. All laryngealization are for geminates. There is also no laryngealized token for /s/. Most laryngealized tokens are liquid geminates, and they mostly come from S5, and some from S8 (Tables 2.21, 2.22). Figure 2.13 below shows some representative tokens with glottal stop insertion and weak laryngealization.

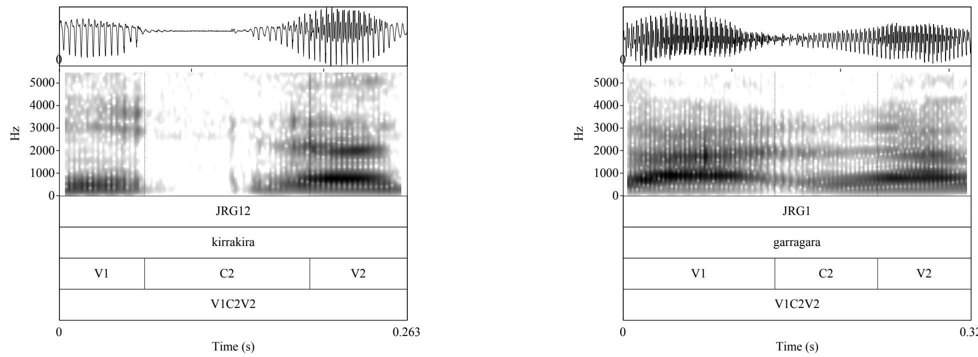
Table 2.21: Number of laryngealized productions for each consonant (excluding singletons).

Consonant	Glottal stop insertion	Weak laryngealization	Possibly	None
t	0	0	9	63
d	0	2	44	98
r	36	21	0	401
n	4	1	0	60
s	0	0	0	72
Total	40	24	53	694

Table 2.22: Number of laryngealized productions for each subject (excluding singletons). Laryngealized consonants in parenthesis.

Subject	Glottal stop insertion	Weak laryngealization	Possibly	None
1	0	0	15 (t, d)	74
2	1 (r)	0	5 (d)	96
3	0	0	2 (d)	103
4	2 (r)	0	5 (t, d)	95
5	34 (r, n)	18 (d, r, n)	12 (t, d)	36
6	0	0	1 (t)	101
7	0	0	6 (t, d)	96
8	3 (r, n)	6 (r)	7 (d)	93
Total	40	24	53	694

Figure 2.13: Sample spectrograms from S5.



(a) S5 glottal stop insertion sample **(b)** S5 weak laryngealization sample

2.4.3.1 Summary

Auditory information suggest that some geminates are produced with a laryngeal component. The notion of geminates accompanied with some laryngeal gesture is not surprising given that some description of *sokuon* has often involved some impression of "chokiness" or "caught-in-the-throatness". For example, Aizawa (1985) describes the "choked sound" in Japanese as having "a simultaneous glottal stop or tension" in addition to the retention of the constriction. Fujimoto et al. (2010) and Kawahara (2013) also point out the possibility that some laryngeal tension is involved in the production/perception of geminates in Japanese, though not conclusive.

While the absolute absence of laryngealization on geminated /s/ and in most obstruent geminates may suggest otherwise, there is still a possibility that there the laryngeal component is realized as creakiness on adjacent vowels (Idemaru & Guion, 2008). Interestingly, in our data, the difference in creakiness on the surrounding vowels between singletons and geminates are relatively more prominent for /t, n, s/, i.e. the consonants during which laryngealization are not expressed a lot.

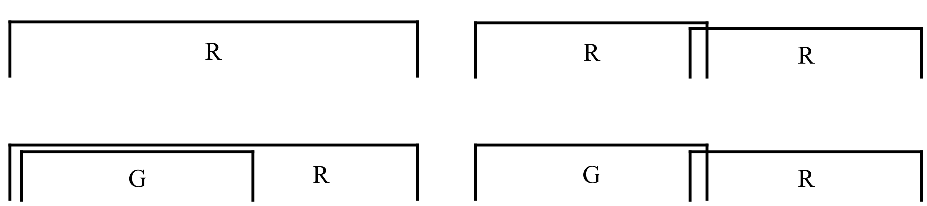
In the meantime, the fact that some geminated /n/ are also laryngealized in our data, may point to an alternative interpretation of these laryngeal gestures, as by-products of emphatic gemination rather than an underlying component of gemination. Geminate /n/ is abundant in Japanese phonology, usually produced without audible laryngealization.

2.5 Discussion & summary

The acoustic results showed that geminated liquids come with a robust acoustic durational contrast, some shared core properties, and a lot of variability. Acoustic properties that are relatively stable are the duration of the VCV region, and the voiced nature of geminated liquids (most productions supported clear formant structures, and despite the laryngeal constriction on some of the geminated liquids, the release was still sonorant). On the other hand, the productions varied within and across individuals in terms of the absolute consonant duration, surrounding vowel durations, intensity on the consonants, and formant structure. The auditory information also clearly indicated variability in the production strategies within and across speakers, such as the use of laryngealization (though further studies are called for in order to understand the nature of this phenomenon).

These acoustic results support both gestural specification of geminated liquids mentioned in section 1.3.3, and give rise to two more possibilities. The four possibilities are exemplified in Figure 2.14.

Figure 2.14: Gestural possibilities for geminated liquids, updated. Top left represents a single long liquid; top right represents two partially overlapping liquids; bottom left represents a single long liquid with overlapping laryngeal gesture; bottom right represents a laryngeal gesture partially overlapped with a short liquid.



Chapter 3

Articulatory Characteristics of Geminated Liquids in Japanese

3.1 Introduction

This chapter summarizes previous articulatory studies on geminates and liquids, and reports on the methodology and articulatory results of the production experiment. The primary purpose of the chapter is to achieve a further understanding of the articulatory characteristics of geminated liquids in Japanese.

Subsections 3.1.1 and 3.1.2 provide an overview of existing research on the articulation of liquid consonants in Japanese and in other languages, and subsections 3.1.3 and 3.1.4 provide an overview of existing research on the articulation of geminate consonants in Japanese and in other languages. Section 3.2 explains the methods of the experiment, and discusses some details of the measurements employed in the analysis. Section 3.3 reports and discusses results pertaining to gestural durations. Section 3.4 reports and discusses the results based on positional data, based on the time point of the maximal tongue tip constriction. Section 3.6 reports and discusses the results based on the trajectory data. Section 3.7 summarizes the chapter.

3.1.1 Articulatory characteristics of liquids

The focal points of articulatory studies on liquids are diverse, reflecting the diversity in the manners of articulation within the category. However, recent work treating the entire category of liquids addressed the question "is there anything articulatory that is shared among the various sounds in this class?". In particular, Proctor (2009, 2011) proposed a gestural characterization of the class of liquid based on ultrasound results, whereby coronal liquids consonants characteristically consist of consonant-like coronal component and vowel-like dorsal component (cf. Delattre & Freeman, 1968; Sproat & Fujimura, 1993).

3.1.1.1 Gestural complexity of laterals

Study on the gestural characteristics of laterals was key to the development of Articulatory Phonology. Sproat and Fujimura (1993) provided a gestural account for the alternation of light and dark /l/ in English, decomposing the segment into two gestures whose timing relative to each other is governed by syllabic position. The phenomenon was taken up in Browman and Goldstein (1992a), together with other gesturally complex phenomena. As mentioned above, Proctor (2009, 2011) also demonstrated that the gestural complexity in English laterals applies to Spanish and Russian laterals as well, requiring the coordination of coronal and dorsal gestures (the anlaysis extends to rhotics as well).

The gestural complexity in the lateral consonants have also been captured in terms of tongue shaping (Narayanan et al., 1997; C. Smith, 2014), and the relationship between each gesture and the acoustic correlate of laterals (Ying et al., 2012).

The complexity of American English /l/, taken together with the fact that native speakers of Japanese have a notoriously hard time learning the sound, also gave rise to several studies investigating the production of English laterals by native speakers of Japanese (Masaki, Akahane-Yamada, Tiede, Shimada, & Fujimoto, 1996; Moore et al., 2018, *inter alia*).

3.1.1.2 Tap/flap and trill

The articulatory difference between taps and flaps is often ignored or simplified (e.g. Pike, 1947; Lindau, 1985), and they are both represented with the same IPA symbol [ɾ] (International Phonetic Association, 2015). However, technically, they are not the same: while both sounds can be characterized as brief, ballistic, and stop-like lingual contact at the dental-alveolar region, Ladefoged and Maddieson (1996) suggests that flap is a sound made with the active articulator moving tangentially towards the contact location, striking the surface of the vocal tract in passing, whereas tap is a sound made with the active articulator by moving it directly towards the palate. He also notes that these two may differ slightly in terms of the point of articulation, flaps at the alveolar ridge (slightly retracted) and taps around the dental or alveolar region. Derrick and Gick (2011) also explains that constrictions in taps characteristically starts and ends in the same location (i.e. it can start above the alveolar ridge and end up back there, or it can start below the alveolar ridge and end up down there), while constrictions in flaps starts tangentially, hitting the target and continuing either upward or downward. The preparatory retraction of the tongue for flaps, in fact, results in a different formant transition across the consonant (see also Monnot & Freeman, 1972).

Building on this distinction, Derrick and Gick (2008) and Derrick and Gick (2011) identified four categorical variations for flaps and taps in American English, based on ultrasound data: alveolar tap, down-flap, up-flap, and post-alveolar tap. They discussed the extent to which they varied inter- and intra-personally, and are phonologically conditioned.

Taps, flaps and trills are quite similar acoustically (Lindau, 1985), and trills are often discussed as if they were just repeated version of taps or flaps (which certainly has phonological grounds: Inouye, 1995). Conversely, taps and flaps are sometimes thought of as an undershot variant of trills (cf. Amengual, 2016). For example, Pike (1947) explains "for a trill, two or more flaps that follow each other in rapid automatic succession." However, they are known to involve quite different articulations. McGowan (1992) modeled the production of trills, showing that certain aerodynamic condition is required to incur the vibration of the active articulator against another surface.

3.1.1.3 Subphonemic variation of English retroflex approximant ɹ

Researchers were well aware that there was more than just one way speakers produce American English [ɹ] (hereafter, AmE /r/), despite the virtual consistency in their acoustic and auditory effects. In traditional dichotomy, one is called "retroflex /r/" and the other, "bunched /r/." Retroflex /r/ is produced with raised tongue tip, and bunched /r/ is produced with the tongue tip down (Ladefoged & Johnson, 1993). Further instrumental studies, however, showed that the two articulatory strategies are in the opposite sides of a continuum, rather than two distinct categories. For example, Delattre and Freeman (1968) argued that articulatory strategies for AmE /r/ are not limited to retroflexed and bunched tongue shape (they also dismiss the traditional view that retroflex articulation is more common than bunched articulation). In an X-ray cineradiography study with speakers of various dialects (covering ten dialect areas in the U.S. in addition to Liverpool, England), they classified the tongue shapes of English /r/ into eight different types. Two of the eight types belonged exclusively to British speakers, and the distribution was clear-cut: one type (retroflex) in onset position, the other (r-less) in coda. The other six types were distributed less systematically across productions by American speakers, but all had in common that they have two constriction locations (see above section) resulting in three resonance cavities. They argued that the six types of tongue shape could be viewed to be on a continuum between retroflex and bunched /r/. Hagiwara (1994) further addressed this wide variety of /r/ productions using probe-contact testing, identifying three major categories. The productions could be analyzed as tongue tip up (retroflex), tongue tip down (bunched), and tongue blade up. He discusses that while we could call the tongue blade up pattern "laminal retroflex," the pattern was produced more by speakers also employing the bunched strategy. Westbury, Hashi, and Lindstrom (1998)'s X-ray microbeam results also supported the view that the tongue shapes in the infamously variable AmE /r/ production vary continuously rather than categorically.

This variability in the articulation of AmE /r/ contributed to theories of phoneme production, and in particular, the issue of whether it involves constriction targets or acoustic targets. Guenther et al. (1998) argued against theories that associate phonemes with specific vocal tract shape, showing that while speakers' tongue configurations during AmE /r/ production vary, they make use of systematic tradeoffs between the shapes of the articulators so as to allow them to maintain the acoustic effects (i.e. reduction of F3) based on EMMA data.

3.1.2 Articulatory studies of liquids in Japanese

The majority of instrumental studies on the articulation of the basic variants of Japanese /r/ has been done using EPG, focusing on the nature of the closure contact. Studies invariably report individual variations, while also pointing out the role of positional and vocalic contexts. In particular, whether /r/ appears word-initially (more precisely, as onset in post-pausal context) or intervocalically, and which vowels are surrounding it. Almost all studies focus on the lingual articulation of the consonant, with very few exceptions.[1]

Palatographic studies Shibata (1968) was one of the first to record the production of Japanese coronals in intervocalic environment using EPG. Results confirm that the intervocalic /r/ is realized as a flap with apical constriction, and with a momentary and incomplete closure. The dynamic contact profile also indicates that when /r/ is surrounded by front vowels (/i, e/), the contact is concentrated to the periphery of the front portion of the palate. In contrast, when /r/ is surrounded by non-front vowels (/a, o, u/), the contact progresses from the core to the periphery of the palate. Furthermore, by comparing the contact profiles of /ori and /iro/, he concluded that the preceding vowel has more influence on the production of /r/ than the following vowel.

Sudo et al. (1982) follow up on Shibata (1968) by testing all twenty-five logically possible combinations of intervocalic environments for Japanese /r/, using EPG (sampling rate was 64 frames/sec). Their results show that there are two contact patterns. For some /ere/ and /ara/, the contact proceeded "posterio-anteriorly," where the contact starts on the rim of the palate in the back of the mouth, then gradually seals the rim toward the front. This pattern is in accordance with Shibata (1968) for the context /a_a/. In another pattern occurring in more than 25% of the vowel environments /a_a, i_i, u_u, e_e, o_o, a_e, o_a, a_u/, the contact starts in the anterior portion first, then the contact expands to the lateral edges of the palate. Both of the patterns were produced by the two subjects in their experiment. These two patterns share the same contact profile at the release of the constriction, in which once the maximum constriction is achieved, the contact is let go of from the center of the anterior rim of the palate towards the back of the mouth. They also report the influence of vowel environments, such that /iri/

[1] As an exception, there is Magnuson (2009), suggesting the presence of a pharyngeal component to the articulation of /r/ in Kansai Japanese.

has more contact overall compared to /ara/ or /oro/. Furthermore, they found that /ara/ and /oro/ sometimes lacked contact at the lateral edge of the palate even when there is evidence for contact in the anterior portion of the palate (which is congruent with the second pattern discussed above). Speakers varied in the frequency of this kind of lateral articulation (the younger, female speaker produced it more). They observed that not all /r/ production attained complete closure, while productions preceding or following /i/ involved closure most frequently.

Sugito (1985) focused on the differences and confusability of /z, d, r/ in Japanese (the confusability was also later investigated by Otsuka, 1997, *inter alia*). Using EPG data from three speakers from Osaka, Tokyo, and Nebraska, they pointed out that there are two patterns in the production of /ro/: once the closure is achieved, the tongue may be pulled away from the tongue tip, or the lateral sides. As for the differences between Japanese /do/ and /ro/, they pointed out that /d/ employs the “top” of the tongue (which could be interpreted as laminal constriction) while /r/ employs the tip of the tongue (which could be interpreted as apical constriction) and the location of the contact was also different in such a way that the tongue tip is in contact with the back of the lower teeth for /d/ but not for /r/.

The experimental setting in Onishi (1987) is similar to Shibata (1968) in that they investigated the production of coronal consonants in Japanese using EPG, but featuring 10 speakers counterbalanced for gender. Among all ten consonants (/t, d, n, s, z, ʃ, ʒ, ts, tʃ, ɾ/), /r/ came out with the least contact surface across vowel and pitch accent environments (preceding vowel was limited to /a/, and the following vowel was /a, e, i, o, u/; pitch accent was either HL or LH/unaccented). They identified six types of linguo-palatal contact profiles for /r/, illustrated in the table below. From his production, it seems that *Lateral 1* refers to a laminal lateral production with incomplete contact on the side(s), while *Lateral 2* refers to an apical lateral production with tongue tip, lacking contact on the sides of the palate. The patterns *Fricative* and *Lateral 1* constitute 76% of all productions (n=106). Overall, they acknowledge the presence of individual differences, none of which were associated with gender, age, or pitch-accent pattern.

Table 3.1: Linguo-palatal contact patterns for /r/ in Onishi (1987).

Pattern	Description	Environment
Plosive	Complete closure around the rim of palate, but for 1/64 second	Common in /-i/, not attested in /-a/
Fricative	Front portion of the palate never comes to complete closure	Common for /-u/, attested in all
Lateral 1	Lack of closure at the side(s) of the front portion	Common for /-a, -e, -o/, attested in all
Lateral 2	Contact only in front portion of the palate but not on the sides	Attested only in /-a, -e/
Vowel 1	Contact only in both sides of the palate, like vowel /i/	Attested only in /-a, -e, -o/
Vowel 2	No contact at all, like vowel /a/	Attested once, only in /-a/

In a cross-linguistic comparison of liquids and nasals in Japanese and Korean (with two speakers for each language) using EPG, Tsuzuki and Lee (1992) also observed variation based on the surrounding environments. Word-initially, Japanese /r/ is a retroflexed lateral in front of /a, e, o/, while it is an alveolar flap in front of /i/, and a retroflexed flap in front of /u/. Intervocalically, they identify an alveolar flap in the /i_i/ context, and a retroflexed flap in /a_a, e_e, o_o, u_u/.

Matsui, Kawahara, and Shaw (2016) and Kawahara and Matsui (2017) conducted an EPG study for the Japanese consonants /t, d, ɾ, z, s, ts, tɕ/ and their geminate counterparts in reduplicative mimetics. The study is unique in that they not only investigated singleton but also geminate /r/. As in the previous studies, in their preliminary report discussing results for two of the five speakers, they support the view that the realization of /r/ varies substantially, in part due to the vocalic environments, illustrated in a table below. As the authors emphasize, exactly which IPA symbols should be used for each production is not the point – rather, the sheer variability in the production of /r/ calls for serious reconsideration to the typical description of Japanese /r/ as “post-alveolar tap.”

Table 3.2: Linguo-palatal contact patterns for /r/ in Kawahara and Matsui (2017).

Pattern	Description	Environment
dentalized lateral [l̪]	closure in the front portion but no lateral constriction	/a_a/
palatalized tap [ɾʲ]	linguo-palatal contact in the hard-palate region	/i_i/
post-alveolar [ɹ̠]	contact is further back	/o_o/

The lateral variants of Japanese /r/ draw special attention. As Price (1981) described as "the folklore," it is a common belief that Japanese speakers are only able to produce rhotics and not laterals (and that that is the reason why they are having such a hard time learning laterals in other languages; Miyawaki et al., 1975). As can be seen in the literature presented above, that does not seem to be the case.

Finally, Kochetov (2018) investigated a wide range of Japanese consonants using EPG (at 100 Hz sampling rate), with the goal of quantifying the articulations with a cross-linguistic perspective. The study was unique in the speaker population: he recruited five female speakers from various regions of Japan: Shizuoka, Shiga, Ibaraki, Kyoto, and Hyogo. The consonants were all in word-initial position (except for the moraic nasal /N/) produced in a carrier phrase, which created a /a_a/ context. He showed that among the coronal consonants, /s/ and /r/ are less anterior compared to /t/ and /n/, and that /r/ have significantly less contact compared to /t, s, n/. Their linguo-palatal profiles for /r/ indicate variability, including an incomplete central occlusion for /r/ for some speakers, which he presents as unexpected result which could have been due to the sampling rate.

Tongue imaging/tracking and hybrid studies Kokuritsu Kokugo Kenkyūjo [National Language Research Institute] (1990, pp. 491–493) examined the production of Japanese /r/ in terms of tongue shape, contact profile, and oral and nasal airflow. Contra some palatographic studies discussed above (e.g. Shibata, 1968; Sudo et al., 1982; Tsuzuki & Lee, 1992), their EPG data suggest that the production of /r/ involves a complete closure, though it is for a very short time. This is probably due to the fact that all the /r/ in their experiments was in utterance-initial position. Their X-ray motion picture data suggest that the closure is achieved by a rather flat tongue shape. They approximate the shape of the tongue tip to a spoon, as it bends upward to lightly touch the alveolar ridge. It then shoots forward and downward, transitioning to the position demanded by the following vowel. For /r/ preceding /i/ and for palatalized /rʲ/, they observed that the front portion of the tongue raised toward the hard palate. Their data on the air pressure in the vocal tract suggest that the spike in pressure is smaller and shorter in duration compared to obstruents. Furthermore, the degree of velum raising is smaller compared to obstruents, suggesting a continuous thin airflow from the nasal cavity. They also acknowledge individual differences in the realization of /r/, but point out that nonetheless, speakers employ various strategies (and combinations thereof) to realize the essential qualities of Japanese /r/ as liquid. Such strategies include: weak closure implemented with relaxed tongue tip, short closure duration, shooting the tongue tip abruptly after the closure, incomplete closure with space in the center or sides of the rim of palate, allowing some air through the slightly lowered soft palate to prevent the pressure from going up, controlling the intraoral pressure during the tongue tip closure to prevent the pressure from going up, etc.

They also report differences in articulation dependent on the vowel contexts. For /ra/, they observed that the highest point of the tongue was fronter than normal during the following vowel, affected by the articulation of /r/. For /ri/, they observed the fronting of the tongue overall, the main contributor to the production of /r/ being the tongue tip. They note that when the raising of tongue body was not front enough, the tongue tip could not reach the alveolar ridge, resulting in the deletion of /r/ or in a retroflex production, [ɽ]. Conversely, when the contributor for the consonant grew bigger than just the tongue tip, the following vowel tended to be undershot, resulting in [ɪ] or [ɪ̈]. For /ru, re, ro/, they observed articulatory influence in the consonant and the vowel, but nothing to be noted in particular. For /rʲ/, they note that the front portion of the tongue is already raised prior to the tongue tip closure.

Using ultrasound, Yamane, Howson, and Wei (2015) investigated the production of plain and palatalized taps in six female Japanese speakers, in the intervocalic contexts /a_a, u_u, o_o/. Their focus was on the apparent incompatibility of rhotics and palatalization reported cross-linguistically (citing Iskarous & Kavitskaya, 2010; Kavitskaya, Iskarous, Noiray, & Proctor, 2009; Mester & Itô, 1989; Proctor, 2009). Their study was set to investigate the realization of palatalization in Japanese taps, with the prediction that there would be much variability for tongue body and tongue dorsum gestures in plain taps (i.e. low coarticulatory resistance), but less variability for tongue body gesture in palatalized taps (i.e. more coarticulatory resistance). They used SSANOVA to quantify the tongue surface contours, and found that (a) the tongue dorsum was more retracted and the tongue body was lower for plain taps compared to palatalized taps (the /u_u/ environment exerted the least difference); (b) the backness and height of the tongue dorsum are significantly more variable for plain taps compared to palatalized taps, depending on the vowel context (conversely, palatalized taps were less variable depending on the vowel context, though speakers varied in terms of the fronting of the tongue dorsum). Given the results, they concluded that Japanese plain taps lack tongue dorsum target (cf. Proctor, 2009) and are more prone to coarticulatory effects, which is consistent with Recasens and Pallarès (1999)'s results for Catalan taps. In their discussion as to why palatalized rhotics are cross-linguistically rare (c.f. T. A. Hall, 2000; Hamann, 2002), they mention the possibility that palatalization may come with a laminal tongue tip/blade gesture, which could interfere with the tongue tip gesture of a tap or trill. Finally, it may be possible that they found a high coarticulatory resistance for their palatalized tokens because palatalization is contrastive in Japanese /r/. Their findings are intriguing in two ways. First, they showed that unlike many articulatory studies on rhotics in Indo-European languages where we have evidence that they are complex segments specified for tongue dorsum gestures, Japanese plain rhotics are not specified for tongue dorsum gestures. Second, they propose the possibility that the cross-linguistic incompatibility between rhotics and palatalization is likely not because of gestural interference at the tongue dorsum, but because of interference at the tongue tip.

Finally, Katz et al. (2018) is an EMA study specifically targeting Japanese /r/ in various syllable positions and vowel contexts. Through the kinematic analyses, they showed that there is substantial variability dependent on vocalic contexts. Tongue width was narrowest for high vowels (/_i, i_i/, /_u, u_u/) and widest for /_a, a_a/. Further differences in the tongue shapes they noticed in the intervocalic environments include tongue flattening for /a_a/ and tongue backing for /o_o/. They also conducted a perceptual experiment in which native speakers of General American English listened to the productions from the earlier experiment and chose among "l, r, d." Results indicate that listeners judged 'd' and 'l' more frequently in post-pausal environment than in intervocalic environment, in which they heard 'r' more; listeners chose 'l' most for /o/ and least for /i/, and 'd' most for /i/ and least for /o/. They also found some talker-specific patterns for the reduplicative tokens.

3.1.3 Articulatory characteristics of geminates

Previous studies on the articulation of geminates fall roughly into two categories: ones that mainly concern the temporal organization of vocalic and consonantal gestures, and ones related to the articulatory nature of gemination more broadly. Here, we will focus more on the latter category.

3.1.3.1 Rearticulation

One of the oldest questions probes whether geminates involve the so-called double articulation or rearticulation. The matter was first discussed in Sievers (1876) as cited in Lehiste, Morton, and Tatham (1973, p.131) and Sievers (1901) as cited in Ham (2001, p.16), claiming that the production of true geminates requires rearticulation. Early experiments using kymography yielded highly inconsistent results for Hungarian and a variety of Swiss German (Meyer & Gombocz, 1909 and Dieth & Brunner, 1943, as cited in Ham, 2001), and no double articulation was observed for a Gallo-Roman dialect of Cellefrouin (Rousselot, 1892 as cited in Lehiste et al., 1973, p.131). For heteromorphemic labial geminates in English, Stetson (1951) as cited in Lehiste et al. (1973, p.132) reported clear evidence for rearticulation, based on lip movement measurement and intraoral air pressure. Hegedüs (1959) as cited in Lehiste et al. (1973, p.132) did not find any evidence for rearticulation for Hungarian tautomorphemic geminates, based on acoustic signal (intensity). Delattre (1971, pp. 41–43), based on amplitude profiles for /n, l, s/, concluded that there is rearticulation in geminates at word boundaries (i.e. for "fake" geminates) for four different languages (English, French, German, and Spanish). Meanwhile, an electromyographic study featuring American English and Estonian bilabial plosives reported that they observed evidence of rearticulation in 'true' or tautomorphemic geminates in Estonian, but not in heteromorphemic geminates in English (Lehiste et al., 1973) (the EMG scores were not significant for either language though).

C. L. Smith (1993), in her microbeam experiments with Japanese and Italian true geminates, did not find solid evidence for rearticulation. In a study following up on her results (Dunn, 1993), optical tracking results indicate that the gestural peak for bilabial geminates in Italian is held steadily, hence showing no physical evidence of rearticulation. However, she concludes that Italian bilabial geminates are produced with two articulatory targets (i.e., a pair of overlapping identical gestures, contra C. L. Smith, 1992), as there was no difference in the kinematics of the movements into bilabial closure between singletons and geminates. The conclusion is also supported by the similarity in relative timing between geminates and heterosyllabic clusters. The lack of evidence for rearticulation, she explains, may be indicative of a tightly constrained degree of overlap. In her Finnish data as well, she did not observe any evidence of rearticulation during the held peak. Geminates also involved lower peak velocity except for some speakers. However, when the preceding vowel was a short one (phonologically), they observed very little difference between the gestural timing for singletons and geminates.

Finally, it should be noted that evidence regarding the re-articulation does not always coincide with conclusions as to the gestural representation of geminates. Byrd (1995), based on EPG results on English geminates at word-boundaries, observed that the linguo-palatal contact profile indicates a "single smooth movement" similar to the consonant clusters at word-boundaries in Munhall and Löfqvist (1992). While she did find a single, smooth gesture for geminates, her conclusion is that phonologically, geminates consist of two identical gestures that are partially overlapped (in favor of Browman and Goldstein (1995)'s view of geminates). In this kind of thinking, rearticulation data may not really provide a good diagnostic for the gestural representations of geminates. Dunn (1993, p. 104) also takes a similar view that she would only conclude that the articulatory structure for singletons and geminates are different (i.e. geminates are specified as single, distinct gesture) "if the kinematics of closure are inexplicably different for singles and for geminates." Otherwise, she would conclude that geminates are two overlapping identical consonant whose second onset is not observable, even if there is no evidence for rearticulation.

3.1.3.2 Linguo-palatal contact

Another aspect frequently addressed in the literature is the relationship between singletons and geminates in terms of linguo-palatal contact profile, such as contact location, the strength of contact, and articulator involved in the contact (i.e. apicality vs. laminality of contact). The motivation for this line of investigation came from acoustic studies on non-durational characteristics of geminates (e.g. formant transition, burst intensity), suggesting some non-temporal gestural differences (Payne, 2005, 2006, and citations therein). Common methodologies include electropalatography (EPG) and electromagnetic articulography (EMA), as well as some successful exploratory use of rtMRI.

Contact/constriction location Payne (2006), with her Italian data collected using EPG, argued that geminated laterals, coronal stops and nasals employ more palatalized tongue configuration compared to singletons, as suspected from auditory/acoustics results for Malayalam (Local & Simpson, 1999) as well as for Italian (Payne, 2005). While the EPG data showed that alveolar consonants are formed with a constriction at the alveolar region (and not in the palatal region) regardless of consonant length, she inferred that the tongue is "higher and flatter in the mouth," contributing to the overall palatal configuration of the vocal tract.[2]

Later, in an experiment designed to establish the use of rtMRI for investigating constriction location, constriction degree and articulatory kinematics, Hagedorn, Proctor, and Goldstein (2011) confirmed that there is no difference between Italian singletons and geminates in terms of constriction location at large. They also found that constriction location differs between coronal oral stops and affricates (advanced) and coronal sonorants (retracted), as well as dorsal stops flanked by vowels with different backness.[3]

[2]In her discussion, Payne (2006) notes that this palatalized quality explains the more clear formant structure of geminated laterals in Payne (2005).

[3]This seems representative of many other languages that have stable manner and place of articulation

Strength of contact Research on the strength of contact (or constriction degree, to include the continuant consonants) are predominantly based on electropalatography (EPG) data (because they are usually concerned with lingual stops), and research mostly agrees that gemination usually involves "stronger" articulation than singletons, based on longer duration of contact and/or more spatially extended contact. For Italian, Payne (2006) showed that there is more linguo-palatal contact for geminated nasals, laterals, and stops generally, with the exception of voiceless affricate.[4] She concludes that gemination should be considered more broadly as "fortition," as it involves changes in the spatial domain in addition to the temporal domain. For Japanese, Matsui et al. (2016) and Kawahara and Matsui (2017) demonstrated (if only preliminarily) the articulatory strengthening in geminated stops and affricate (t∼tt, d∼dd, z/dz∼dz).

3.1.4 Articulatory studies of geminates in Japanese

The majority of the work on the articulation of geminates in Japanese looks at lingual articulation, sometimes accompanied with labial articulation. One of the earliest articulatory studies on geminates in Japanese was conducted by C. L. Smith (1993) and C. L. Smith (1995). Based on an X-ray microbeam study, she concluded that the typologically rather unusual lengthening of the vowel preceding geminates in Japanese can be accounted for as a result of the language's consonant-vowel coordination scheme. The conclusion was not supported in Löfqvist (2006, 2017). Fujimoto, Funatsu, and Hoole (2015), also using EMA, investigated the relationship between consonantal gestures and preceding vowels for singletons and geminates. Based on Takada (1985) and Fujimoto (2013)'s finding that the jaw or the tongue tend to be more lowered during the preceding vowel for geminates than for singletons, she hypothesized that the length-

across consonant length. There are some exceptions though, such as Korean (singleton tap & geminate laterals), and possibly Japanese.

[4] There are also syntactic/stress contexts where the difference does not hold up.

ening of the vowel preceding geminates is a result of slower tongue movement. Their results showed some variability in the duration of the preceding vowels, and they identify two parameters for the articulatory patterns: (a) the timing of the tongue rising out of the preceding vowel and (b) tongue peak timing (generally delayed for geminates). They concluded that the delayed peak attainment for geminates compared to singletons has nothing to do with the lengthening of the preceding vowels.

Ishii (1999) used X-ray microbeam to investigate the articulatory movements of lower lips and the tongue (only one subject). While they observed a great deal of stability in terms of the articulatory speed of the lower lip across utterances and speech speeds, they report high degree of variability for the movements of tongue body and tongue dorsum, compared to singletons or long vowels. They invoke the idea of underspecification to explain the pattern. They also report that the articulatory movement of tongue body and tongue dorsum was significantly slower, although the up-down movement of the lower lip (i.e. jaw) was not.

Studies focusing more on the place and degree of constriction tend to use EPG. Kochetov (2012) confirmed the hypothesis that geminate stops involve longer and tighter constriction. The contact profile of EPG suggested that geminates [t] and [k] in Japanese were about twice as long as their singleton counterparts, and had higher degree of linguo-palatal contact on average. The results are consistent with Payne (2006), which showed a greater degree of linguo-palatal contact in Italian geminates. Kochetov and Kang (2013, 2017) further showed that the constriction degree and duration profiles were similar between Japanese length contrast and Korean lenis/fortis contrast. Matsui et al. (2016) and Kawahara and Matsui (2017) report on EPG results for alveolar singletons and geminates, including liquids. Their findings point to an articulatory strengthening (as indicated by more extensive linguo-palatal contact, in more extended regions and increased number of frames of contact) for geminated stops.

Another line of articulatory research for Japanese geminates involves the laryngeal gestures during the production of geminates. Several scholars have expressed the impression that there is something going on in the larynx during the production of geminate consonants. For example, in her article Aizawa (1985) seems to equate the term "choked sounds" with geminates (though confusingly not completely so). Hattori (1984, as cited in Fujimoto et al. 2010) also noted that there is some glottal tension during the production of the first half of geminate consonants. Perceptually, T. Arai, Iwagami, and Yanagisawa (2016) showed that glottal stops at the beginning of consonants can be indicative of geminate production, and acoustically, Idemaru and Guion (2008) addressed the involvement of laryngeal constriction through creakiness in the vowels surrounding geminates. Fujimoto et al. (2010) used high-speed digital video recording system as well as photoelectric glottogram (PGG) to record and analyze the laryngeal activities during the production of geminates. While they found no constriction or tenseness in the larynx or glottis during the production of geminates based on the video recordings, PGG signals indicate that the production of geminates involves tighter closure or faster movement for making the closure in the vocal tract, or increased tension in the laryngeal muscle(s). The glottal opening width was only slightly wider for geminates compared to singletons. They also observed differences between stops and fricatives. Fujimoto (2014) shows similar results, further supporting the presence of some tension in the vocal folds during the onset of geminate production.

3.2 Method

In order to investigate the articulation of geminated liquids in Japanese, a production experiment using EMA (electromagnetic articulography) was conducted. EMA is a flesh-point tracking system designed to track and record articulatory movements in speech (Perkell et al., 1992). The position and orientation of the small sensor coils attached to the speech articulators are tracked, enabling the recording of the articulator trajectories during speech production.

In this study, EMA was chosen over other techniques commonly applied to articulatory studies such as ultrasound, EPG, or MRI, for its fine temporal and spatial resolutions needed to achieve the research goals. In particular, the involvement of ballistic movements in singleton tap/flap meant that we needed access to the tip of the tongue and a reasonably high temporal resolution. This precludes ultrasound, which has relatively lower sampling rate (though see Derrick and Gick (2011) for a successful analysis of taps and flaps using ultrasound), and often provides obscure images of the tongue tip due to the shadow of the jaw. At the same time, the prediction that at least some production of geminated liquids may be lateral approximants suggested that incomplete constriction, which is not directly detectable through EPG, will be key in characterizing the manner of articulations of geminated liquids in Japanese.[5] EMA, as is often also called EMMA (electromagnetic midsagittal articulography), is commonly used for midsagittal flesh-point tracking. However, it is clear that midsagittal data alone cannot capture the lateral side-channels (Masaki et al., 1996, MRI study calling for 3D MRI). In order to collect the information for lateral tongue surface, we placed the EMA sensor coils bilaterally (Katz, Mehta, Wood, & Wang, 2017; Ying et al., 2017). In fact, we could have used the ultrasound with a coronal view, turning the transducer by 90° (Stone, 2005, and citations therein). However, we would then have missed out on everything going on on the mid-sagittal plane.

Compared to flesh-point tracking methods such as EMA or X-ray microbeam, whole-tongue imaging methods such as ultrasound or MRI are arguably more informative (and perhaps even complements our EMA results; see also Narayanan, Byrd, and Kaun (1999) for a comparison of EMA and MRI) – especially so with 3D MRI and recent

[5]Several studies have shown that extrapolation from the contact profile is possible (e.g. Payne, 2006; Kawahara & Matsui, 2017; Matsui et al., 2016).

technological advance in the modeling of the vocal tract (see Hagedorn et al., 2011 for reason to prefer rtMRI, as well as Ong & Stone, 1998). However, I think simultaneous collection of acoustic data would be more difficult with MRI noise (given the high variability of Japanese liquids, simultaneous acoustic data seemed crucial), and the 3D EMA system we chose was highly portable.

3.2.1 Subjects

The subjects were the same from the ones introduced in the previous chapter (section 2.2.1).

3.2.2 Speech materials

The stimuli were the same from the ones introduced in the previous chapter (section 2.2.2). As in the previous chapter, we will report only results pertaining to /t, d, r, n, s/. Some productions were omitted due to error in gestural annotation, resulting in a total of 1473 productions.

Table 3.3: Number of productions subject to articulatory analysis.

Target consonant	Singleton productions	Geminate productions
t	69	70
d	139	137
r	405	392
n	59	64
s	70	68

3.2.3 Procedure

Because acoustic and articulatory recordings were made simultaneously, the general settings of the experiment were the same as the ones introduced in the previous chapter (section 2.2.3). The trajectories of the speech articulators were recorded using the NDI (Northern Digital Inc.) Wave Speech Research System, at 400 Hz. The 3D EMA system uses an external magnetic field generator to record the position and orientation of the sensor coils attached to the speakers' articulators. Prior to the experiment, five 5DOF (Degree of Freedom) sensors were placed to the tongue of each participant: on the sagittal midline, tongue tip (TT; 5mm from the tip of the tongue), tongue dorsum (TD; as far back as was comfortable for the participant, ranging from 5.22mm to 9.29mm from the tongue tip when the tongue was extended to the furthest), and tongue blade (TB; mid-point between TT and TD). There were also two lateral sensors, 1cm to the left of TB (TL) and to the right of TB (TR). An additional sensor on the gums beneath the lower incisors (LI) was placed to track jaw movement, as well as a 6DOF reference sensor on the nasion area (N) in order to correct the data for the movement of the participant's head. Table 3.4 and Figure 3.1 shows the sensor positions.

Table 3.4: Labels and placement of the sensors.

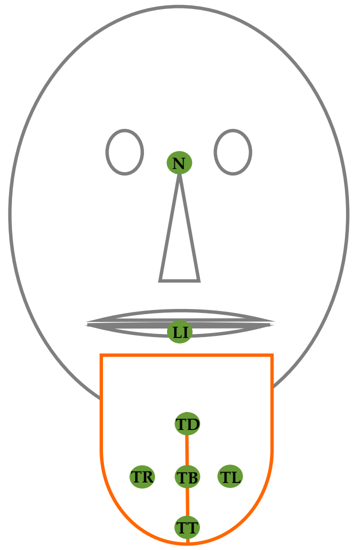
Label	Placement
TT	tongue tip; 5mm from the tip
TB	tongue blade; mid-point between TT and TD
TD	tongue dorsum; as far as possible from the tip
TL	tongue left; 1cm left from TB
TR	tongue right; 1cm right from TB
LI	lower incisor; gum of lower incisor (to track jaw movement)
N	nasion; between the eyes

Participants were asked to bite a 50 mm x 100 mm x 3 mm acrylic plate (the *bite plate*) with embedded 5DoF sensors in order to obtain the measurements for occlusal plane.[6]

Participants were seated comfortably on a chair, and the field generator was placed so that the articulator is included in a cube of $30cm^2$ from the device. After the sen-

[6] In addition, following Kitamura, Nota, Hashi, and Hatano (2014) and Ji, Johnson, and Berry (2013), the shape of the palate was molded. Combining the palate shape (recorded by tracing the mold using a pen with built-in 5DOF sensor) and the bite plate allows for a more precise estimation of the coordinates of the articulatory space by stabilizing the palate surface against the occlusion surface. This part of the analysis was left for future.

Figure 3.1: Sensor position.



sors were affixed, participants were asked to read the experiment instruction aloud to get used to the articulation with the sensors. The first six trials were practice trials. Participants could take a break anytime during the experiment (not many participants did).

The articulatory data was head-corrected by rotating and transposing the data based on the reference position. Extreme outliers in the articulatory signals were removed and filled using linear interpolation. Garcia (2010)'s robust smoothing algorithm was then applied to all articulatory signals (Shaw & Kawahara, 2018), as well as a low-pass filter (10Hz) for removing noise. We used the Mview package (Tiede, 2005) for visualizing trajectories and calculating articulatory landmarks (Gafos, 2002; Gafos, Kirov, & Shaw, 2010), which detailed in section 3.2.4.1.

Data analyses were implemented using R (R Core Team, 2013), *lme4* package (Bates et al., 2012) and *lmerTest* package (Kuznetsova et al., 2017), as well as *gss* package (Gu, 2014) for SSANOVA (Davidson, 2006).

3.2.4 Measurements

3.2.4.1 Plateau and gestural durations

The durational measurements of the gestures are based on the gestural landmarks generated using Mview (Tiede, 2005; Gafos et al., 2010).[7] In order to identify the gestural landmarks for the target consonants, I used the function *lp_findgest* in Mview on the tongue tip (TT) sensor.[8] The function uses the velocity signals to define the gestural landmarks. First, the *Maximal constriction point* is identified as the time point of minimum velocity around the visually identified gestural maxima. Then, *peak velocity* points for the beginning and end of gesture are identified around the maximal constriction point, within the region onto which *findgest* function was applied (in our case, it was the VCV region based on the acoustic information, i.e., [ata] in [gatagata]; sample interface in figure 3.2). The beginning and the end of a gesture are then defined as the *gestural onset* and *gestural offset*, which are calculated at 30% threshold of the peak velocity points (i.e. where the velocity signals drops below 30% of the respective peak velocity) on the other sides of the maximal constriction point. The beginning and the end of a gestural nucleus or the gestural plateau are identified as the *plateau onset* and the *plateau offset* (in Mview, "nuclear onset" and "nuclear offset," respectively), and are calculated at the 30% and 25% of the peak velocity after and before the peak velocity points, respectively.[9]

[7] I would like to thank Mark Tiede, Jason Shaw, and Jeff Moore for kindly sharing their MATLAB software/scripts and their expertise in EMA data processing. All errors are my own.

[8] While it would be ideal to analyze the gestural landmarks for all sensors (or at least all the sensors on the mid-sagittal line), in this chapter, we report the results based on the tracking of the tongue tip (TT) sensor.

[9] The default value for the threshold is 20% and 15%. For our data, we used the 30% threshold in order to track the gestural span more accurately.

Figure 3.2: Sample gestural tracking interface for the target singleton /t/ in [gatagata], using the *findgest* script for Mview.

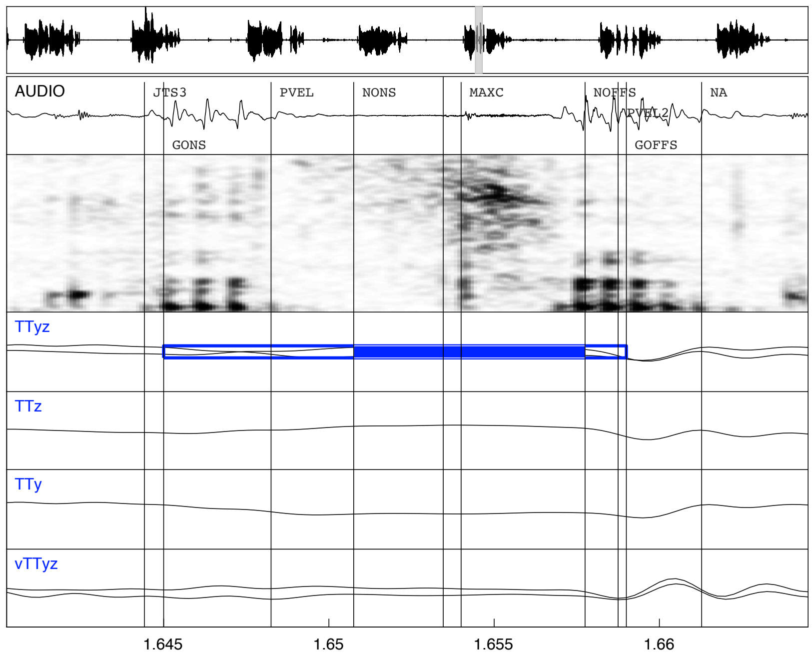
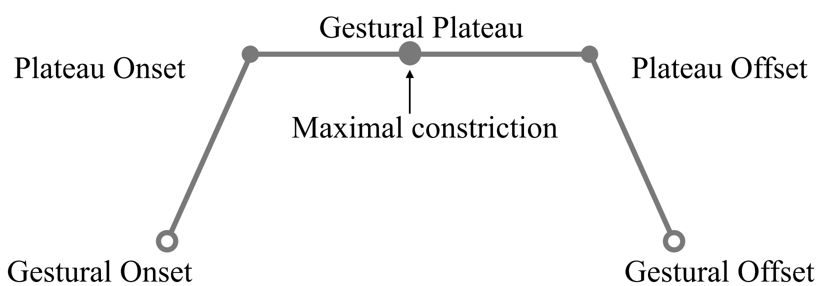


Figure 3.3: Gestural landmarks.



3.2.4.2 Positional and trajectory data

The vertical and horizontal positions of the TT and TB sensors, as well as the horizontal position of the TD sensor at the TT maximal constriction point are reported to obtain a snapshot of the tongue shape at TT maximal constriction. This measures are first reported as static measure at the TT maximal constriction point, but also visualized as dynamic trajectory during the VCV span.

Lateralization: para-sagittal curvature We adapt a lateralization index from Ying et al. (2017), taking the difference of the vertical position of TB and the two lateral sensors, TL and TR, at the point of gestural maxima (minimal velocity point) of TB. A positive value would indicate that the side of the tongue is lower than TB; a negative value would indicate that the side of the tongue is higher than TB. Preliminary results have shown that speakers vary in their use of different patterns, but fairly consistent within themselves: Concave (index is negative for TL and TR), Convex (index is positive for both), Right-lowering (index is negative for TL and positive for TR), and Left-lowering (index is positive for TL and negative for TR).

In the results, this measure is first reported as static measure at the TT maximal constriction point, but also visualized as dynamic trajectory during the VCV span.

In reporting the degree of tongue-side lowering, we first determined the dominant lateralization side for each subject. Based on the averaged lateralization index within the gestural span of all the target consonants (regardless of length, for each subject; see Table 3.5 and Figure 3.4), the side that had more lowering were selected for each subject, following Ying et al. (2017). The lateralization indices used for this purpose are raw (in mm). For S3, S4, and S8, the non-dominant side included a lot of mistracking.

Figure 3.4: Raw lateralization indices for each side of the tongue in each subject, during consonant production (TL=TB height minus TL height; TR=TB height minus TR height).

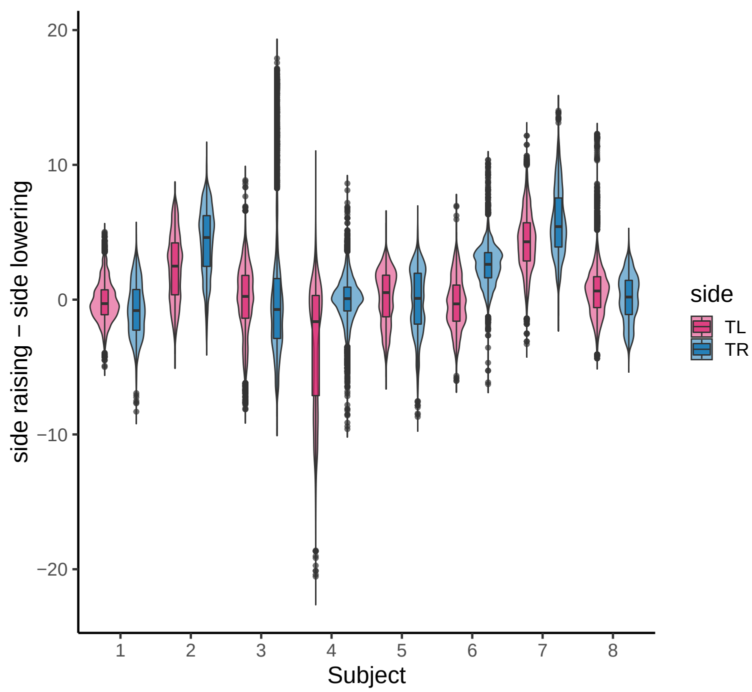


Table 3.5: Dominant lateralization side based on average lateralization indices for each side of the tongue in each subject (SD), during consonant production.

Subject	TL lowering	TR lowering	Dominant side
1	-0.15 (1.45)	-0.74 (1.99)	Left
2	2.36 (2.48)	4.31 (2.51)	Right
3	0.02 (2.48)	0.19 (4.85)	Left
4	-3.32 (4.64)	0 (1.64)	Right
5	0.2 (1.98)	-0.1 (2.38)	Left
6	-0.26 (1.89)	2.56 (1.46)	Right
7	4.33 (2.12)	5.76 (2.48)	Right
8	0.7 (2.02)	0.09 (1.74)	Right

Mid-sagittal curvature This measure is obtained as the difference in height between TT and TB at the gestural extrema of TB, as an indirect index of tongue curling (C. Smith, 2014; Ying et al., 2017). A positive value suggests tongue curling (TB is lower than TT), while a negative value suggests otherwise (TB is higher than TT). This will also give us some ideas as to whether the tongue is relatively flat, or cupped, during the articulation of geminated liquids (cf. Payne, 2006).

In the results, this measure is reported as static measure at the TT maximal constriction point, but also visualized as dynamic trajectory during the VCV span.

3.3 Durational results

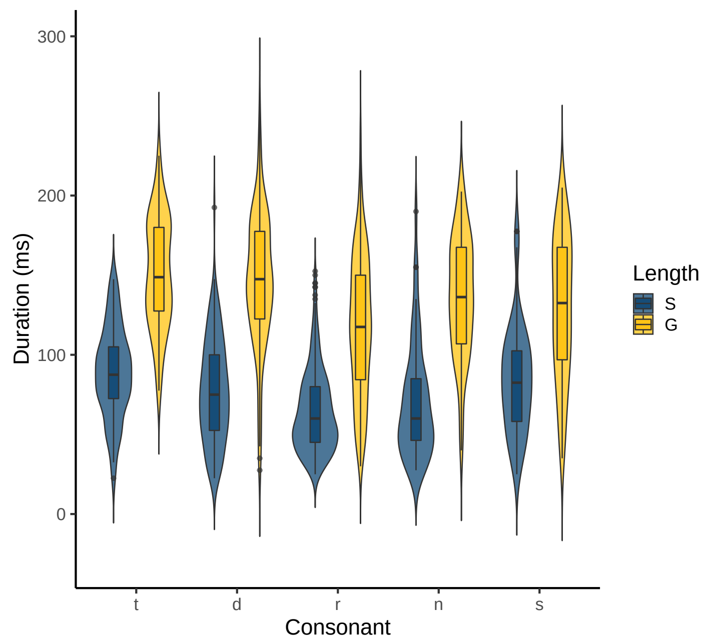
3.3.1 Gesture duration

For the movement of TT, there was a significant difference between the gestural duration of singletons and geminates overall, in each consonant, and in each subject. The duration of all consonants in singleton and geminate conditions as well as the geminate-to-singleton ratio (GSR) is summarized in Table 3.6 and Figure 3.5. For all consonants, there is a robust difference between the singleton and geminate durations, geminates being about 1.5 to two times longer than singletons. This ratio is smaller than the differences in the acoustic durations.

Table 3.6: Mean gestural duration and GSR (SD) per consonant.

Consonant (*n*)	Singleton	Geminate	GSR
t (69, 70)	88.97 ms (28.48)	151.32 ms (34.50)	1.71 (0.15)
d (139, 137)	77.23 ms (32.04)	146.70 ms (41.60)	1.9 (0.12)
r (405, 392)	64.46 ms (25.70)	117.81 ms (43.94)	1.84 (0.21)
n (59, 64)	70.21 ms (35.52)	136.25 ms (37.54)	1.96 (0.19)
s (70, 68)	84.11 ms (33.88)	129.23 ms (44.52)	1.53 (0.13)

Figure 3.5: Violin plots showing the mean durations per consonant and length. The overlaid box plots show median and the interquartile range (25% and 75%). The width of each violin represent the probability for the value to occur at any value.



We performed a linear mixed effects analysis of the relationship between consonant gestural duration in milliseconds and phonological length (S or G) and consonant. As random effects, we had intercepts for subjects and surrounding vowel environments,[10] as well as by-subject random slope for the effect of length. P-values were obtained by likelihood ratio tests.

The best model of acoustic consonant duration includes an interaction between Length and Consonant (Table 2.5). Overall, there is a main effect of Length (χ^2(1)=29.912, p<0.001), lengthening C2 by about 57.63 ms $\pm$ 3.2 (standard error). There is also a main effect of Consonant (χ^2(4)=56.539, p<0.001).

[10]The same note as in the acoustic results applies here, regarding the legitimacy of putting Vowel Environment as random intercept.

Table 3.7: Fixed effects coefficients table for the model of the TT gestural duration of the consonant.

TT gesture duration $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	83.772	5.442	65.144	15.395	< 2e-16	***
LengthG	62.188	6.404	117.412	9.711	< 2e-16	***
Consonantd	-8.163	5.544	371.504	-1.472	0.142	
Consonantr	-18.994	4.941	301.024	-3.844	0.0001	***
Consonantn	-14.075	6.731	382.118	-2.091	0.037	*
Consonants	-1.245	6.066	996.378	-0.205	0.837	
LengthG:Consonantd	7.088	7.122	1427.165	0.995	0.32	
LengthG:Consonantr	-8.678	6.298	1429.71	-1.378	0.168	
LengthG:Consonantn	4.995	8.496	1433.124	0.588	0.557	
LengthG:Consonants	-16.859	8.228	1426.671	-2.049	0.041	*

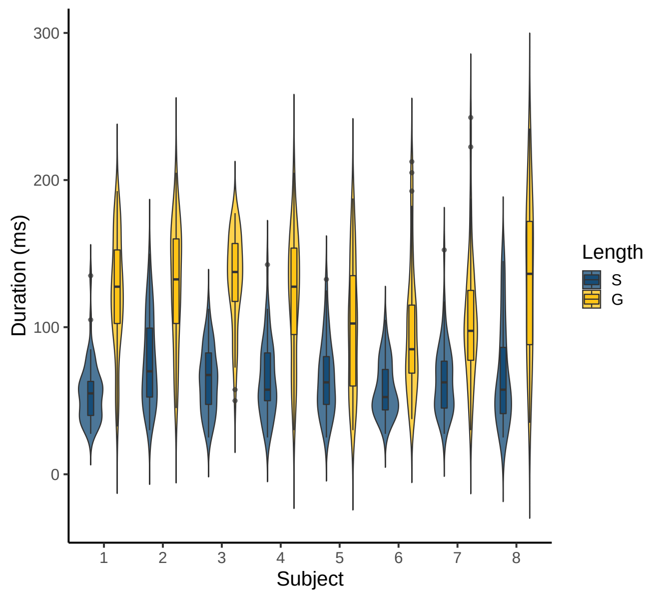
3.3.1.1 Gestural duration and ratio for liquids

Subjects differed considerably among and within themselves. It may worth noting that subjects are generally more inconsistent as to the gestural duration of geminated liquids compared to singleton liquids.

Table 3.8: Gestural durations and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1 (52, 53)	55.48 ms (20.23)	123.63 ms (38.98)	2.33 (0.64)
2 (54, 47)	76.94 ms (30.34)	129.79 ms (40.69)	1.75 (0.50)
3 (53, 58)	63.77 ms (21.95)	132.33 ms (31.58)	2.21 (0.57)
4 (49, 47)	64.59 ms (25.44)	121.70 ms (42.60)	2.07 (0.76)
5 (53, 49)	65.05 ms (25.09)	100.30 ms (43.78)	1.65 (0.64)
6 (51, 47)	57.84 ms (18.53)	96.65 ms (44.01)	1.70 (0.78)
7 (54, 53)	64.44 ms (23.94)	105.05 ms (42.56)	1.63 (0.48)
8 (39, 38)	67.82 ms (34.59)	134.41 ms (53.86)	2.41 (0.93)

Figure 3.6: C2 gestural duration for liquids per subject and length.



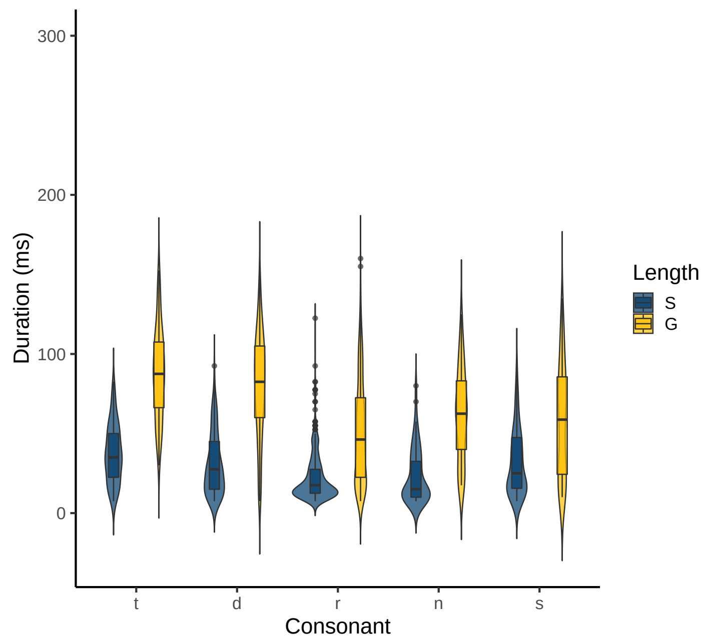
3.3.2 Plateau duration

For the plateau duration of TT, there was a significant effect of Length overall and in each consonant. The duration for all consonants in singleton and geminate conditions as well as the geminate-to-singleton ratio (GSR) is summarized in Table 3.9 and Figure 3.7. For all consonants, there is a robust difference between the singleton and geminate durations, geminates being about 1.8 to 2.8 times longer than singletons. This ratio is larger than the differences in the gestural durations, but still smaller than acoustic durations.

Table 3.9: Mean plateau duration and GSR (SD) per consonant.

Consonant	Singleton	Geminate	GSR
t	37.83 ms (18.31)	87.96 ms (28.69)	2.36 (0.41)
d	30.92 ms (19.17)	80.44 ms (32.79)	2.6 (0.15)
r	22.67 ms (15.67)	51.75 ms (32.99)	2.36 (0.41)
n	23.69 ms (17.19)	62.11 ms (29.05)	2.77 (0.67)
s	31.61 ms (20.40)	59.04 ms (36.12)	1.85 (0.42)

Figure 3.7: C2 plateau duration per consonant and length.



The best model of acoustic consonant duration includes an interaction between Length and Consonant (Table 2.5). Overall, there is a main effect of Length ($\chi^2(1)$=27.075, p<0.001), lengthening the plateau duration by about 35.65 ms $\pm$ 2.4 (standard error). There is also a main effect of Consonant ($\chi^2(4)$=83.7, p<0.001).

Table 3.10: Fixed effects coefficients table for the model of the TT plateau duration of the consonant.

TT plateau duration $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	31.741	3.714	166.173	8.546	7.99e-15	***
LengthG	50.136	4.636	121.241	10.814	< 2e-16	***
Consonantd	-2.178	4.108	636.688	-0.53	0.596	
Consonantr	-8.775	3.674	517.245	-2.389	0.017	*
Consonantn	-5.628	4.975	671.35	-1.131	0.258	
Consonants	-4.052	4.43	1236.281	-0.915	0.361	
LengthG:Consonantd	-0.683	5.142	1443.529	-0.133	0.894	
LengthG:Consonantr	-20.974	4.546	1444.085	-4.614	4.30e-06	***
LengthG:Consonantn	-11.503	6.126	1443.46	-1.878	0.061	.
LengthG:Consonants	-22.316	5.941	1443.399	-3.756	0.0002	***

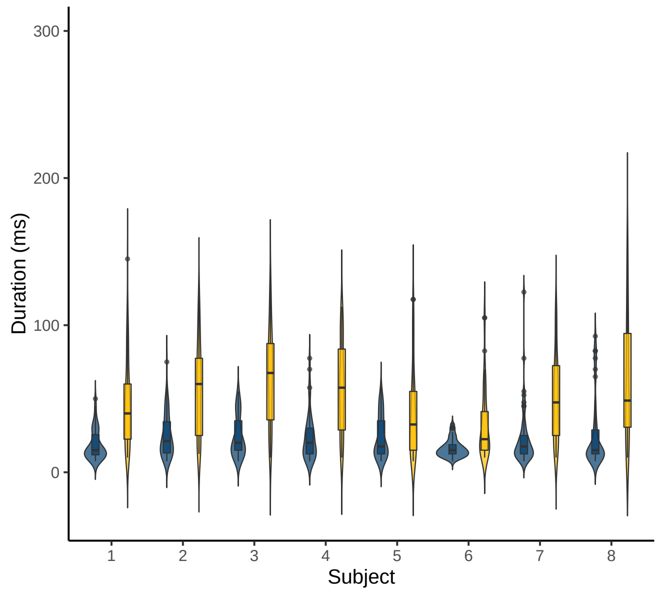
3.3.2.1 Plateau duration and ratio for liquids

Again, subjects differed considerably among and within themselves, and as in gestural duration, plateau durations are less consistent for geminates compared to liquids.

Table 3.11: Mean plateau durations and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1	18.61 ms (10.10)	47.83 ms (30.69)	3.00 (1.55)
2	25.14 ms (14.75)	57.45 ms (31.62)	2.50 (1.20)
3	24.15 ms (13.85)	65.09 ms (32.66)	3.21 (2.07)
4	24.08 ms (16.32)	57.50 ms (30.93)	2.92 (1.70)
5	24.06 ms (14.21)	40.66 ms (30.48)	2.07 (1.38)
6	16.23 ms (5.90)	33.19 ms (23.57)	2.12 (1.36)
7	23.48 ms (19.73)	49.43 ms (28.73)	2.27 (0.96)
8	26.35 ms (24.40)	63.22 ms (43.82)	3.38 (1.95)

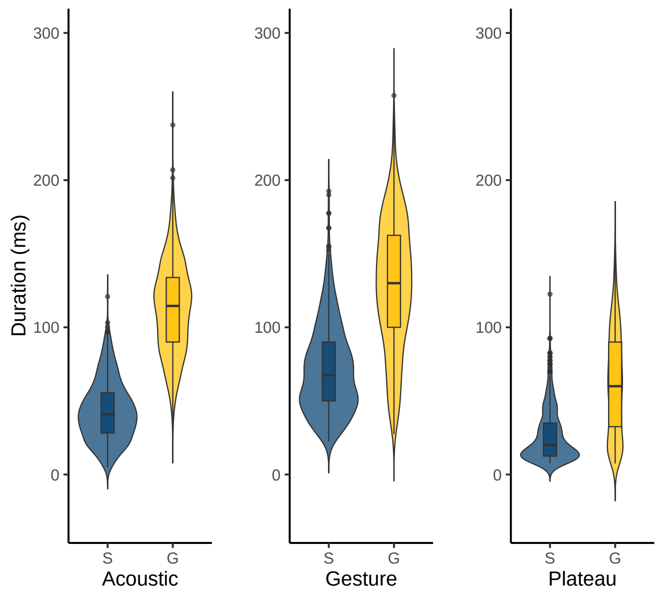
Figure 3.8: C2 plateau duration for liquids per subject and length.



3.3.3 Gestural duration vs. acoustic duration

In general, gestural durations are longer than the acoustic durations. In addition, when all consonants for all subjects are pooled, gestural durations and acoustic durations are largely in agreement in a way that longer gestural duration corresponds to longer acoustic duration. Overall, there is a positive correlation between acoustic and gestural durations (Pearson's correlation coefficient $r(1471)=.64$, $p<0.001$) as well as acoustic duration and plateau duration ($r(1471)=.6$, $p<0.001$), and gestural duration and plateau duration ($r(1471)=.81$, $p<0.001$).

Figure 3.9: Acoustic, gestural, and plateau durations per length.



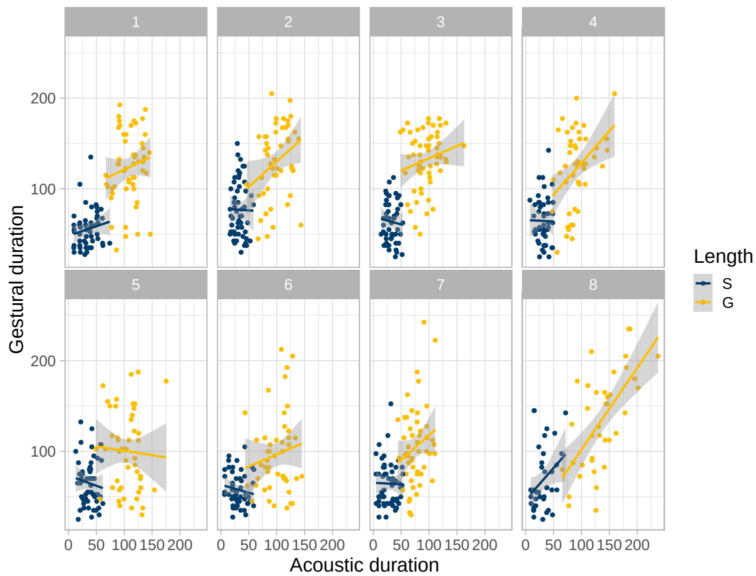
However, subjects vary in terms of the relationship between the acoustic durations and gestural durations. In the following table, I report Pearson's correlation coefficients for each subject.

Table 3.12: Pearson's correlation coefficients for acoustic duration and gestural duration for all consonants and for liquids.

Subject	For all consonants			For liquids		
	r	df	p-value	*r*	df	p-value
1	.77	174	< 2.2e-16	.71	103	< 2.2e-16
2	.7	185	< 2.2e-16	.61	99	< 2.2e-16
3	.7	199	< 2.2e-16	.72	109	< 2.2e-16
4	.7	171	< 2.2e-16	.67	94	< 2.2e-16
5	.51	185	< 2.2e-16	.36	100	< 2.2e-16
6	.58	185	< 2.2e-16	.48	96	< 2.2e-16
7	.44	192	< 2.2e-16	.5	105	< 2.2e-16
8	.71	166	< 2.2e-16	.74	75	< 2.2e-16

While the correlation is pretty high for all subjects, the gestural durations of geminated liquids for S5 appear to map less onto the acoustic durations. The following figures visualize the relationship between acoustic constriction duration and TT gestural duration. While for most speakers, the gestural duration is proportional to the acoustic constriction duration, the panel for S5 in Figure 3.10 shows that such relationship is not always present.

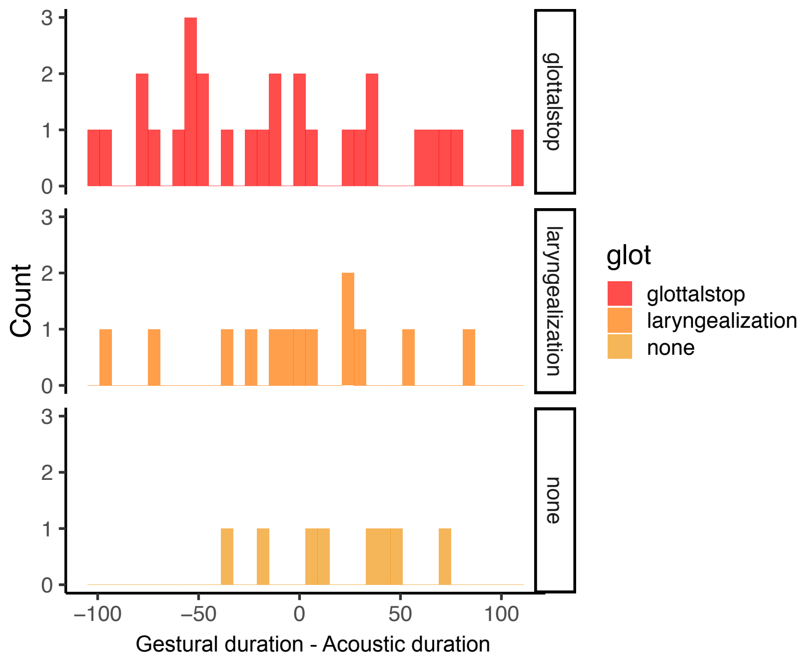
Figure 3.10: Relationship between acoustic and gestural durations (ms) per subject.



As seen in the previous chapter, some of the productions were accompanied with laryngeal activities during the consonants. The fact that the TT gestural duration in S5 are not proportionate to the acoustic duration can be partially accounted for by her frequent use of glottal insertion. At the same time, the results show that the timing relationship between the lingual gesture and glottal gesture is not uniform within this speaker. The following histograms show the distribution of the difference between acoustic duration and gestural duration of geminated liquids for S5. Positive value indicates that gestural duration was longer than the acoustic duration, and negative value indicates that gestural duration was shorter than the acoustic duration. It shows that the durational difference between the two measures are more spread for the productions with weak laryngealization (-96.7∼84.82 ms) and glottal stop insertion (-101.8∼110.5

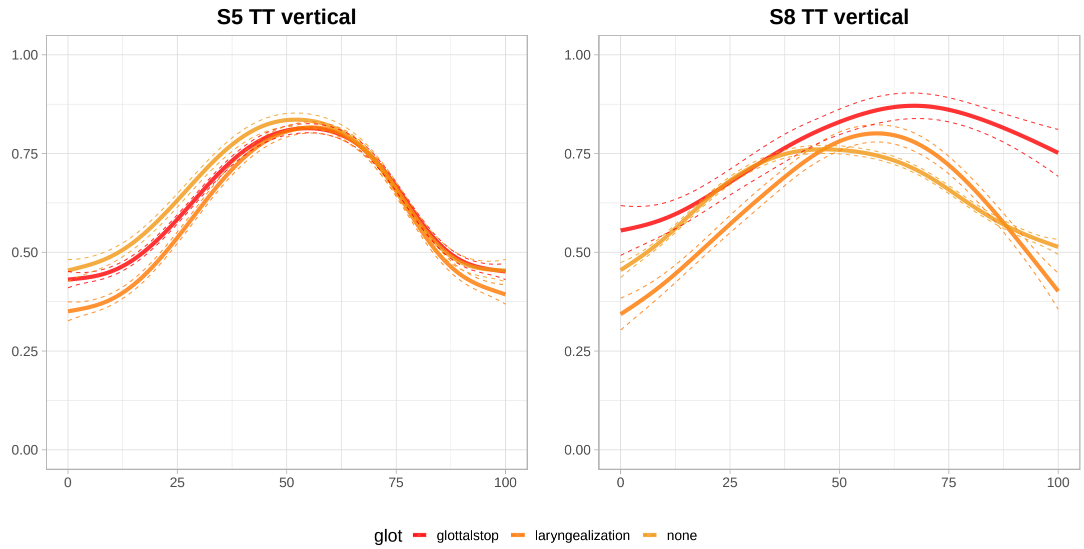
ms) compared to non-laryngealized productions (-33.95∼72.36 ms).

Figure 3.11: Distribution of the difference between acoustic and gestural durations (ms) from S5, faceted by laryngeal information.



While gestural duration and acoustic duration are largely in agreement for the non-laryngealized tokens, laryngealized tokens involve more gaps between the two measures. While some productions suggest that the laryngeal component and the TT gesture are overlayed, for some of the laryngealized tokens, the onset of the TT constriction gesture is delayed, as shown in Figure 3.12 below.

Figure 3.12: Smoothing splines of the temporal dynamics of TT vertical movement over the VCV region, for liquid geminates with glottal stop insertion, weak laryngealization, and no laryngealization from S5 and S8.



3.3.4 Summary

To summarize, TT gestural durations embody the length contrast, and is able to account for the acoustic contrast for geminated liquids.[11] The analysis of TT gestural duration also confirms that geminated liquids are not produced as lingual trills. While TT gestural duration largely correlates with the acoustic durational contrast between singleton and geminates, TT constriction is not always fully responsible for the acoustic contrast. Through a case study of S5, who employs laryngealization for gemination, I showed that the acoustic contrast can also be created as a combinatory effect of glottal and lingual constrictions. The timing relationship between the lingual and laryngeal constrictions was variable. In some cases, glottal stop was followed by a shorter (sometimes as short as singleton liquids) TT gesture; in some other cases, the lingual articulation was not shorter than the acoustic duration despite glottal insertion, during which the lingual gesture was taking place.

[11] Future research will evaluate the role of TT and TB gestures and the timing between the two.

3.4 Positional results

This section reports on the positions of tongue tip (TT) and tongue blade (TB) sensors in terms of height and backness, at the time point of TT maximal constriction.

3.4.1 TT position at TT maximal constriction point

3.4.1.1 TT Height

Overall, the previously reported tendency for geminates to have a higher point of constriction appears in our data, but with variability across consonants and speakers. Average TT height (standardized within each subject across consonants) at the point of TT maximal constriction suggests that overall, geminate constrictions are higher than singletons ($\chi^2(1)$=18.206, p<0.001). There is also a main effect of Consonant ($\chi^2(4)$=395.36, p<0.001), as well as an interaction of Length and Consonant. The effect of consonant length appeared only for /t, r/. Individually, the effect of length was only present for S1 and S7. The effect of consonant length for each consonant is summarized in Table 3.14 below. The interaction indicates that the maximal TT constriction point for liquids are generally higher compared to other consonants. This tendency may be explained by the anterio-posterior location of TT constriction for liquids (section 3.4.1.2).

Table 3.13: Mean TT height (SD) per consonant (standardized within each subject across consonants).

Consonant (*n*)	Singleton	Geminate	GSR
t (67, 67)	0.63 (0.12)	0.67 (0.11)	1.06 (0.06)
d (138, 137)	0.62 (0.1)	0.65 (0.09)	1.06 (0.03)
r (405, 390)	0.71 (0.11)	0.81 (0.09)	1.15 (0.03)
n (59, 63)	0.62 (0.11)	0.65 (0.08)	1.04 (0.08)
s (69, 67)	0.61 (0.1)	0.62 (0.09)	1.03 (0.02)

Figure 3.13: TT height at TT maximal constriction point per consonant and length, standardized within each speaker.

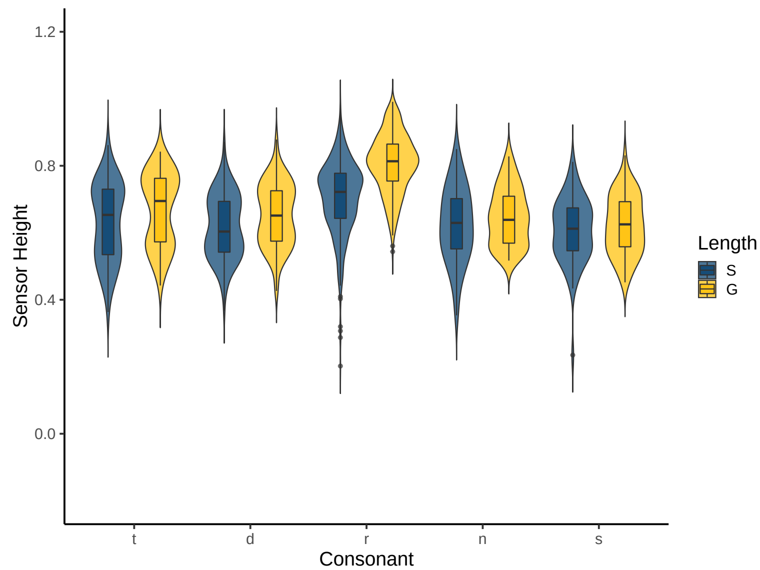
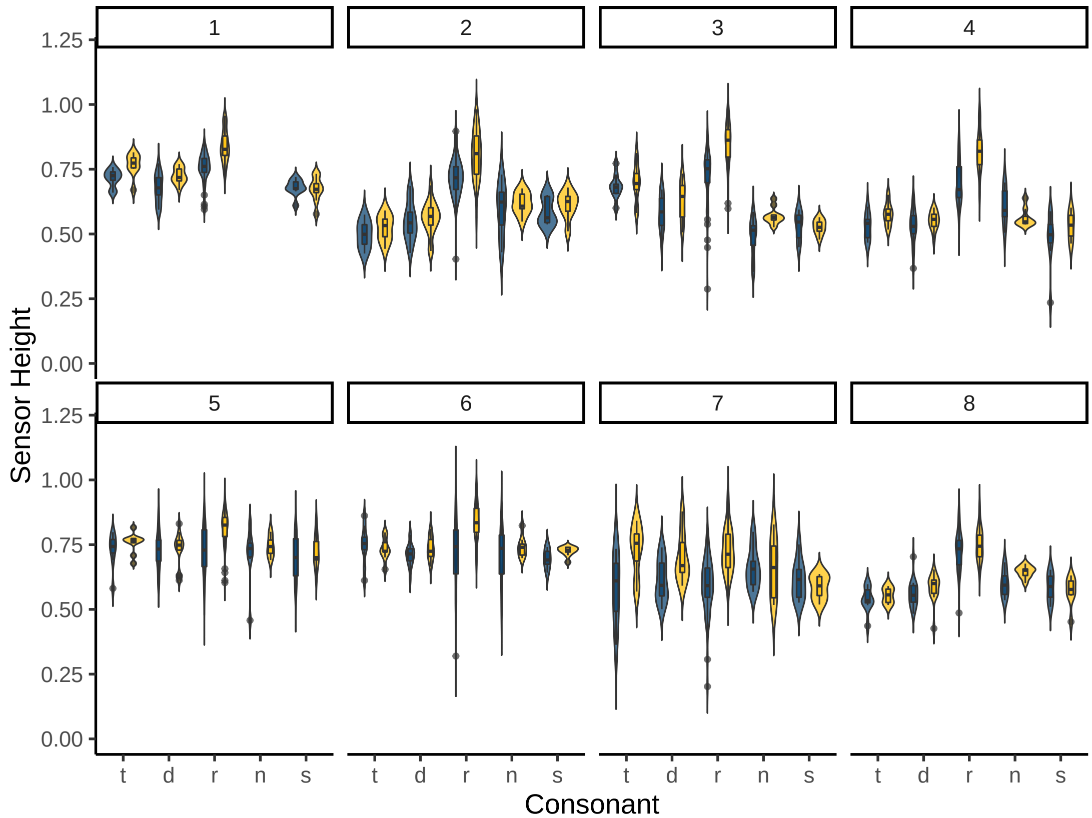


Table 3.14: Fixed effects coefficients table for the model of the TT height (standardized) at maximal constriction point for each consonant.

TT height ∼ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.636	0.021	20.495	30.258	< 2e-16	***
LengthG	0.04	0.016	179.045	2.5	0.013	*
Consonantd	-0.02	0.015	920.376	-1.319	0.188	
Consonantr	0.069	0.013	775.156	5.152	3.28e-07	***
Consonantn	-0.005	0.018	969.975	-0.271	0.786	
Consonants	-0.023	0.016	1350.976	-1.426	0.154	
LengthG:Consonantd	-0.006	0.018	1425.905	-0.345	0.73	
LengthG:Consonantr	0.062	0.016	1427.615	3.869	0.0001	***
LengthG:Consonantn	-0.014	0.022	1431.724	-0.634	0.526	
LengthG:Consonants	-0.028	0.021	1425.781	-1.332	0.183	

The following figure suggests that in most speakers, the tendency for liquids to be constricted higher than other consonants is present, except for S3, S5, and S7 (S3 is particular in that TT heigh for geminates is high). We will see in the next section that TT in S7 is not as retracted as in other subjects.

Figure 3.14: TT height at TT maximal constriction point per subject and length.



3.4.1.2 TT Backness

Overall, TT maximal constriction backness is not different across consonant length ($\chi^2(1)$=1.889, p=0.1693). However, there is a main effect of consonant ($\chi^2(4)$=902.44, p<0.001). The effect of Length is marginally present only for /n/ (Table 3.16). As shown in Figure 3.15, the TT constriction position for /r/ is more posterior than in other consonants, regardless of length. Taken together with the TT height results, liquid constrictions are probably post-alveolar for both singletons and geminates, allowing for a higher point of constriction compared to the other consonants.

Table 3.15: Mean TT backness (SD) per consonant (standardized within each subject across consonants).

Consonant	Singleton	Geminate	GSR
t	0.28 (0.11)	0.29 (0.11)	1.04 (0.15)
d	0.28 (0.13)	0.27 (0.11)	0.97 (0.17)
r	0.53 (0.15)	0.51 (0.13)	0.98 (0.08)
n	0.32 (0.12)	0.27 (0.11)	0.86 (0.07)
s	0.32 (0.12)	0.32 (0.1)	1.00 (0.08)

Figure 3.15: TT backness at TT maximal constriction point per consonant and length.

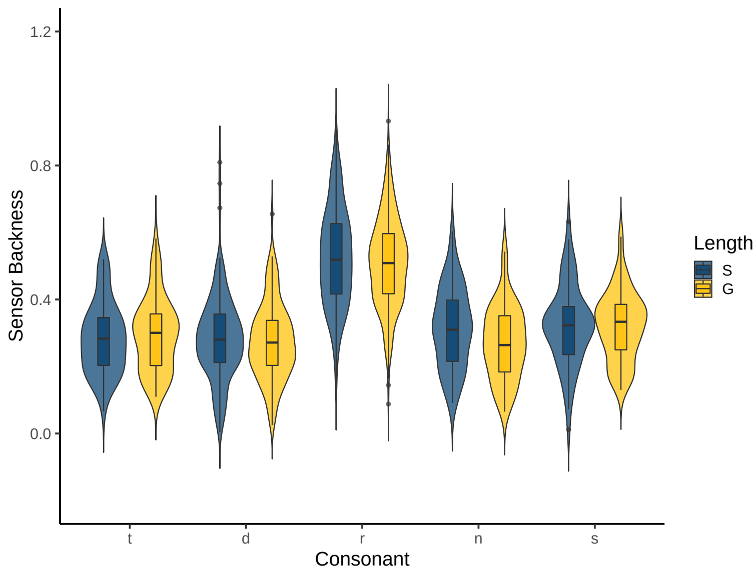
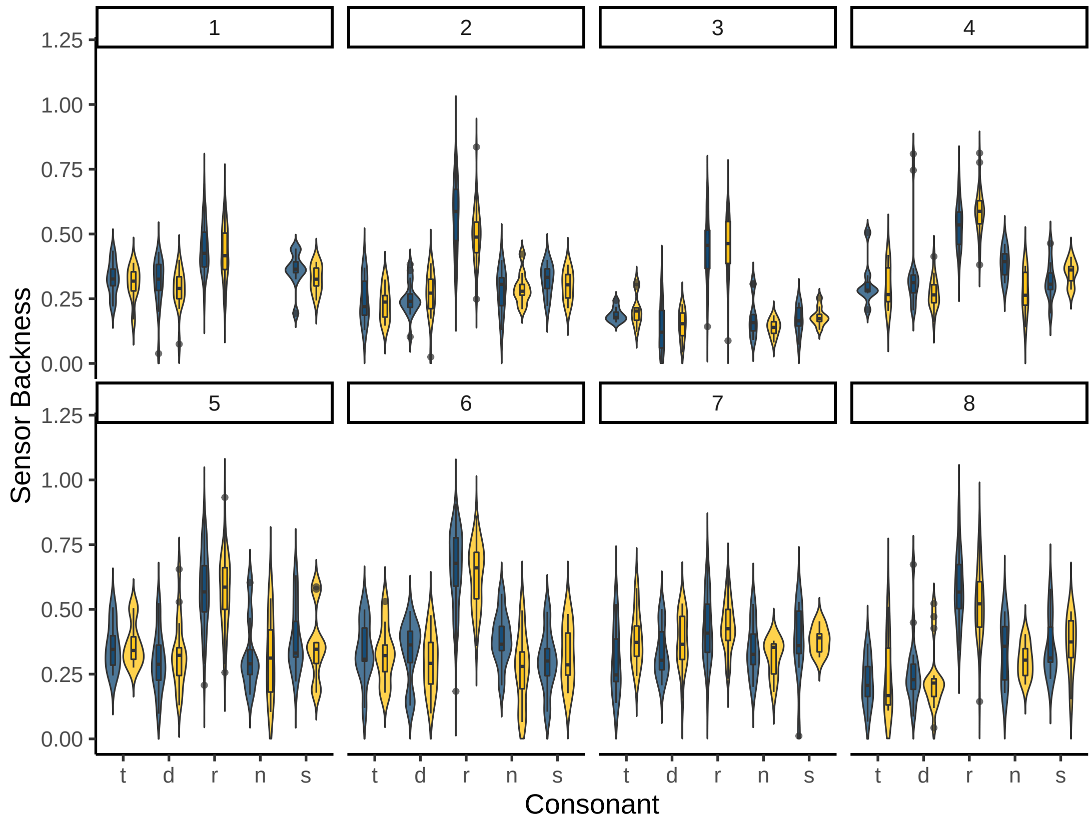


Table 3.16: Fixed effects coefficients table for the model of the TT backness (standardized for each subject) at maximal constriction point for each consonant.

TT backness $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.229	0.029	29.571	7.943	8.05e-09	***
LengthG	0.011	0.02	386.423	0.548	0.584	
Consonantd	0.032	0.02	1385.606	1.626	0.104	
Consonantr	0.303	0.018	1337.621	16.842	< 2e-16	***
Consonantn	0.094	0.024	1403.718	3.942	8.47e-05	***
Consonants	0.056	0.021	1446.256	2.699	0.007	**
LengthG:Consonantd	-0.021	0.023	1426.466	-0.913	0.361	
LengthG:Consonantr	-0.022	0.021	1428.829	-1.055	0.292	
LengthG:Consonantn	-0.053	0.028	1433.745	-1.909	0.056	.
LengthG:Consonants	-0.013	0.027	1426.313	-0.486	0.627	

Figure 3.16 below shows that TT constriction position is more posterior for liquids compared to other consonants in most subjects. While this difference is also significantly present in S7, it is pretty small compared to the other speakers. From the previous section, S7 appears to differ from other speakers in that the TT constriction for liquids share more similarity with the other alveolar consonants. In the meantime, TT is more back for liquids in S5 and S6, regardless of length. At this point, we can group S7, S5 and S6, and all the other speakers into three different groups. The figure also shows that the effect of length is true for /n/, in a way that there is more fronting for geminates than singletons.

Figure 3.16: TT backness at TT maximal constriction point per subject and length.



3.4.2 TB position at TT maximal constriction point

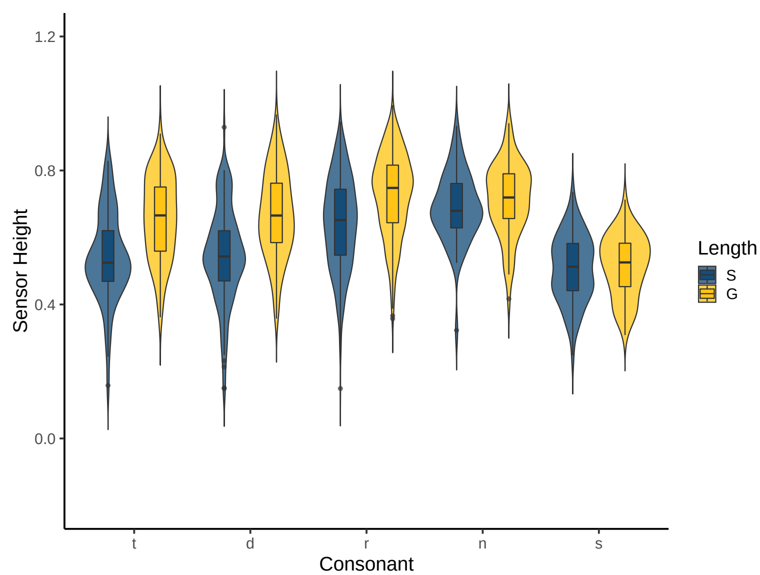
3.4.2.1 TB Height

As in TT height results, geminates tend to be constricted at a higher position overall ($\chi^2(1)$=19.748, p<0.001). There is also a main effect of Consonant ($\chi^2(1)$=84.532, p<0.001). The best model for TB height includes an interaction between Length and Consonant (Table 3.18).

Table 3.17: Mean TB height (SD) per consonant (standardized within each subject across consonants).

Consonant	Singleton	Geminate	GSR
t	0.54 (0.13)	0.66 (0.12)	1.22 (0.03)
d	0.55 (0.14)	0.67 (0.13)	1.24 (0.15)
r	0.64 (0.14)	0.73 (0.12)	1.14 (0.08)
n	0.69 (0.1)	0.71 (0.11)	1.04 (0.08)
s	0.51 (0.1)	0.52 (0.09)	1.02 (0.01)

Figure 3.17: TB height at TT maximal constriction point per consonant and length.



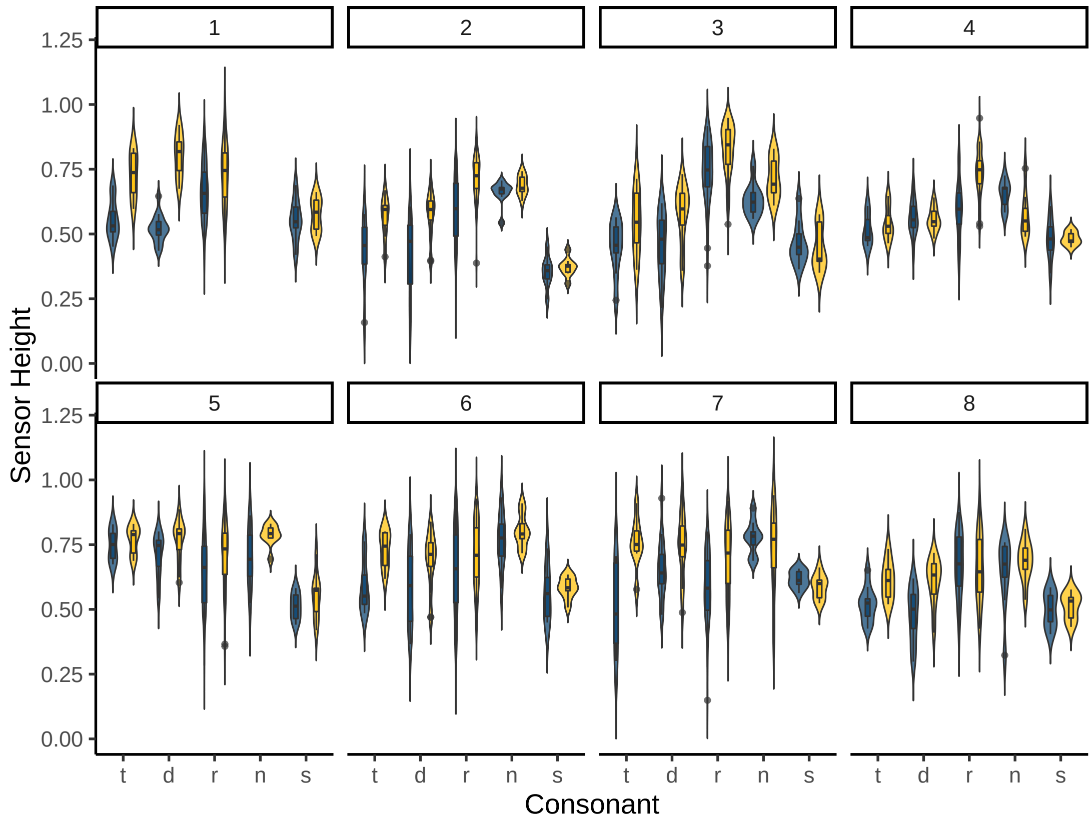
TB height difference based on consonant length is stark for /t, d, r/, but appears to be less in /n/ and none in /s/. The TB height patterns differ from TT height patterns in that TB height is more similar across consonants. TB height for liquids are not standing out as much as in TT height, which could be indicative of increased distance between TT and TB (such that TT is higher than TB; we will examine this aspect with the tongue curling index, in section 3.5.2). On the other hand, in /t, d/, TT is higher than TB for singleton, but the two sensors are at level for geminates. This is consistent with previous reports on EPG data that geminate obstruents tend to have a more complete contact between the palate and the tongue tip - tongue blade region. Nasals are quite unique in that they are produced with relatively lower TT height and higher TB height. For /s/, TT and TB height remain relatively low compared to the other consonants, regardless of length.

Table 3.18: Fixed effects coefficients table for the model of the TB Height (standardized for each subject) at maximal constriction point for each consonant.

TB height $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.625	0.026	56.394	24.228	< 2e-16	***
LengthG	0.117	0.019	221.621	6.13	3.97e-09	***
Consonantd	-0.044	0.019	1438.997	-2.354	0.019	*
Consonantr	0.013	0.017	1427.196	0.785	0.432	
Consonantn	0.022	0.023	1445.358	0.972	0.331	
Consonants	-0.048	0.02	1445.258	-2.437	0.015	*
LengthG:Consonantd	0.003	0.022	1426.708	0.153	0.878	
LengthG:Consonantr	-0.034	0.02	1428.443	-1.742	0.082	.
LengthG:Consonantn	-0.089	0.026	1433.221	-3.377	0.001	***
LengthG:Consonants	-0.108	0.026	1426.578	-4.246	2.31e-05	***

The following figure indicates that most of the subjects have a relatively high TB position compared to other consonants, except for S5, S6, and S7.

Figure 3.18: TB height at TT maximal constriction point per subject and length.



3.4.2.2 TB Backness

There is no main effect of Length on TB horizontal position ($\chi^2(1)$=2.2063, p=0.1375). However, there is a strong effect of consonant ($\chi^2(4)$=977.94, p<0.001). There is no significant difference between a model with an additive effect of Length and Consonant and interaction effect ($\chi^2(4)$=5.0758, p=0.2796), but the interaction terms indicate some marginal effect of Length on /n/ (Table 3.20).

Again, liquids are produced at a more posterior region compared to the other alveolar consonants (and the tendency appears in all subjects except S7). There appears to be no difference dependent on consonant length. Among the consonants, the only one that shows the effect of length is /n/, in which geminates are more fronted (as in TT).

Table 3.19: Mean TB backness (SD) per consonant (standardized within each subject across consonants).

Consonant	Singleton	Geminate	GSR
t	0.3 (0.08)	0.3 (0.11)	0.98 (0.1)
d	0.31 (0.11)	0.28 (0.1)	0.92 (0.11)
r	0.54 (0.17)	0.53 (0.15)	0.99 (0.09)
n	0.32 (0.11)	0.27 (0.11)	0.85 (0.09)
s	0.38 (0.11)	0.38 (0.1)	1.01 (0.05)

Figure 3.19: TB backness at TT maximal constriction point per consonant and length.

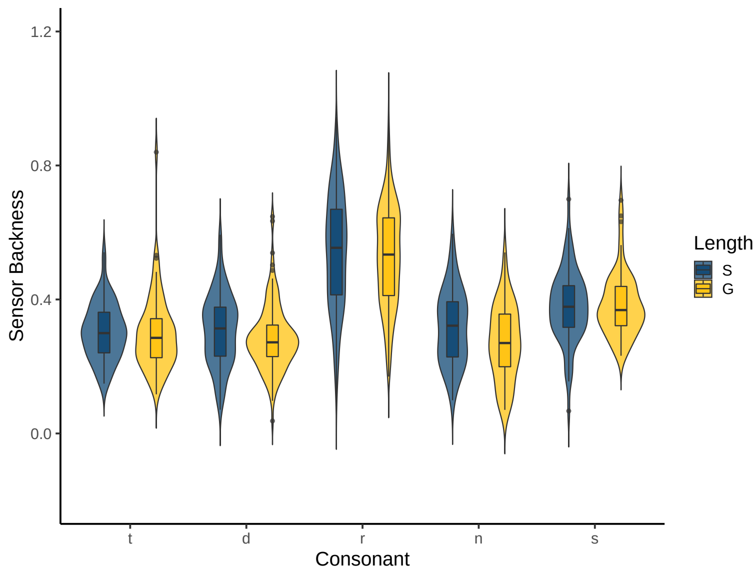
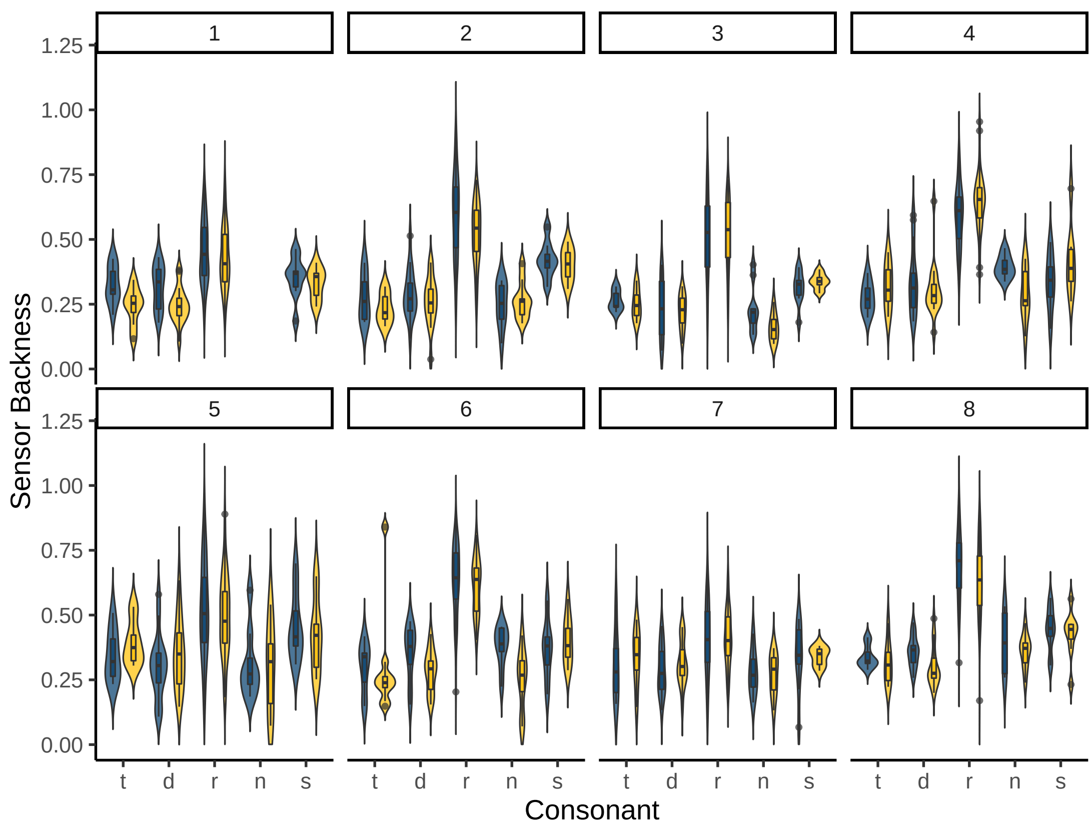


Table 3.20: Fixed effects coefficients table for the model of the TB Backness (standardized for each subject) at maximal constriction point for each consonant.

TB backness ∼ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.223	0.032	31.676	6.918	8.28e-08	***
LengthG	-0.002	0.02	163.745	-0.091	0.928	
Consonantd	0.047	0.02	1441.181	2.366	0.018	*
Consonantr	0.329	0.018	1431.408	18.182	< 2e-16	***
Consonantn	0.106	0.024	1446.152	4.419	1.07e-05	***
Consonants	0.093	0.021	1444.619	4.484	7.90e-06	***
LengthG:Consonantd	-0.025	0.023	1426.574	-1.067	0.286	
LengthG:Consonantr	-0.009	0.021	1427.976	-0.443	0.658	
LengthG:Consonantn	-0.046	0.028	1432.177	-1.651	0.099	.
LengthG:Consonants	0.007	0.027	1426.479	0.254	0.799	

Figure 3.20: TB backness at TT maximal constriction point per subject and length.



3.4.3 TD backness at TT maximal constriction point

There is no effect of Length on TD backness ($\chi^2(1)$=1.2686, p=0.26), but there is a strong main effect of Consonant ($\chi^2(4)$=1.2686, p<0.001). There is no significant difference between an additive model and interaction model ($\chi^2(4)$=5.0414, p=0.2831). It is clear that for both singletons and geminates, liquids have a retracted tongue body compared to the other consonants. This tendency is present in all subjects, though the effect is smaller for S7 compared to the other speakers (individual models can be found in Appendix B).

Table 3.21: Mean TD backness (SD) per consonant (standardized within each subject across consonants).

Consonant	Singleton	Geminate	GSR
t	0.37 (0.13)	0.35 (0.13)	0.94 (0.06)
d	0.36 (0.14)	0.34 (0.13)	0.93 (0.09)
r	0.53 (0.19)	0.52 (0.17)	1.00 (0.09)
n	0.37 (0.15)	0.33 (0.16)	0.90 (0.07)
s	0.44 (0.14)	0.43 (0.12)	1.00 (0.05)

Figure 3.21: TD backness at TT maximal constriction point per consonant and length.

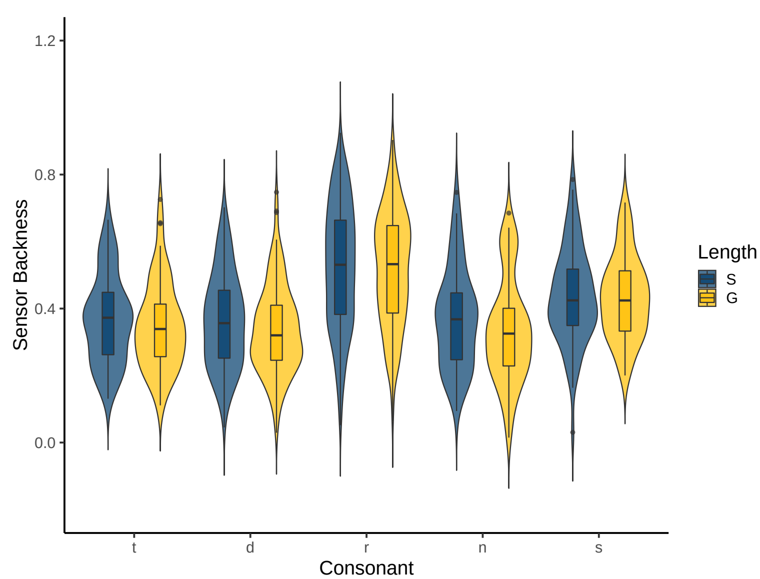


Table 3.22: Fixed effects coefficients table for the model of the TD Backness (standardized for each subject) at maximal constriction point for each consonant.

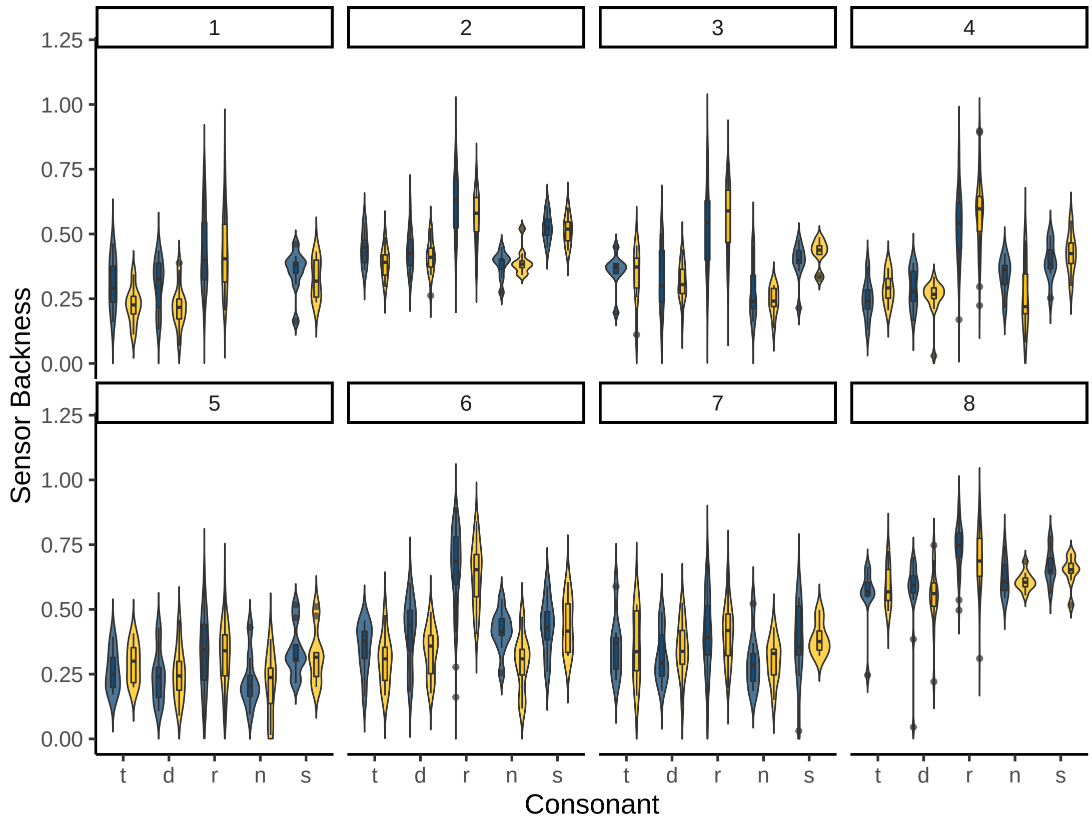
TD backness $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.272	0.047	14.228	5.802	4.30e-05	***
LengthG	-0.013	0.019	174.632	-0.652	0.515	
Consonantd	0.055	0.019	1445.224	2.923	0.004	**
Consonantr	0.266	0.017	1440.631	15.584	< 2e-16	***
Consonantn	0.105	0.023	1448.743	4.656	3.51e-06	***
Consonants	0.094	0.019	1442.864	4.805	1.71e-06	***
LengthG:Consonantd	-0.015	0.022	1426.836	-0.698	0.485	
LengthG:Consonantr	0.011	0.019	1428.289	0.557	0.578	
LengthG:Consonantn	-0.022	0.026	1432.607	-0.835	0.404	
LengthG:Consonants	0.013	0.025	1426.743	0.502	0.616	

Table 3.23 and Figure 3.22 below summarize the average TD backness for each speaker, during the production of singleton and geminate liquids.

Table 3.23: TD backness and GSR (SD) for liquids by subject.

Subject	Singleton	Geminate	GSR
1	0.44 (0.15)	0.43 (0.15)	0.98
2	0.62 (0.13)	0.57 (0.1)	0.92
3	0.52 (0.16)	0.57 (0.13)	1.10
4	0.53 (0.13)	0.58 (0.14)	1.09
5	0.33 (0.14)	0.32 (0.12)	0.97
6	0.66 (0.16)	0.63 (0.12)	0.95
7	0.41 (0.15)	0.41 (0.11)	1.00
8	0.74 (0.09)	0.7 (0.12)	0.95

Figure 3.22: TD backness at TT maximal constriction point per subject and length.



3.5 Lateralization and tongue curling

3.5.1 Lateralization at TT maximal constriction point

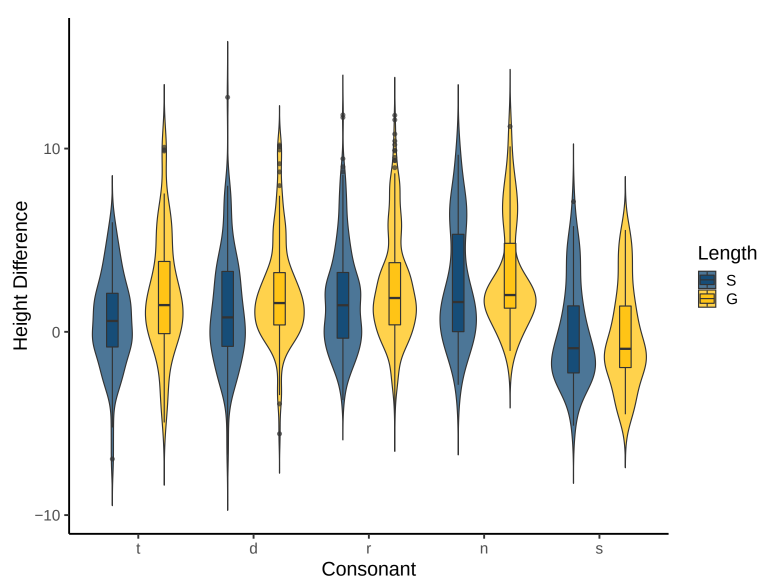
Lateralization index at the TT maximal constriction point (for the dominant side on each subject; see section 3.2.4.2) is reported. Positive values indicate that the tongue blade sensor on the mid-sagittal line is positioned higher than the lowered side of the tongue. Note that a positive lateralization index does not necessarily imply that there is a lateral channel that lets the air through – they need to be interpreted as giving a sense of what the coronal profile of the tongue looks like, unless paired with precise palate shape information. It should be kept in mind as well that taken together with the consonantal effect on anterior-posterior position, the volume of the lateral opening may differ considerably between /r/ and the other consonants.

Overall, geminates involve more side-lowering than singletons (χ^2(1)=12.386, p<0.001). There was also a main effect of Consonant (χ^2(4)=70.133, p<0.001). In particular, /s/ has a low value for this index compared to the other consonants, indicating that the side of the tongue is raised compared to the center of the tongue. While singleton /t/ also has some side-raising, there is more side-lowing when geminated (which goes in the opposite direction as /s/). The index is highest for nasals, then liquids.

Table 3.24: Mean lateralization per consonant at TT maximal constriction point (mm). Standard deviation is provided in parenthesis.

Consonant	Singleton side-lowering	Geminate side-lowering	G-S Difference
t	0.59 (2.52)	1.99 (3.24)	1.39 (0.22)
d	1.17 (3.02)	2.07 (2.76)	0.92 (0.74)
r	1.72 (2.80)	2.44 (2.97)	0.71 (56)
n	2.50 (3.20)	3.01 (2.89)	0.54 (0.70)
s	-0.15 (2.72)	-0.29 (2.71)	-0.14 (0.06)

Figure 3.23: Lateralization (mm) per consonant and length.



The best model of lateralization at TT maximal constriction point includes an interaction between Length and Consonant, where geminated /s/ has tongue-side raising (Table 3.25).

Table 3.25: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant.

Lateralization $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	1.604	0.824	10.865	1.947	0.078	.
LengthG	1.233	0.317	86.192	3.891	0.0002	***
Consonantd	-0.058	0.289	1412.36	-0.201	0.841	
Consonantr	-0.004	0.262	1380.654	-0.014	0.989	
Consonantn	0.202	0.348	1423.625	0.582	0.56	
Consonants	-0.957	0.3	1446.385	-3.186	0.001	**
LengthG:Consonantd	-0.225	0.339	1426.635	-0.663	0.508	
LengthG:Consonantr	-0.468	0.301	1427.766	-1.555	0.12	
LengthG:Consonantn	-0.625	0.404	1431.179	-1.547	0.122	
LengthG:Consonants	-1.401	0.392	1426.558	-3.573	0.0004	***

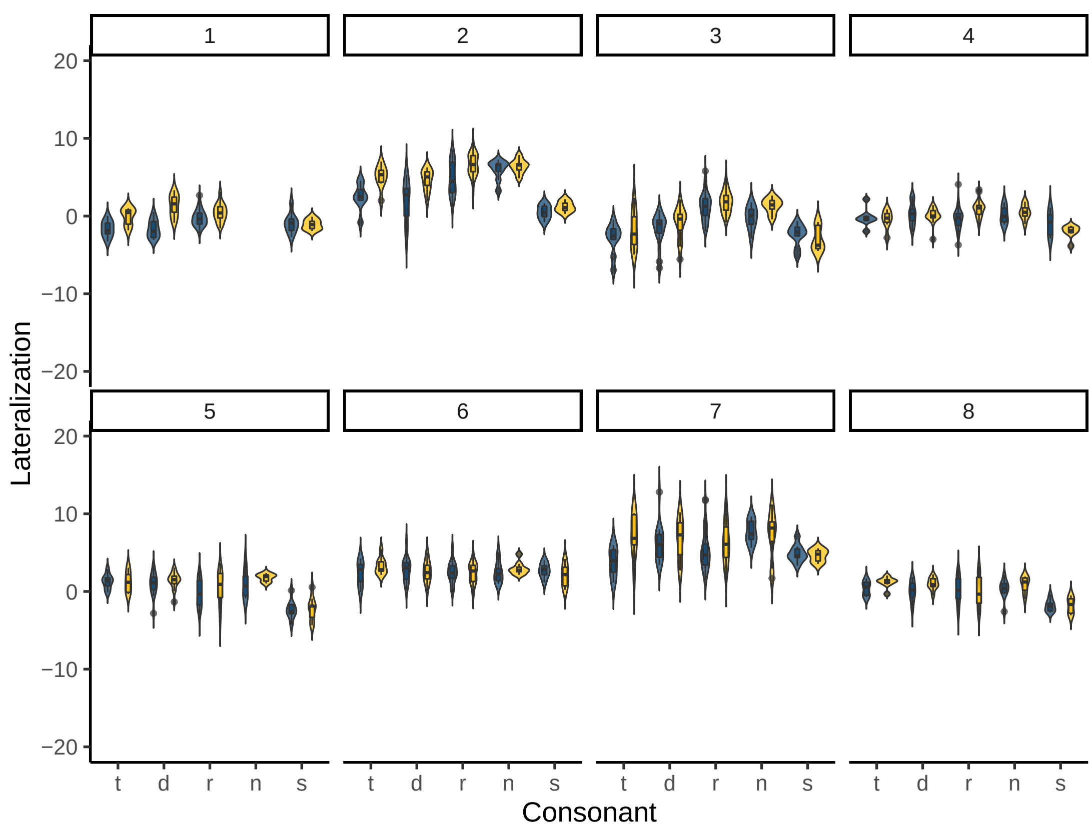
The following table breaks down the lateralization index for each speaker. As tendencies, we can see that S2, S3, and S7 are lateralizing, and more so for geminates than for singletons. The other speakers maintain the heights of TB and TL/TR at level or with slight side-raising. All of them except S8 show more an increased lateralization index for geminates compared to singletons. Interestingly, S8 shows less side-lowering for geminates. S5 is the most side-raising speaker during singletons, and while there is less side-raising for geminates, there is no sign of side-lowering.

Table 3.26: Liquid lateralization at TT maximal constriction point per subject (mm).

Subject	Singleton lateralization	Geminate lateralization	G-S difference
1	-0.27 (1.05)	0.47 (1.13)	0.86 (1.56)
2	4.88 (2.12)	6.62 (1.4)	4.01 (2.78)
3	1.25 (1.75)	1.8 (1.39)	-1.04 (1.76)
4	-0.37 (1.42)	0.89 (1.04)	0.5 (1.82)
5	-0.21 (1.74)	0.65 (2.09)	0.9 (1.67)
6	2.45 (1.34)	2.36 (1.29)	1.15 (1.82)
7	5.19 (2.4)	6.33 (2.6)	2.2 (2.25)
8	0.18 (1.76)	-0.01 (1.97)	-2.74 (3.21)

The following figure shows the lateralization tendencies for each subject, and it is evident that not all subjects are lateralizing the liquids more than other consonants, while others show more side-lowering. The three most lateralizing subjects are S2, S3, and S7.

Figure 3.24: Lateralization (mm) on dominant side for each subject and length.



Tables B.57∼B.64 are coefficients tables for linear mixed effects models for each speaker. For these models, only the vowel environments were entered as random effect.

3.5.2 Tongue curling at TT maximal constriction point

The tongue curling indices (TT height minus TB height) are mostly negative values, indicating that TT is generally lower than TB. Overall, there is no main effect of Length on tongue curling ($\chi^2(1)=1.9291$, $p=0.1649$). There is a strong effect of consonant on tongue curling ($\chi^2(4)=176.28$, $p<0.001$). For singletons, /t/ and /s/ have the most "flat" profile. While /s/ maintains the profile for geminates, /t/ does not.

Table 3.27: Mean tongue curling per consonant (mm). Standard deviation is provided in parenthesis.

Consonant	Singleton tongue curling	Geminate tongue curling	G-S difference
t	-2.92 (2.89)	-4.53 (2.96)	-1.60 (0.74)
d	-3.45 (3.17)	-4.95 (2.58)	-1.54 (1.03)
r	-3.49 (2.89)	-3.18 (2.98)	0.34 (0.71)
n	-6.22 (2.7)	-6.2 (2.49)	0.02 (0.34)
s	-2.83 (2.56)	-2.68 (2.3)	0.14 (0.24)

Figure 3.25: Tongue curling (mm) per consonant and length.

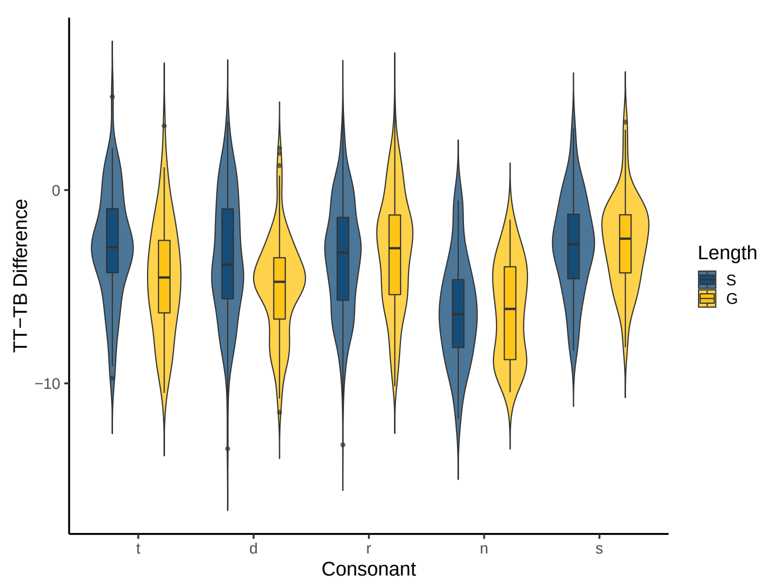


Table 3.28 shows the fixed effects coefficients for the best model of the tongue curling index.

Table 3.28: Fixed effects coefficients table for the model of the tongue curling index at maximal constriction point for each consonant.

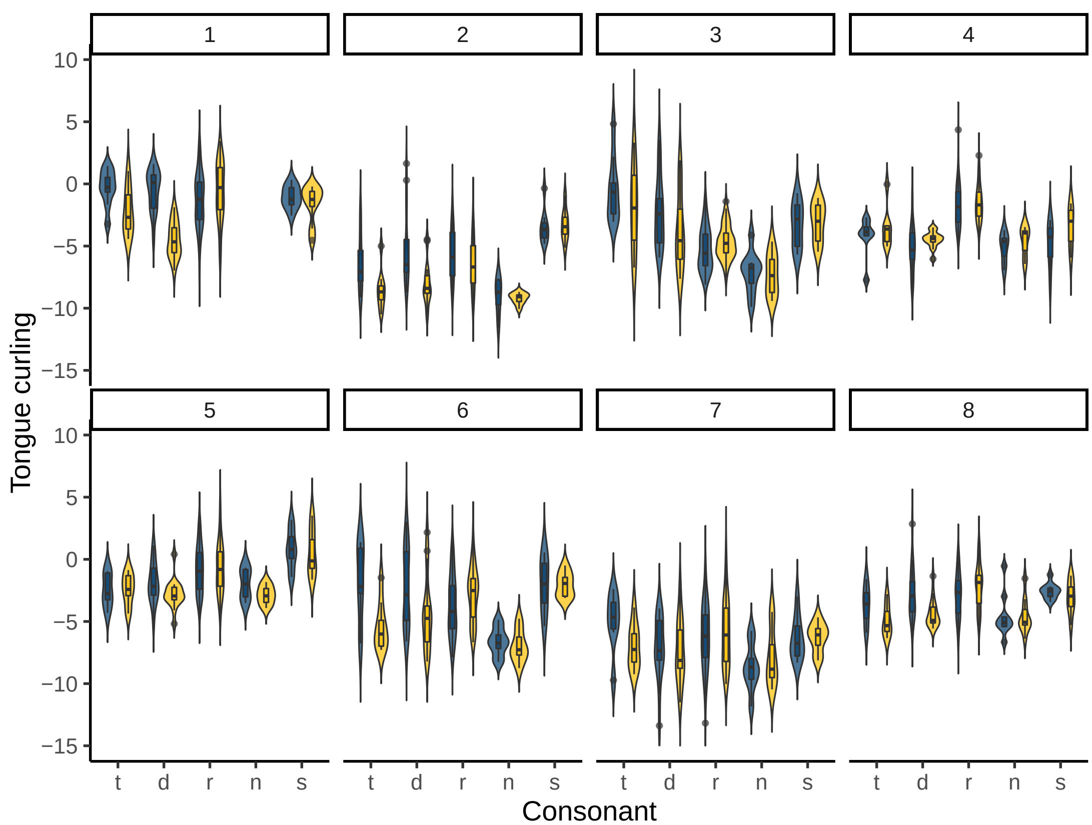
Tongue curling $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-4.507	0.77	15.042	-5.85	3.16e-05	***
LengthG	-1.482	0.335	138.699	-4.419	1.99e-05	***
Consonantd	0.407	0.322	1445.075	1.263	0.207	
Consonantr	1.112	0.293	1440.498	3.795	0.0002	***
Consonantn	-0.488	0.388	1448.525	-1.259	0.208	
Consonants	0.366	0.334	1442.808	1.095	0.274	
LengthG:Consonantd	-0.119	0.376	1426.944	-0.316	0.752	
LengthG:Consonantr	1.829	0.334	1428.242	5.485	4.88e-08	***
LengthG:Consonantn	1.465	0.448	1432.195	3.272	0.001	**
LengthG:Consonants	1.604	0.434	1426.856	3.694	0.0002	***

We notice that the three most lateralizing speakers have a largely negative tongue curling index, indicating that TT is lower than TB, pointing to a domed shape of the tongue surface. Two of these speakers (S3 and S7) have less difference between TT and TB height for geminates compared to singletons (TT is slightly raised; S3 and S7 are also speakers whose average F3 was relatively low), but S2 exaggerates the domed shape for geminates compared to singletons. On the other hand, the non-lateralizing speakers have a raised TT, which tend to be even more raised for geminates than for singletons (the effect is significant for S1, S6, and S8).

Table 3.29: Liquid tongue curling at TT maximal constriction point per subject (mm).

Subject	Singleton curling	Geminate curling	G-S difference
1	-1.3(2.18)	-0.57 (2.33)	1.13 (1.95)
2	-5.63(2.1)	-6.52 (2)	-2.51 (2.32)
3	-5.26(1.71)	-4.72 (1.34)	0.56 (1.05)
4	-1.7(1.79)	-1.55 (1.45)	1.83 (2.27)
5	-0.83(1.9)	-0.69 (2.03)	0.85 (1.6)
6	-3.73(2.45)	-2.88 (2.13)	-0.45 (1.66)
7	-6.22(2.67)	-5.94 (2.71)	-0.8 (1.91)
8	-2.87(1.8)	-2.17 (1.75)	2.13 (2.83)

Figure 3.26: Tongue curling (mm) for each consonant and subject and length.



3.6 Trajectory results

The tendencies reported above must be taken with a grain of salt for mainly two reasons. First, the measures taken at the time point of TT maximal constriction give us only a limited window to the articulatory characteristics of liquids because it does not take into account the temporal dynamics of each measure. This is especially so given the articulatory complexity with which liquids are considered to be produced. Second, all vowel environments are pooled in the above results, and as will be shown below, vowel environments have considerable effects on some of these measures.

In this section, we use a restricted data set including all three items with target /t/ consonant, three selected items for /r/, and three selected /r/ items with the vowel /i/ in the surroundings.

Table 3.30: Restricted data set for trajectory analysis.

#	Item ID	Regular	Emphasized	Consonant	Group	Gloss
1	JR1	garagara	garragara	r	R	empty
2	JR2	girigiri	girrigiri	r	Ri	barely
5	JR5	dorodoro	dorrodoro	r	R	gooey
7	JR7	garigari	garrigari	r	Ri	skinny
11	JR11	berobero	berrobero	r	R	drunk
12	JR12	kirakira	kirrakira	r	Ri	shiny
20	JT1	gatagata	gattagata	t	T	rattling
23	JT4	gotegote	gottegote	t	T	gaudy
24	JT5	gotogoto	gottogoto	t	T	rumbling

Temporal dynamics of lateralization using SSANOVA (following Ying et al., 2017, using R and the package gss; Gu, 2014) show that lateralization in liquids differ drastically for different vowels. In particular, the presence of /i/ on either or both sides of the consonant promotes lateralization for many subjects. Additionally, during the TT gesture, lateralization indices are fairly consistent. In contrast, tongue curling transition throughout the TT gesture, in varying directions per subject.

3.6.1 Temporal dynamics of lateralization and tongue curling

Overall, based on Figures 3.27 and 3.28, we observe that liquids surrounded by /i/ are generally highly lateralized, regardless of consonant length. Even speakers who do not lateralize much more than /t/ in other vowel environments do: S1, S5, S7, and S8. S4 is unique in that he shows this tendency for singleton liquids, but not for geminated liquids. Speakers who do lateralize more than others, S2 and S3, also show increased lateralization throughout the consonant when surrounded by /i/. Similar trends is absent in S6, who apparently never lateralizes during the consonantal gesture.

The lateralization trajectory for the non-/i/ environments mostly corresponds to the results at TT maximal constriction point: S1, S4, S5, S6, S7, and S8 all show no different or lower lateralization indices throughout, compared to /t/. S3 has higher lateralization especially at the onset of the TT gesture, although it converges towards the end of the articulation. Lateralization for S2 disagrees with the earlier results in that there is no difference between /t/ and /r/ lateralization for singleton, and that there is consistent lateralization throughout geminated liquids, while it converges with /t/ at the mid-portion of the TT gesture.

Figure 3.27: Smoothing splines of the temporal dynamics of lateralization over the VCV region, for group T, R, and Ri for singletons.

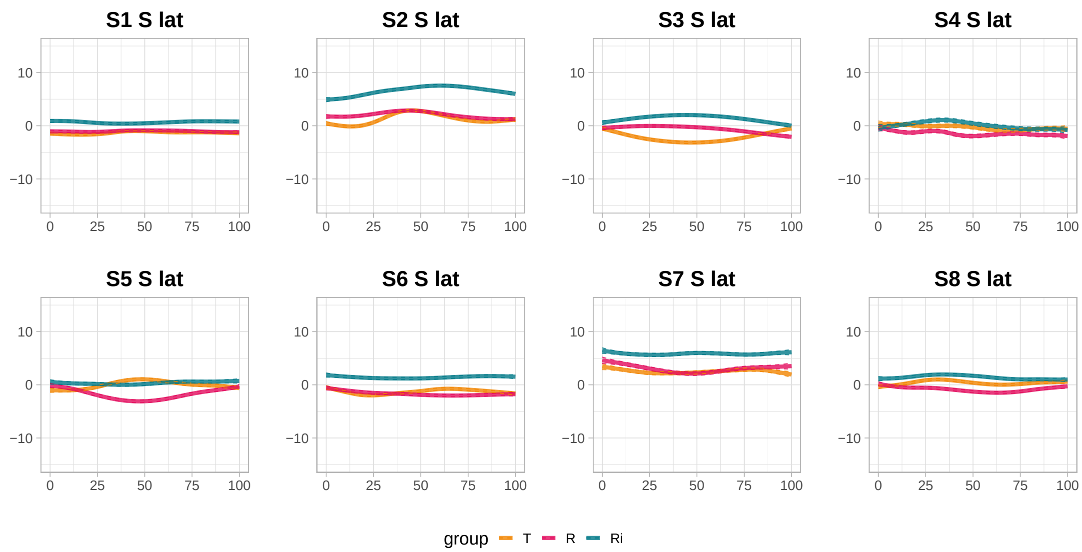
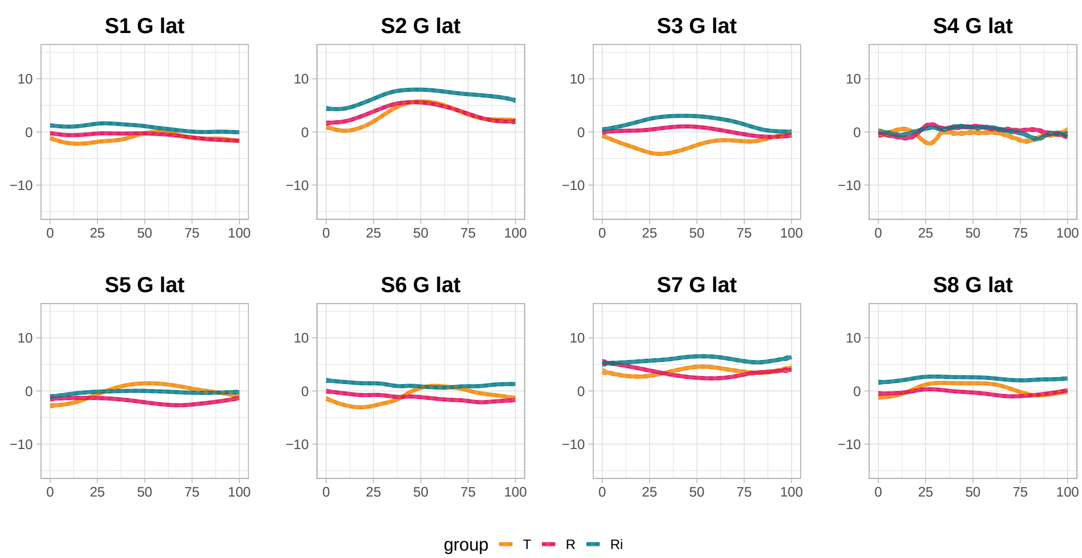


Figure 3.28: Smoothing splines of the temporal dynamics of lateralization over the VCV region, for group T, R, and Ri for geminates.



For tongue curling as well, we see a strong disparity between liquids surrounded by /i/ and liquids that are not. Liquids in /i/ conditions are much less curled compared to the other liquids, and sometimes even less than for /t/. Difference in tongue curling degree between /t/ and /d/ vary considerably among speakers.

In general, however, speakers who had consistently low lateralization have high tongue curling tendencies: S1, S4, S5, S7, and S8. Most of them have a U-shaped contour for tongue curling index, indicating that there is increased distance between TT and TB heights at the middle portion of the consonant, and less towards the onset and offset of the TT gesture. This pattern is largely the opposite of the tongue curling contour in /t/, decreasing the TT and TB heights at the plateau. S6 is an exception to the general negative correlation between lateralization and tongue curling, as he does not show significant tongue curling for singletons, while does so a lot for geminates. Consistent with the static results, S2 has high tongue curling index for both singleton and geminates. This means that S2 is not lateralizing but curling during singletons, and is lateralizing and curling during geminates. As for S3, there is no more tongue curling compared to /t/ across length.

Figure 3.29: Smoothing splines of the temporal dynamics of tongue curling over the VCV region, for group T, R, and Ri for singletons.

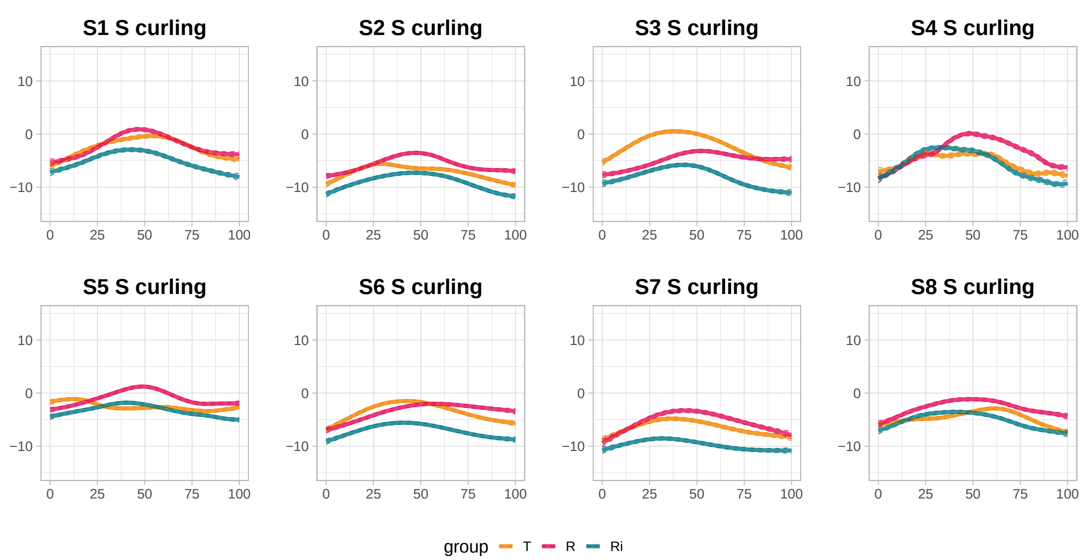
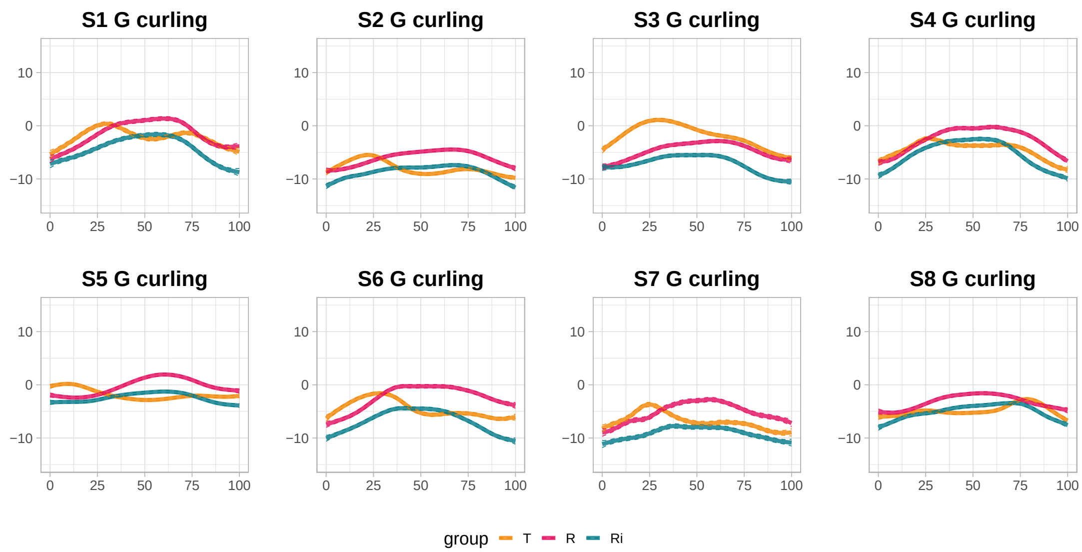


Figure 3.30: Smoothing splines of the temporal dynamics of tongue curling over the VCV region, for group T, R, and Ri for geminates.



3.6.2 Temporal dynamics of TT and TB rising gestures

The following trajectories show that the rising movements are relatively consistent across speakers, with some variability. The geminate panel for S5 shows that the TT rising gestures for R are achieved slightly later and is maintained for a shorter timeframe than the other speakers, which is consistent with what we observed in section 3.3.3.

Figure 3.31: Smoothing splines of the temporal dynamics of TT vertical movement over the VCV region, for group T, R, and Ri for singletons.

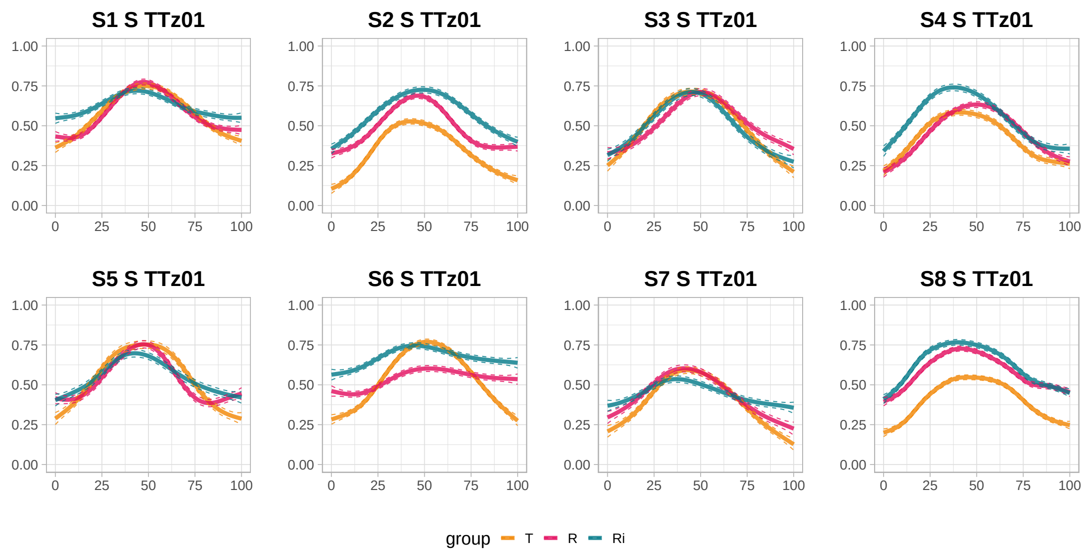
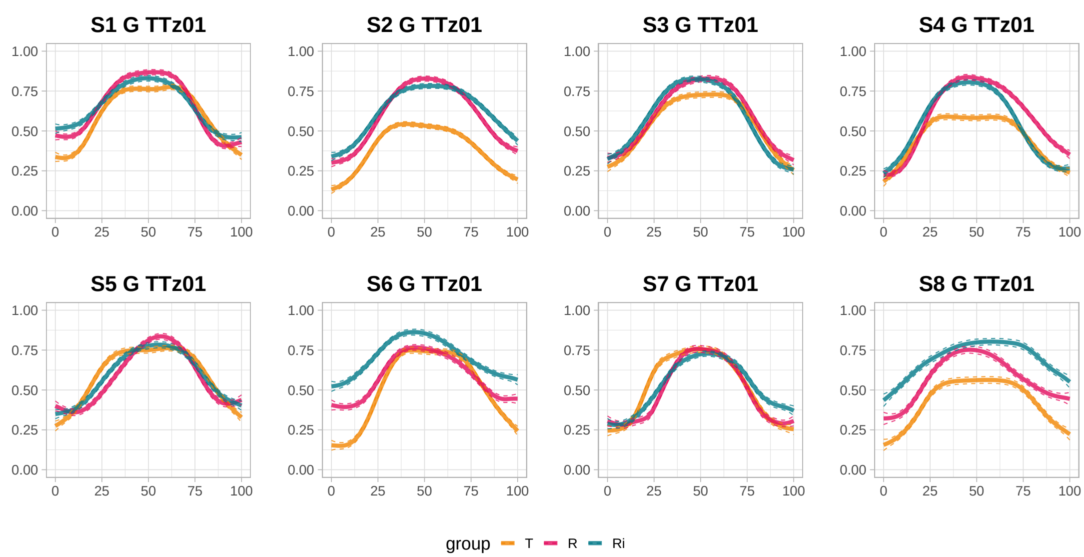


Figure 3.32: Smoothing splines of the temporal dynamics of TT vertical movement over the VCV region, for group T, R, and Ri for geminates.



It is also noteworthy that the TT vertical movements for geminated R are fairly consistent with that of T. In contrast, TB vertical movements for geminated R show more variability, most of the time TB for T attaining a higher target. For both TT and

TB, the vertical movements are flatter for singletons.

Figure 3.33: Smoothing splines of the temporal dynamics of TB vertical movement over the VCV region, for group T, R, and Ri for singletons.

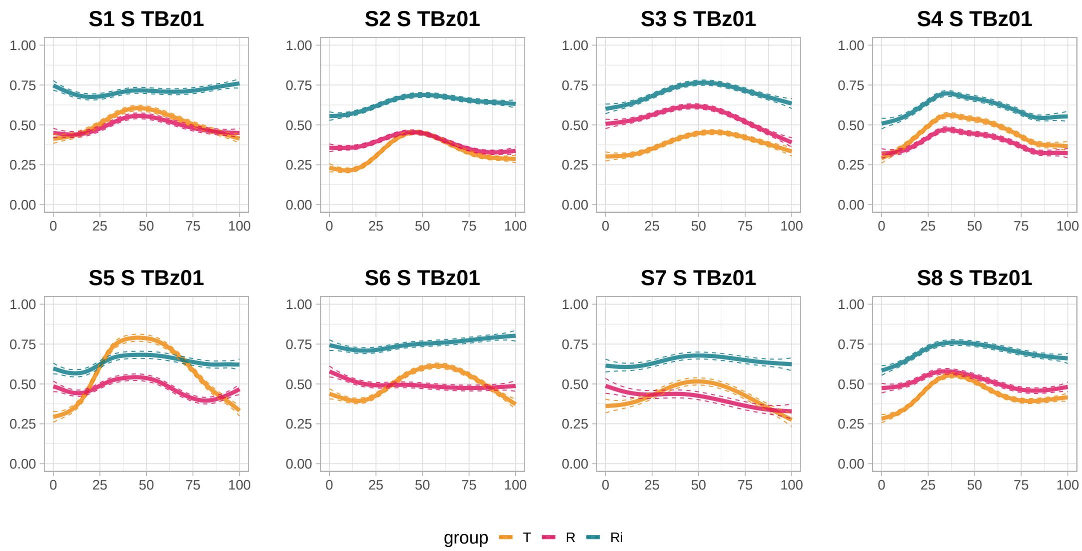
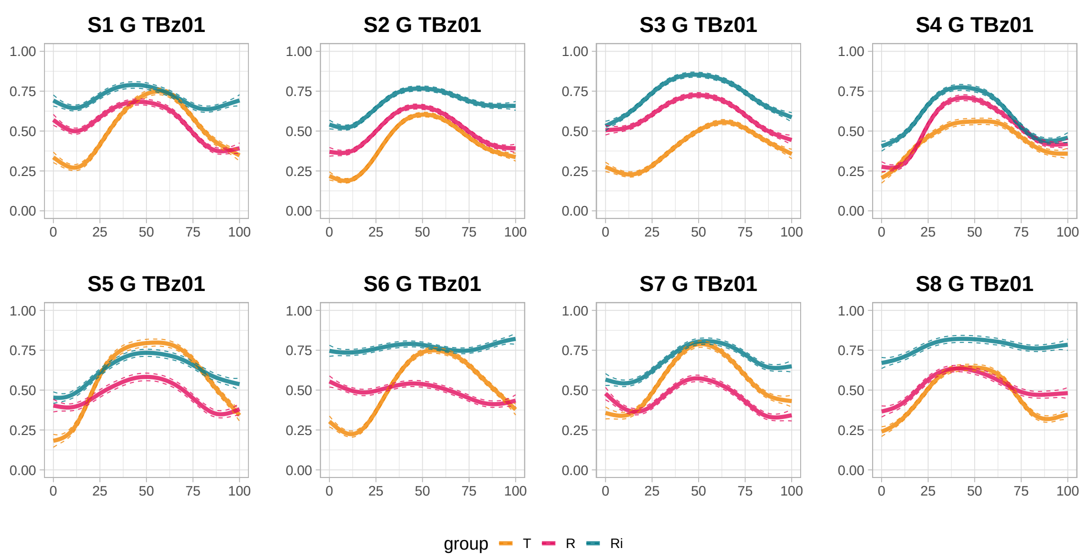


Figure 3.34: Smoothing splines of the temporal dynamics of TB vertical movement over the VCV region, for group T, R, and Ri for geminates.



3.6.3 Temporal dynamics of TD backing gestures

Finally, Figures 3.35 and 3.36 show that the dorsal gesture for R and T are quite different, as well as the effect of the vowel /i/ on the dorsum for liquids.

Figure 3.35: Smoothing splines of the temporal dynamics of TD horizontal movement over the VCV region, for group T, R, and Ri for singletons.

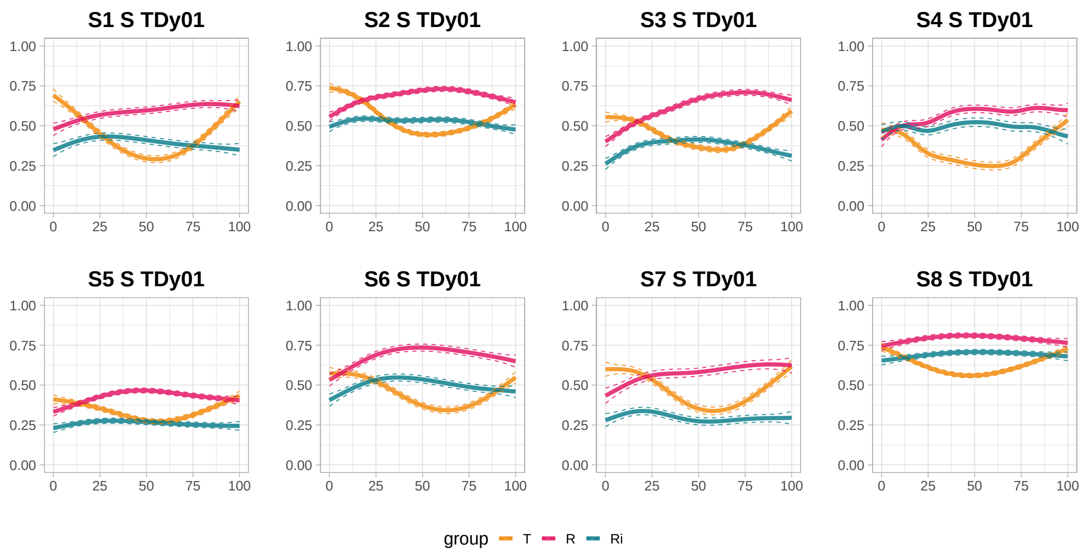
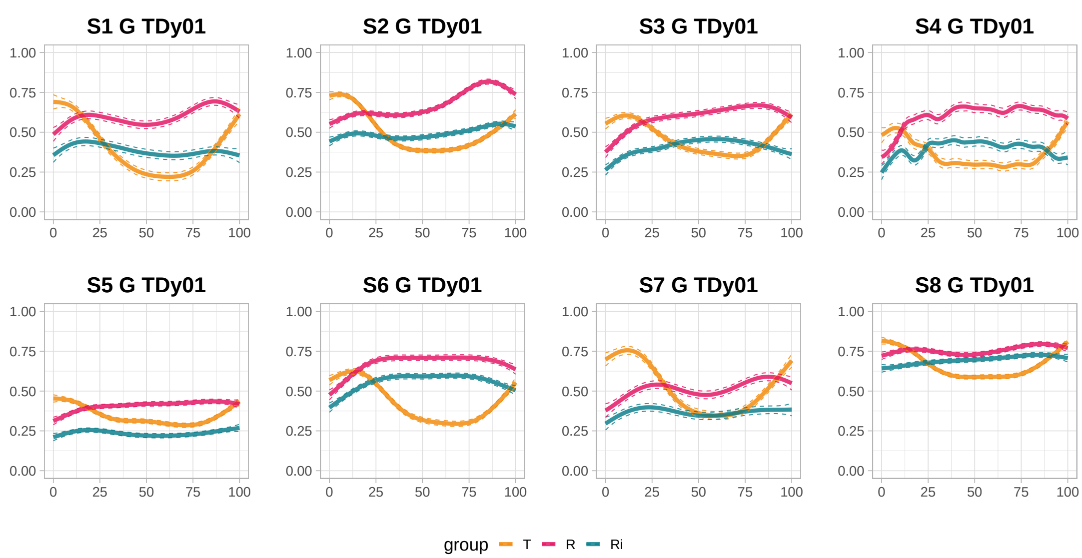


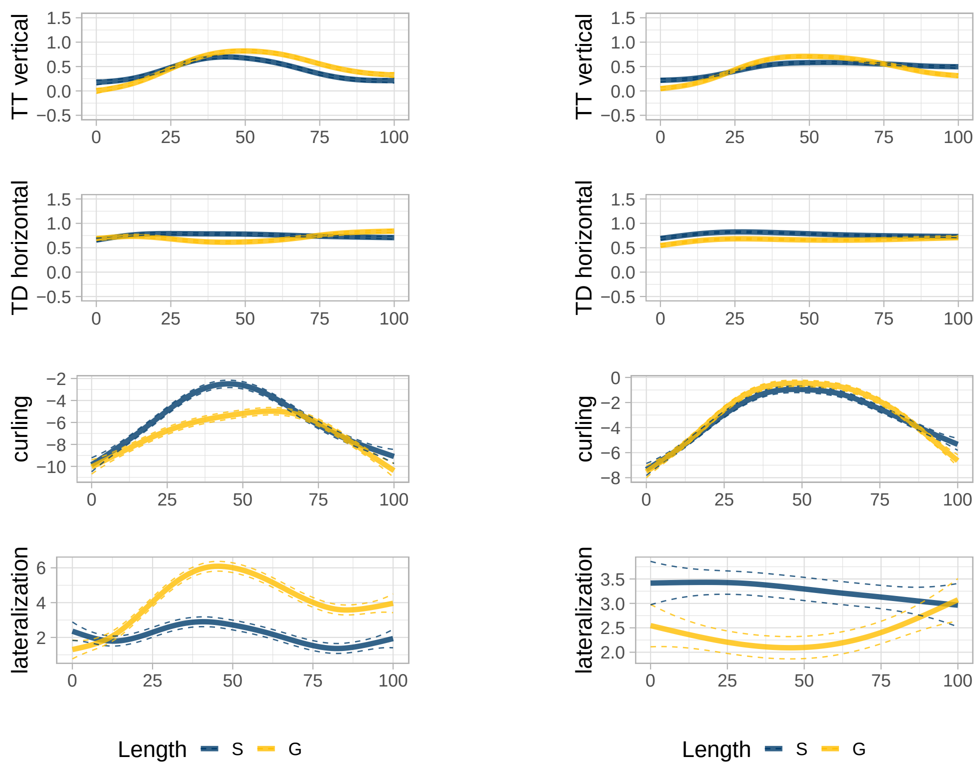
Figure 3.36: Smoothing splines of the temporal dynamics of TD horizontal movement over the VCV region, for group T, R, and Ri for geminates.



3.6.4 Relative timings of gestures

Overall, tongue lateralization negatively correlates with tongue curling (r(67340)=-0.72, p<0.001). The following panels belong to the [garragara] tokens (JR1) for two different subjects, and point to different gemination strategies. For S2, there is high lateralization followed by high tongue curling; for S6, the quality of the liquid appears to be more consistent.

Figure 3.37: Smoothing splines for TT height, TD backness, tongue curling, and lateralization, for [arra] produced by S2 and S6.



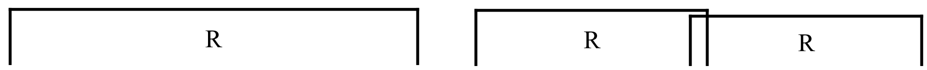
(a) S2 [arra]

(b) S6 [arra]

At the preliminary level, this difference points to the two different representation of geminates discussed in earlier chapters, replicated below.

A production of geminated liquids that is gesturally consistent throughout as in S6 (Figure 3.37b) is corresponds to the right image in Figure 3.38. On the other hand, a

Figure 3.38: Gestural possibilities for geminated liquids, repeated. Left image represents a single long liquid; right image represents two partially overlapping liquids.



production with gestural phasing as in S2 (Figure 3.37a) is more consistent with the left image in Figure 3.38. It should be pointed out, however, that a production as in S2 does not necessarily preclude the long, single gesture representation of geminates. This is precisely because of the presumed gestural complexity of liquids. The apparent gestural phasing in Figure 3.37a may be the results of a sequence of vocalic dorsal gesture followed by a consonantal, apical gesture, both of which belong to a single implementation of a liquid consonant.

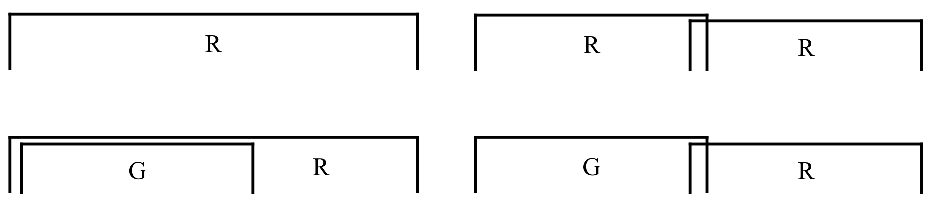
3.7 Discussion & summary

The articulatory results showed that liquids are variable within and across speakers in terms of manner, position, and duration of the articulation. Subjects employ lateralization and tongue curling to a different degree. Articulatory evidence, though not so reliably in the face of lacking the palate information, points to both lateral and retroflex flavor of liquid productions. Most speakers employed retracted tongue body (and tongue tip also), which is consistent with both retroflex and dark-flavored lateral productions. There was also an effect of the vocalic context, whereby the presence of the vowel /i/ induced more lateralization in all subjects.

The combination of retracted tongue body, higher TT constriction location, and tongue curling that we saw in several speakers seemed to point to a strategy for creating a lateral channel in the posterior portion of the vocal tract. This complex gestural profile is reminiscent of English laterals and retroflex (and liquids in some other languages; however at odds with previous report on Japanese tap by Yamane et al., 2015; Akamatsu, 1997). These productions are similar to an articulatory strategy Moore et al. (2018) called “cup in retroflex”, which a Japanese lower intermediate learner of English used often when asked to produce English /l/ and /r/.

Finally, we observed various productions of geminated liquids that point to all of the following representations. Further research is needed to explore the strategic inventory of each speaker, as well as how the vocalic context and consonant type can affect the use of different articulatory strategies.

Figure 3.39: Gestural possibilities for geminated liquids, repeated again. Top left represents a single long liquid; top right represents two partially overlapping liquids; bottom left represents a single long liquid with overlapping laryngeal gesture; bottom right represents a laryngeal gesture partially overlapped with a short liquid.



Chapter 4

Conclusion

The current study aimed to describe the production of geminated liquids in Japanese, focusing on the variability and the lack thereof across productions.

4.1 Summary of the results

Overall, results of the present study show that speakers employ various strategies to produce geminated liquids. Acoustically, there was a high variability in the durational correlates among speakers. For example, the geminate-to-singleton ratio (GSR) of the constriction duration for liquids varied from about 3 to 5 depending on the speaker, and speakers varied as to the effect of length on the preceding and following vowels. Variability in intensity and formant tendencies of the liquid consonant suggest that liquids in Japanese come in various flavors, from retroflex (or post-alveolar) to lateral.

Articulatorily, speakers used varying degrees of lateralization and tongue curling, suggesting different manners of articulation. Furthermore, speakers varied as to the timing among the different components of the articulation. For some speakers, the production of geminated liquids involved the shaping of the tongue at the early stage and maintaining the shape throughout, and for other speakers, geminated liquids were produced by a sequence of different gestures. Vocalic context also affected the production. In particular, high front vowel environments induced lateralization of the liquids in most speakers. Some speakers also made use of laryngeal constrictions to produce geminated liquids, by inserting a glottal stop coda before or during a liquid, or inserting some creakiness on a long liquid.

On the other hand, the realizations of geminated liquid had certain characteristics in common across speakers and productions. First, the variable acoustic durational correlates for individual segments culminated to a quite similar GSR at the VCV level (VCV regions including geminated liquids were 1.5 to 1.8 times longer than singletons) across speakers and consonant types. In addition, while the absolute acoustic durations for singleton and geminated liquid consonants were much shorter compared to obstruents, the duration of VCV region including geminated liquids was quite similar to that of VCV region for obstruent geminates. Furthermore, despite the variability in the amplitude and formant structure tendencies of geminated liquids, as well as the laryngealized nature of some of the productions, all the geminated liquid productions preserved the sonorant nature of the consonant in one way or another.

Finally, the rising movement of the tongue tip and retracted tongue body were characteristics of singleton and geminate liquids, when compared to the other coronal consonants. This is in line with the view that gestural complexity is the universal characteristics of the class of liquids (while in conflict with existing literature on Japanese singleton liquid; Yamane et al., 2015; Akamatsu, 1997).

4.2 Implications and future research

First, the variability in the ways geminated liquids are produced is consistent with the view that Japanese liquids are to some extent featurally underspecified. Especially, the range of flavors of liquids that were available to the speakers supports the underspecification of the place of articulation. Furthermore, the similarity we saw in the realizations of geminated liquids, in particular their (fully or partially) resonant characteristics, is also consistent with the view that they are sonorants. The fact that some of the productions were not fully sonorous all the way could be interpreted as congruent with the underspecification for the [voice] feature.[1] Another explanation for the variability is the marginal or emerging status of this phenomenon, whereby either the canonical strategy or the end-product of the orthographically presented geminated liquids was not clear to some speakers. Future study should explore the production variability in speakers who are more familiar with geminated liquids (e.g. staff at an Italian restaurant in Japan) and speakers who are not.

Laryngealization of geminated liquids we observed in this study may be many things, including the possibilities of being (a) part of a representation of geminates in general, (b) part of a representation of emphatic geminates, or (c) a repair strategy to produce geminated liquids which is somehow problematic. The first possibility is consistent with some previous literature addressing the laryngeal component of geminates in Japanese, and the default value of the *sokuon* phoneme /Q/ (c.f. Vance, 2008). The second possibility is that laryngealization is a side-product of the current experiment employing emphatic gemination. This view is worth exploring especially given the presence of some laryngealized nasal geminates, as an effect of the orthography (using orthographical representation for *sokuon* rather than *hatsuon*, or coda nasal) is suspected. The third possibility includes several scenarios, and is not mutually exclusive with the first two possibilities. Geminated liquids, because of their marginality

[1] The underspecified view of Japanese liquids is appealing given our results, but further study is needed to reconcile their predicted ingeminability and the robust durational contrast observed in our experiment. For the moment, I propose that an Optimality Theoretic analysis (Prince & Smolensky, 1993) would be called for, involving the ranking of a constraint requiring the realization of the inherent mora and a constraint against the docking of a mora to an empty or underspecified node. Their ranking relationship would be different depending on the lexical strata, to reflect the marginal status of geminated liquids.

and low frequency, might be laryngealized in a way that reveals a default strategy for gemination or emphatic gemination. Alternatively, it could be the requirement for the momentary-ness of the liquid, or the general ban on geminated liquids (*/rr/) that is problematic to the speakers. Further study is needed to understand the nature of this laryngealization and assess its implications for the representation of gemination.

In the meantime, the stability in the duration of VCV region, taken together with the wide range of variability in articulation, suggests that the goal of gemination is not articulatory, but rather, acoustic. This is in a way reminiscent of the AmE /ɹ/ discussed in section 3.1.1.3, in which the articulation is not uniform across speakers and productions while achieving similar acoustic effects. Rather than sharing a universal gestural target, speakers share an acoustic temporal target in order to realize phonological length.

The combination of tongue tip gesture and tongue body gesture is consistent with the universal, complex characteristics of liquids. This view is in conflict with previous studies, and further studies with more careful control on the vocalic environments are necessary. Meanwhile, the current study may have obviated a previously overlooked gestural component of Japanese liquids by having them in coda position and requiring them to be fully articulated over a prolonged period of time. The current results also support the view that rhotics do not mesh well with palatalization. On the other hand, despite these observations that are more or less in agreement with cross-linguistic tendencies of liquids, speakers varied as to the the coordination of the different components of the liquid gestures. Further probing this may provide some insights into the learning of gesturally complex liquids in non-native languages as well.

In terms of gestural representation of geminates, the current study could not adjudicate between the single-gesture representation and the double-gesture representation. A more careful study is needed on this issue, keeping in mind the possibility that (a) the core gestural specification for geminates is the coordination between the gestures of the two surrounding vowels, rather than the duration of the consonantal gesture (especially given the consistency in the VCV region discussed above), and that (b) speakers may have different geminate representations.

As a first step in the acoustic and articulatory analysis of geminated liquids, the current study described the general tendencies in geminated liquids in Japanese and their variability, as well as the gestural complexity of liquids that are shared with other languages. The experiment and the analysis presented here had some crucial limitations: the lack of palate shape and position data, the skew in the item and vowel environments, lack of TB and TD gestural tracking data, to name a few. In the future, it would be important to study the perceptual side of this phenomenon as well. Further investigation in this topic would contribute to the understanding of the nature of liquids and geminates in general, as well as the learning and teaching of these sounds.

Appendix A

Supplemental Materials: Acoustic

A.1 Mixed effects models of C2 duration per subject

Table A.1: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S1.

S1 C2 duration ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	66.104	5.907	144.024	11.191	< 2e-16	***
LengthG	71.661	7.235	159.774	9.905	< 2e-16	***
Consonantd	-22.274	6.949	174.707	-3.205	0.002	**
Consonantr	-31.057	6.161	172.039	-5.041	1.17e-06	***
Consonants	-8.19	7.556	175.391	-1.084	0.28	
LengthG:Consonantd	38.073	8.861	159.774	4.297	3.00e-05	***
LengthG:Consonantr	1.537	7.82	159.806	0.197	0.844	
LengthG:Consonants	25.554	10.231	159.774	2.498	0.014	*

Table A.2: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S2.

S2 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	76.978	5.506	161.142	13.982	< 2e-16	***
LengthG	66.691	7.289	188.91	9.149	< 2e-16	***
Consonantd	-27.247	6.634	190.289	-4.107	5.94e-05	***
Consonantr	-44.015	5.839	183.081	-7.538	2.13e-12	***
Consonantn	-20.172	7.739	181.329	-2.607	0.01	**
Consonants	-6.232	7.449	205.644	-0.837	0.404	
LengthG:Consonantd	16.539	8.927	188.91	1.853	0.065	.
LengthG:Consonantr	0.248	7.835	188.963	0.032	0.975	
LengthG:Consonantn	-11.984	10.308	188.91	-1.163	0.246	
LengthG:Consonants	5.423	10.308	188.91	0.526	0.599	

Table A.3: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S3.

S3 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	84.107	5.87	155.658	14.329	< 2e-16	***
LengthG	55.647	7.512	185.862	7.408	4.36e-12	***
Consonantd	-28.452	6.996	194.405	-4.067	6.91e-05	***
Consonantr	-51.815	6.185	186.163	-8.378	1.29e-14	***
Consonantn	-48.281	8.183	189.109	-5.9	1.65e-08	***
Consonants	-9.533	7.755	205.765	-1.229	0.22	
LengthG:Consonantd	8.213	9.2	185.862	0.893	0.373	
LengthG:Consonantr	7.263	8.075	185.918	0.899	0.37	
LengthG:Consonantn	12.516	10.493	186.021	1.193	0.234	
LengthG:Consonants	-5.729	10.624	185.862	-0.539	0.59	

Table A.4: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S4.

S4 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	63.212	5.595	153.306	11.298	< 2e-16	***
LengthG	71.695	7.701	186.295	9.31	< 2e-16	***
Consonantd	-19.697	6.81	180.262	-2.892	0.004	**
Consonantr	-31.056	5.984	174.501	-5.19	5.81e-07	***
Consonantn	-12.749	7.905	162.023	-1.613	0.109	
Consonants	-7.432	8.017	203.984	-0.927	0.355	
LengthG:Consonantd	7.047	9.432	186.295	0.747	0.456	
LengthG:Consonantr	-12.928	8.282	186.324	-1.561	0.12	
LengthG:Consonantn	1.555	10.891	186.295	0.143	0.887	
LengthG:Consonants	-12.754	11.062	186.771	-1.153	0.25	

Table A.5: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S5.

S5 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	88.366	6.819	150.779	12.96	< 2e-16	***
LengthG	55.117	9.164	181.977	6.015	9.67e-09	***
Consonantd	-29.235	8.25	180.592	-3.544	0.001	***
Consonantr	-51.013	7.266	174.201	-7.021	4.74e-11	***
Consonantn	-33.79	9.885	171.313	-3.418	0.001	***
Consonants	-18.581	9.32	200.788	-1.994	0.048	*
LengthG:Consonantd	10.953	11.223	181.977	0.976	0.33	
LengthG:Consonantr	11.786	9.874	182.161	1.194	0.234	
LengthG:Consonantn	-4.555	13.164	182.389	-0.346	0.73	
LengthG:Consonants	2.474	12.96	181.977	0.191	0.849	

Table A.6: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S6.

S6 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	58.074	6.983	160.326	8.316	3.69e-14	***
LengthG	56.408	8.875	186.017	6.356	1.56e-09	***
Consonantd	-17.823	8.302	194.747	-2.147	0.033	*
Consonantr	-27.082	7.344	187.805	-3.687	0.0003	***
Consonantn	-16.288	9.714	191.005	-1.677	0.095	.
Consonants	-0.49	9.18	202.731	-0.053	0.957	
LengthG:Consonantd	10.636	10.869	186.017	0.979	0.329	
LengthG:Consonantr	13.027	9.55	186.017	1.364	0.174	
LengthG:Consonantn	19.476	12.551	186.017	1.552	0.122	
LengthG:Consonants	9.933	12.551	186.017	0.791	0.43	

Table A.7: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S7.

S7 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	55.37	5.685	159.354	9.739	< 2e-16	***
LengthG	66.918	7.418	187.073	9.021	2.22e-16	***
Consonantd	-7.252	6.819	191.212	-1.063	0.289	
Consonantr	-28.274	6.013	184.363	-4.702	5.02e-06	***
Consonantn	-24.961	7.966	184.262	-3.134	0.002	**
Consonants	-3.724	7.612	204.239	-0.489	0.625	
LengthG:Consonantd	-8.172	9.085	187.073	-0.899	0.37	
LengthG:Consonantr	-18.117	7.978	187.093	-2.271	0.024	*
LengthG:Consonantn	4.841	10.491	187.073	0.461	0.645	
LengthG:Consonants	-1.29	10.491	187.073	-0.123	0.902	

Table A.8: Fixed effects coefficients table for the model of the consonant duration for each consonant, for S8.

S8 C2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	65.667	7.981	167.825	8.228	5.04e-14	***
LengthG	96.089	10.165	197.6	9.453	< 2e-16	***
Consonantd	-2.418	9.443	210.637	-0.256	0.798	
Consonantr	-34.746	8.333	205.064	-4.17	4.50e-05	***
Consonantn	1.728	11.253	209.09	0.154	0.878	
Consonants	2.579	10.262	213.481	0.251	0.802	
LengthG:Consonantd	6.082	12.506	197.7	0.486	0.627	
LengthG:Consonantr	6.389	10.93	197.752	0.585	0.559	
LengthG:Consonantn	-4.942	14.375	197.604	-0.344	0.731	
LengthG:Consonants	-24.369	14.38	197.672	-1.695	0.092	.

A.2 Mixed effects models of V1 duration per subject

Table A.9: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S1.

S1 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	51.95	6.891	135.293	7.539	6.17e-12	***
LengthG	22.001	7.769	155.716	2.832	0.005	**
Consonantd	5.414	7.776	178.968	0.696	0.487	
Consonantr	1.472	6.924	178.806	0.213	0.832	
Consonants	-5.979	8.248	169.394	-0.725	0.47	
LengthG:Consonantd	-0.544	9.515	155.716	-0.057	0.955	
LengthG:Consonantr	15.083	8.398	155.741	1.796	0.074	.
LengthG:Consonants	4.895	10.987	155.716	0.446	0.657	

Table A.10: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S2.

S2 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	69.357	6.706	156.918	10.342	<2e-16	***
LengthG	15.239	7.857	185.251	1.94	0.054	.
Consonantd	4.873	7.684	205.042	0.634	0.527	
Consonantr	11.913	6.845	201.17	1.74	0.083	.
Consonantn	11.077	9.009	204.877	1.23	0.22	
Consonants	6.73	8.286	200.867	0.812	0.418	
LengthG:Consonantd	-2.834	9.622	185.251	-0.295	0.769	
LengthG:Consonantr	18.989	8.445	185.283	2.248	0.026	*
LengthG:Consonantn	17.855	11.111	185.251	1.607	0.11	
LengthG:Consonants	-9.459	11.111	185.251	-0.851	0.396	

Table A.11: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S3.

S3 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	67.375	7.145	151.536	9.429	< 2e-16	***
LengthG	21.998	8.341	183.449	2.637	0.009	**
Consonantd	-12.171	8.171	206.054	-1.49	0.138	
Consonantr	6.5	7.286	202.127	0.892	0.373	
Consonantn	-8.032	9.58	205.905	-0.838	0.403	
Consonants	-6.187	8.803	200.946	-0.703	0.483	
LengthG:Consonantd	0.107	10.216	183.449	0.01	0.992	
LengthG:Consonantr	6.647	8.966	183.484	0.741	0.459	
LengthG:Consonantn	16.556	11.652	183.515	1.421	0.157	
LengthG:Consonants	4.054	11.796	183.449	0.344	0.732	

Table A.12: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S4.

S4 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	56.658	6.62	152.109	8.559	1.15e-14	***
LengthG	12.557	8.172	181.159	1.537	0.126	
Consonantd	-1.829	7.778	197.492	-0.235	0.814	
Consonantr	3.642	6.897	189.47	0.528	0.598	
Consonantn	13.563	9.114	195.273	1.488	0.138	
Consonants	-4.293	8.801	201.361	-0.488	0.626	
LengthG:Consonantd	11.256	10.008	181.159	1.125	0.262	
LengthG:Consonantr	21.146	8.788	181.173	2.406	0.017	*
LengthG:Consonantn	-4.768	11.557	181.159	-0.413	0.68	
LengthG:Consonants	13.803	11.742	181.319	1.176	0.241	

Table A.13: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S5.

S5 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	51.816	6.977	146.289	7.427	8.50e-12	***
LengthG	8.123	8.032	177.276	1.011	0.313	
Consonantd	0.803	7.914	200.779	0.101	0.919	
Consonantr	18.844	7.068	198.132	2.666	0.008	**
Consonantn	14.599	9.514	200.905	1.534	0.126	
Consonants	4.045	8.498	193.787	0.476	0.635	
LengthG:Consonantd	8.423	9.837	177.276	0.856	0.393	
LengthG:Consonantr	15.652	8.656	177.433	1.808	0.072	.
LengthG:Consonantn	9.066	11.542	177.375	0.785	0.433	
LengthG:Consonants	11.997	11.359	177.276	1.056	0.292	

Table A.14: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S6.

S6 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	86.074	7.652	152.959	11.249	<2e-16	***
LengthG	17.485	8.922	182.109	1.96	0.052	.
Consonantd	-9.581	8.744	203.283	-1.096	0.275	
Consonantr	-13.207	7.799	199.862	-1.693	0.092	.
Consonantn	-18.67	10.252	203.165	-1.821	0.07	.
Consonants	-9.952	9.418	198.227	-1.057	0.292	
LengthG:Consonantd	6.199	10.927	182.109	0.567	0.571	
LengthG:Consonantr	10.47	9.601	182.109	1.091	0.277	
LengthG:Consonantn	25.974	12.618	182.109	2.059	0.041	*
LengthG:Consonants	2.188	12.618	182.109	0.173	0.863	

Table A.15: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S7.

S7 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	74.654	6.532	142.384	11.429	< 2e-16	***
LengthG	30.506	8.963	181.841	3.404	0.001	***
Consonantd	-14.67	7.945	174.672	-1.846	0.067	.
Consonantr	0.244	6.982	167.994	0.035	0.972	
Consonantn	-6.886	9.226	153.707	-0.746	0.457	
Consonants	-11.57	9.053	204.897	-1.278	0.203	
LengthG:Consonantd	12.3	10.978	181.841	1.12	0.264	
LengthG:Consonantr	18.411	9.639	181.878	1.91	0.058	.
LengthG:Consonantn	-3.911	12.676	181.841	-0.309	0.758	
LengthG:Consonants	10.733	12.676	181.841	0.847	0.398	

Table A.16: Fixed effects coefficients table for the model of the preceding vowel duration for each consonant, for S8.

S8 V1 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	47.123	6.904	144.145	6.825	2.26e-10	***
LengthG	24.102	9.229	188.491	2.612	0.01	**
Consonantd	0.733	8.326	194.673	0.088	0.93	
Consonantr	14.037	7.32	185.446	1.918	0.057	.
Consonantn	10.894	9.9	185.229	1.1	0.273	
Consonants	6.761	9.203	214.531	0.735	0.463	
LengthG:Consonantd	-7.321	11.354	188.794	-0.645	0.52	
LengthG:Consonantr	0.218	9.923	188.797	0.022	0.983	
LengthG:Consonantn	10.604	13.053	188.533	0.812	0.418	
LengthG:Consonants	-7.929	13.056	188.728	-0.607	0.544	

A.3 Mixed effects models of V2 duration per subject

Table A.17: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S1.

S1 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	39.684	5.396	144.831	7.354	1.31e-11	***
LengthG	8.478	6.404	159.776	1.324	0.187	
Consonantd	32.662	6.261	177.614	5.216	5.04e-07	***
Consonantr	31.98	5.56	175.85	5.751	3.85e-08	***
Consonants	29.298	6.736	173.823	4.35	2.32e-05	***
LengthG:Consonantd	-24.346	7.843	159.776	-3.104	0.002	**
LengthG:Consonantr	-5.99	6.922	159.803	-0.865	0.388	
LengthG:Consonants	-26.176	9.056	159.776	-2.89	0.004	**

Table A.18: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S2.

S2 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	78.708	6.045	155.954	13.021	<2e-16	***
LengthG	-3.693	6.949	185.604	-0.532	0.596	
Consonantd	10.122	6.852	205.789	1.477	0.141	
Consonantr	11.363	6.114	203.383	1.858	0.065	.
Consonantn	4.958	8.034	205.765	0.617	0.538	
Consonants	-4.873	7.354	199.949	-0.663	0.508	
LengthG:Consonantd	-8.665	8.511	185.604	-1.018	0.31	
LengthG:Consonantr	14.11	7.47	185.632	1.889	0.06	.
LengthG:Consonantn	13.881	9.827	185.604	1.412	0.159	
LengthG:Consonants	-5.245	9.827	185.604	-0.534	0.594	

Table A.19: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S3.

S3 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	53.495	4.521	153.98	11.832	< 2e-16	***
LengthG	0.179	5.115	186.47	0.035	0.972	
Consonantd	21.92	5.075	206.994	4.319	2.43e-05	***
Consonantr	26.712	4.538	205.706	5.887	1.58e-08	***
Consonantn	32.021	5.95	206.996	5.381	1.99e-07	***
Consonants	-5.398	5.428	200.093	-0.994	0.321	
LengthG:Consonantd	1.401	6.265	186.47	0.224	0.823	
LengthG:Consonantr	8.442	5.499	186.495	1.535	0.126	
LengthG:Consonantn	-1.988	7.146	186.514	-0.278	0.781	
LengthG:Consonants	5.804	7.234	186.47	0.802	0.423	

Table A.20: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S4.

S4 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	54.383	4.641	154.529	11.717	< 2e-16	***
LengthG	4.659	5.734	182.428	0.813	0.417	
Consonantd	14.827	5.455	197.785	2.718	0.007	**
Consonantr	21.199	4.837	190.175	4.383	1.93e-05	***
Consonantn	26.891	6.392	195.649	4.207	3.94e-05	***
Consonants	3.815	6.174	201.554	0.618	0.537	
LengthG:Consonantd	-6.846	7.022	182.428	-0.975	0.331	
LengthG:Consonantr	2.831	6.166	182.441	0.459	0.647	
LengthG:Consonantn	-1.292	8.108	182.428	-0.159	0.874	
LengthG:Consonants	-5.165	8.238	182.581	-0.627	0.531	

Table A.21: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S5.

S5 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	58.045	7.092	142.911	8.185	1.37e-13	***
LengthG	-9.261	8.872	174.849	-1.044	0.298	
Consonantd	29.801	8.38	190.896	3.556	0.0005	***
Consonantr	29.065	7.425	181.412	3.915	0.0001	***
Consonantn	53.065	10.076	189.461	5.266	3.75e-07	***
Consonants	-1.701	9.216	198.275	-0.185	0.854	
LengthG:Consonantd	-12.222	10.865	174.849	-1.125	0.262	
LengthG:Consonantr	15.964	9.56	175.077	1.67	0.097	.
LengthG:Consonantn	12.886	12.747	175.091	1.011	0.313	
LengthG:Consonants	0.272	12.546	174.849	0.022	0.983	

Table A.22: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S6.

S6 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	63.179	6.794	151.81	9.3	<2e-16	***
LengthG	-1.295	8.087	180.954	-0.16	0.873	
Consonantd	18.357	7.85	201.783	2.339	0.02	*
Consonantr	14.257	6.988	196.501	2.04	0.043	*
Consonantn	9.438	9.202	201.307	1.026	0.306	
Consonants	11.1	8.501	199.123	1.306	0.193	
LengthG:Consonantd	8.903	9.904	180.954	0.899	0.37	
LengthG:Consonantr	11.896	8.702	180.954	1.367	0.173	
LengthG:Consonantn	11.946	11.436	180.954	1.045	0.298	
LengthG:Consonants	-11.759	11.436	180.954	-1.028	0.305	

Table A.23: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S7.

S7 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	79.907	6.156	152.721	12.981	<2e-16	***
LengthG	-6.426	7.428	182.009	-0.865	0.388	
Consonantd	6.009	7.16	201.358	0.839	0.402	
Consonantr	2.334	6.358	195.162	0.367	0.714	
Consonantn	10.917	8.392	200.463	1.301	0.195	
Consonants	-7.705	7.778	200.682	-0.991	0.323	
LengthG:Consonantd	12.098	9.097	182.009	1.33	0.185	
LengthG:Consonantr	18.472	7.989	182.022	2.312	0.022	*
LengthG:Consonantn	22.061	10.505	182.009	2.1	0.037	*
LengthG:Consonants	4.738	10.505	182.009	0.451	0.652	

Table A.24: Fixed effects coefficients table for the model of the following vowel duration for each consonant, for S8.

S8 V2 duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	52.086	6.131	159.519	8.495	1.33e-14	***
LengthG	-13.673	7.714	193.628	-1.772	0.078	.
Consonantd	15	7.214	211.258	2.079	0.039	*
Consonantr	22.957	6.372	205.123	3.603	0.0004	***
Consonantn	21.582	8.599	210.096	2.51	0.013	*
Consonants	-17.77	7.81	212.251	-2.275	0.024	*
LengthG:Consonantd	14.033	9.491	193.725	1.478	0.141	
LengthG:Consonantr	13.533	8.295	193.794	1.631	0.104	
LengthG:Consonantn	13.738	10.91	193.628	1.259	0.209	
LengthG:Consonants	17.904	10.914	193.697	1.641	0.103	

A.4 Mixed effects models of VCV duration per subject

Table A.25: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S1.

S1 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	156.825	8.534	137.263	18.377	<2e-16	***
LengthG	102.14	9.477	158.105	10.777	<2e-16	***
Consonantd	16.185	9.539	178.712	1.697	0.092	.
Consonantr	3.39	8.5	178.998	0.399	0.691	
Consonants	14.098	10.085	169.653	1.398	0.164	
LengthG:Consonantd	13.184	11.607	158.105	1.136	0.258	
LengthG:Consonantr	10.589	10.245	158.125	1.034	0.303	
LengthG:Consonants	4.273	13.403	158.105	0.319	0.75	

Table A.26: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S2.

S2 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	223.859	8.741	149.422	25.609	< 2e-16	
LengthG	78.237	9.721	184.959	8.048	9.88e-14	***
Consonantd	-9.378	9.702	205.871	-0.967	0.335	***
Consonantr	-19.462	8.682	205.528	-2.242	0.026	
Consonantn	0.625	11.375	205.844	0.055	0.956	*
Consonants	-5.427	10.342	197.905	-0.525	0.6	
LengthG:Consonantd	5.04	11.905	184.959	0.423	0.673	
LengthG:Consonantr	33.285	10.449	184.982	3.185	0.002	**
LengthG:Consonantn	19.752	13.747	184.959	1.437	0.152	
LengthG:Consonants	-9.281	13.747	184.959	-0.675	0.5	

Table A.27: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S3.

S3 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	201.485	7.82	143.331	25.764	<2e-16	***
LengthG	77.824	8.5	185.43	9.156	<2e-16	***
Consonantd	-12.781	8.542	206.258	-1.496	0.136	
Consonantr	-14.758	7.66	206.996	-1.927	0.055	.
Consonantn	-17.507	10.015	206.155	-1.748	0.082	.
Consonants	-18.844	9.071	197.495	-2.077	0.039	*
LengthG:Consonantd	9.721	10.411	185.43	0.934	0.352	
LengthG:Consonantr	22.353	9.137	185.45	2.446	0.015	*
LengthG:Consonantn	26.74	11.875	185.463	2.252	0.026	*
LengthG:Consonants	4.129	12.021	185.43	0.343	0.732	

Table A.28: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S4.

S4 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	172.257	8.868	151.439	19.424	< 2e-16	***
LengthG	88.912	10.153	182.207	8.757	1.33e-15	***
Consonantd	-2.055	10.022	203.892	-0.205	0.838	
Consonantr	-3.989	8.952	201.785	-0.446	0.656	
Consonantn	33.606	11.756	203.868	2.859	0.005	**
Consonants	-7.433	11.113	197.248	-0.669	0.504	
LengthG:Consonantd	11.457	12.435	182.207	0.921	0.358	
LengthG:Consonantr	11.027	10.919	182.214	1.01	0.314	
LengthG:Consonantn	-4.504	14.358	182.207	-0.314	0.754	
LengthG:Consonants	-3.965	14.589	182.281	-0.272	0.786	

Table A.29: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S5.

S5 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	193.594	9.523	139.616	20.329	< 2e-16	***
LengthG	53.979	10.467	177.772	5.157	6.65e-07	***
Consonantd	9.228	10.484	200.465	0.88	0.38	
Consonantr	2.011	9.398	200.908	0.214	0.831	
Consonantn	42.833	12.596	200.142	3.4	0.001	***
Consonants	-14.811	11.153	191.118	-1.328	0.186	
LengthG:Consonantd	7.154	12.82	177.772	0.558	0.578	
LengthG:Consonantr	43.64	11.282	177.895	3.868	0.0002	***
LengthG:Consonantn	17.845	15.042	177.836	1.186	0.237	
LengthG:Consonants	14.742	14.803	177.772	0.996	0.321	

Table A.30: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S6.

S6 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	207.802	9.531	157.917	21.802	< 2e-16	***
LengthG	72.598	11.587	184.016	6.265	2.57e-09	***
Consonantd	-9.863	11.126	200.104	-0.886	0.376	
Consonantr	-26.573	9.884	194.195	-2.688	0.008	**
Consonantn	-26.297	13.038	199.061	-2.017	0.045	*
Consonants	0.543	12.123	200.836	0.045	0.964	
LengthG:Consonantd	25.738	14.192	184.016	1.814	0.071	.
LengthG:Consonantr	35.393	12.469	184.016	2.839	0.005	**
LengthG:Consonantn	57.396	16.387	184.016	3.503	0.001	***
LengthG:Consonants	0.363	16.387	184.016	0.022	0.982	

Table A.31: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S7.

S7 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	204.963	7.773	152.657	26.369	<2e-16	***
LengthG	90.997	9.171	182.275	9.923	<2e-16	***
Consonantd	-9.937	8.939	203.523	-1.112	0.268	
Consonantr	-20.522	7.954	199.111	-2.58	0.011	*
Consonantn	-12.122	10.48	203.242	-1.157	0.249	
Consonants	-22.29	9.648	199.482	-2.31	0.022	*
LengthG:Consonantd	16.226	11.232	182.275	1.445	0.15	
LengthG:Consonantr	18.82	9.863	182.286	1.908	0.058	.
LengthG:Consonantn	22.992	12.969	182.275	1.773	0.078	.
LengthG:Consonants	14.182	12.969	182.275	1.094	0.276	

Table A.32: Fixed effects coefficients table for the model of the VCV duration for each consonant, for S8.

S8 VCV duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	161.744	9.751	154.469	16.588	< 2e-16	***
LengthG	106.416	11.406	194.458	9.33	< 2e-16	***
Consonantd	18.751	11.009	215.999	1.703	0.09	.
Consonantr	5.792	9.783	214.92	0.592	0.554	
Consonantn	42.968	13.128	215.997	3.273	0.001	**
Consonants	-8.054	11.703	208.346	-0.688	0.492	
LengthG:Consonantd	13.206	14.034	194.483	0.941	0.348	
LengthG:Consonantr	19.813	12.266	194.551	1.615	0.108	
LengthG:Consonantn	20.005	16.131	194.441	1.24	0.216	
LengthG:Consonants	-14.352	16.137	194.473	-0.889	0.375	

A.5 Mixed effects models of C2 amplitude per subject

Table A.33: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S1.

S1 C2 amplitude ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.382	0.086	141.142	4.422	1.93e-05	***
LengthG	-0.257	0.101	157.68	-2.551	0.012	*
Consonantd	0.477	0.099	178.452	4.798	3.37e-06	***
Consonantr	0.703	0.088	177.119	7.949	2.12e-13	***
Consonants	0.13	0.106	172.199	1.223	0.223	
LengthG:Consonantd	-0.459	0.124	157.68	-3.712	0.0003	***
LengthG:Consonantr	-0.1	0.109	157.707	-0.915	0.362	
LengthG:Consonants	-0.082	0.143	157.68	-0.576	0.565	

Table A.34: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S2.

S2 C2 amplitude ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.061	0.043	130.327	1.418	0.159	
LengthG	-0.027	0.057	174.277	-0.463	0.644	
Consonantd	0.102	0.052	172.375	1.981	0.049	*
Consonantr	0.412	0.045	161.089	9.051	4.44e-16	***
Consonantn	0.451	0.06	153.806	7.476	5.44e-12	***
Consonants	0.012	0.058	205.603	0.198	0.843	
LengthG:Consonantd	-0.078	0.07	174.277	-1.106	0.27	
LengthG:Consonantr	-0.341	0.062	174.374	-5.528	1.17e-07	***
LengthG:Consonantn	-0.124	0.081	174.277	-1.532	0.127	
LengthG:Consonants	-0.011	0.081	174.277	-0.133	0.895	

Table A.35: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S3.

S3 C2 amplitude $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.011	0.034	160.185	0.31	0.757	
LengthG	-0.002	0.041	187.432	-0.052	0.959	
Consonantd	0.101	0.04	205.63	2.54	0.012	*
Consonantr	0.364	0.035	201.683	10.303	< 2e-16	***
Consonantn	0.412	0.046	205.376	8.857	4.44e-16	***
Consonants	0	0.043	202.59	0.011	0.991	
LengthG:Consonantd	-0.014	0.05	187.432	-0.274	0.784	
LengthG:Consonantr	-0.17	0.044	187.464	-3.887	0.0001	***
LengthG:Consonantn	-0.159	0.057	187.495	-2.802	0.006	**
LengthG:Consonants	-0.012	0.058	187.432	-0.216	0.829	

Table A.36: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S4.

S4 C2 amplitude $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.167	0.074	155.359	2.248	0.026	*
LengthG	-0.103	0.09	182.658	-1.15	0.252	
Consonantd	0.358	0.086	200.9	4.138	5.15e-05	***
Consonantr	0.598	0.077	194.951	7.781	4.09e-13	***
Consonantn	1.011	0.101	200.017	9.967	< 2e-16	***
Consonants	0.072	0.097	200.349	0.741	0.46	
LengthG:Consonantd	-0.201	0.11	182.658	-1.832	0.069	.
LengthG:Consonantr	-0.294	0.096	182.669	-3.044	0.003	**
LengthG:Consonantn	-0.075	0.127	182.658	-0.593	0.554	
LengthG:Consonants	-0.065	0.129	182.776	-0.501	0.617	

Table A.37: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S5.

S5 C2 amplitude $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.051	0.042	156.567	1.227	0.222	
LengthG	-0.018	0.052	181.64	-0.354	0.724	
Consonantd	0.109	0.049	196.145	2.225	0.027	*
Consonantr	0.42	0.044	189.857	9.636	< 2e-16	***
Consonantn	0.513	0.059	195.814	8.685	1.33e-15	***
Consonants	0.006	0.054	198.345	0.115	0.908	
LengthG:Consonantd	-0.111	0.063	181.64	-1.763	0.08	.
LengthG:Consonantr	-0.367	0.056	181.807	-6.612	4.09e-10	***
LengthG:Consonantn	-0.28	0.074	181.794	-3.783	0.0002	***
LengthG:Consonants	-0.013	0.073	181.64	-0.177	0.86	

Table A.38: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S6.

S6 C2 amplitude ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.12	0.065	153.67	1.831	0.069	.
LengthG	-0.074	0.083	182.821	-0.885	0.377	
Consonantd	0.396	0.078	192.641	5.087	8.59e-07	***
Consonantr	0.666	0.069	184.497	9.69	< 2e-16	***
Consonantn	0.721	0.091	188.027	7.929	1.91e-13	***
Consonants	0.12	0.086	202.548	1.4	0.163	
LengthG:Consonantd	-0.177	0.102	182.821	-1.732	0.085	.
LengthG:Consonantr	-0.199	0.09	182.821	-2.22	0.028	*
LengthG:Consonantn	0.032	0.118	182.821	0.274	0.785	
LengthG:Consonants	-0.115	0.118	182.821	-0.98	0.328	

Table A.39: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S7.

S7 C2 amplitude ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.065	0.067	155.058	0.974	0.332	
LengthG	-0.034	0.081	183.227	-0.42	0.675	
Consonantd	0.224	0.078	201.725	2.867	0.005	**
Consonantr	0.672	0.069	195.971	9.687	< 2e-16	***
Consonantn	0.545	0.091	200.932	5.954	1.15e-08	***
Consonants	-0.051	0.085	200.861	-0.597	0.551	
LengthG:Consonantd	-0.108	0.099	183.227	-1.09	0.277	
LengthG:Consonantr	-0.339	0.087	183.239	-3.897	0.0001	***
LengthG:Consonantn	-0.075	0.114	183.227	-0.654	0.514	
LengthG:Consonants	-0.002	0.114	183.227	-0.017	0.986	

Table A.40: Fixed effects coefficients table for the model of the averaged amplitude of the consonant, for each consonant, S8.

S8 C2 amplitude ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.277	0.049	158.949	5.623	8.25e-08	***
LengthG	-0.228	0.062	193.355	-3.696	0.0003	***
Consonantd	0.046	0.058	211.651	0.798	0.426	
Consonantr	0.275	0.051	205.637	5.382	2.00e-07	***
Consonantn	0.461	0.069	210.632	6.681	2.08e-10	***
Consonants	-0.213	0.063	212.025	-3.398	0.001	***
LengthG:Consonantd	-0.023	0.076	193.447	-0.298	0.766	
LengthG:Consonantr	-0.003	0.066	193.518	-0.044	0.965	
LengthG:Consonantn	0.151	0.087	193.353	1.733	0.085	.
LengthG:Consonants	0.196	0.087	193.42	2.248	0.026	*

A.6 Word duration

Word durations are strikingly similar across consonants and length, as well as the GSR. The best model of Word duration (Table A.42) shows that word duration for liquids is most greatly increased when geminated.

Table A.41: Mean Word duration (SD) and GSR per consonant.

Consonant	Singleton	Geminate	GSR
t (73, 72)	483.79 (42.67)	589.81 (53.47)	1.22 (0.02)
d (145, 144)	497.68 (44.47)	607.58 (51.70)	1.22 (0.02)
r (459, 458)	499.81 (45.74)	622.02 (52)	1.24 (0.03)
n (62, 65)	510.19 (54.06)	630.36 (61.6)	1.24 (0.01)
s (72 , 72)	513.76 (51.04)	612.39 (51.74)	1.19 (0.02)

Figure A.1: Word duration per consonant and length.

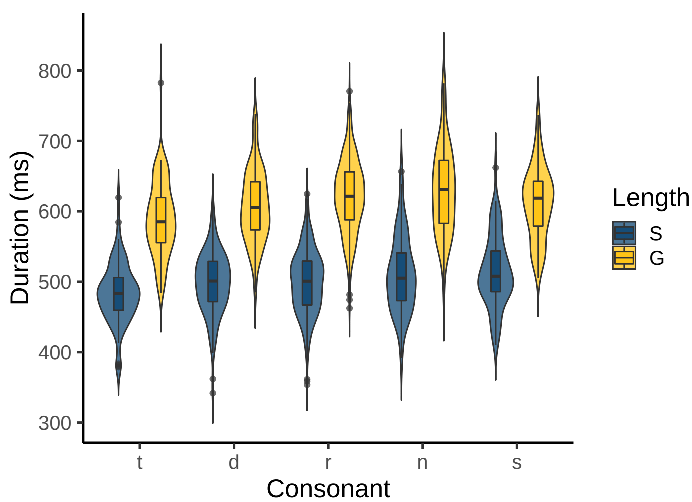


Table A.42: Fixed effects coefficients table for the model of the word duration.

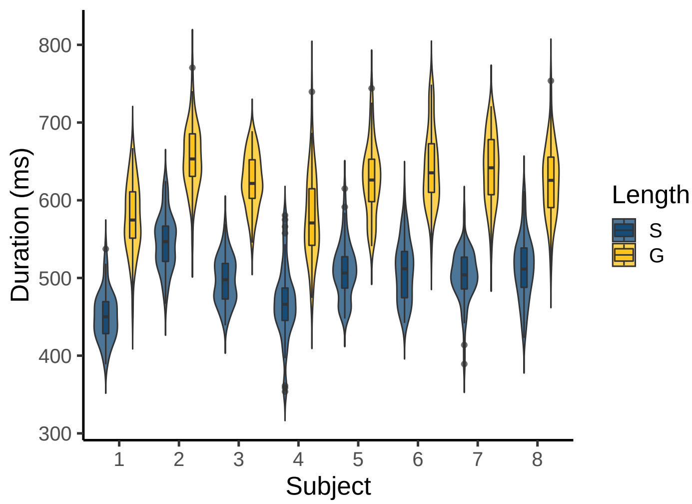
Word duration $\sim$ Length * Consonant + (1 + Length | Subj) + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	490.334	11.284	15.987	43.455	< 2e-16	***
LengthG	106.105	7.493	135.49	14.16	< 2e-16	***
Consonantd	6.887	6.877	1178.97	1.001	0.317	
Consonantr	9.524	6.161	1012.277	1.546	0.122	
Consonantn	10.182	8.329	1235.979	1.223	0.222	
Consonants	35.281	7.314	1546.852	4.824	1.55e-06	***
LengthG:Consonantd	3.568	8.405	1587.194	0.425	0.671	
LengthG:Consonantr	16.218	7.381	1587.288	2.197	0.028	*
LengthG:Consonantn	14.581	10.06	1592.749	1.449	0.147	
LengthG:Consonants	-7.072	9.716	1587.216	-0.728	0.467	

The durations of words with target liquid consonants are quite uniform across speakers.

Table A.43: Word durations and GSR (SD) of word for liquids by subject.

Subject	Singleton	Geminate	GSR
1 (54, 53)	450.51 (31.26)	578.47 (44.04)	1.28 (0.07)
2 (59, 57)	545.88 (35.44)	656.3 (40.95)	1.21 (0.05)
3 (57, 59)	496.97 (29.93)	624.91 (34.49)	1.26 (0.07)
4 (58, 57)	468.2 (47.9)	578.96 (54.15)	1.24 (0.09)
5 (57, 55)	510.02 (36.59)	626.29 (46.52)	1.24 (0.07)
6 (57, 57)	508.46 (38.58)	642.42 (49.14)	1.27 (0.09)
7 (58, 57)	501.82 (33.04)	640.56 (44)	1.28 (0.08)
8 (59, 63)	512.46 (40.92)	624.92 (45.59)	1.22 (0.06)

Figure A.2: Word duration for liquids per subject and length.



A.7 Mixed effects models of Word duration per subject

Table A.44: Fixed effects coefficients table for the model of the Word duration for each consonant, for S1.

S1 Word duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	442.488	12.472	137.849	35.477	< 2e-16	***
LengthG	93.988	15.136	155.646	6.21	4.62e-09	***
Consonantd	29.812	14.618	174.943	2.039	0.043	*
Consonantr	9.163	12.966	171.943	0.707	0.481	
Consonants	36.261	15.842	173.975	2.289	0.023	*
LengthG:Consonantd	4.419	18.537	155.646	0.238	0.812	
LengthG:Consonantr	33.812	16.361	155.683	2.067	0.04	*
LengthG:Consonants	38.79	21.405	155.646	1.812	0.072	.

Table A.45: Fixed effects coefficients table for the model of the Word duration for each consonant, for S2.

S2 Word duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	551.471	14.009	151.3	39.364	< 2e-16	***
LengthG	96.337	17.471	182.141	5.514	1.19e-07	***
Consonantd	-11.4	16.535	197.088	-0.689	0.491	
Consonantr	-5.901	14.636	187.813	-0.403	0.687	
Consonantn	9.797	19.364	194.114	0.506	0.613	
Consonants	26.693	18.164	203.476	1.47	0.143	
LengthG:Consonantd	-16.499	21.397	182.141	-0.771	0.442	
LengthG:Consonantr	14.486	18.779	182.195	0.771	0.441	
LengthG:Consonantn	-10.246	24.708	182.141	-0.415	0.679	
LengthG:Consonants	-0.148	24.708	182.141	-0.006	0.995	

Table A.46: Fixed effects coefficients table for the model of the Word duration for each consonant, for S3.

S3 Word duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	497.449	12.203	162.349	40.764	< 2e-16	***
LengthG	113.219	15.496	188.873	7.306	7.50e-12	***
Consonantd	10.981	14.504	197.546	0.757	0.45	
Consonantr	-0.124	12.831	190.492	-0.01	0.992	
Consonantn	11.578	16.971	193.781	0.682	0.496	
Consonants	14.087	16.033	205.756	0.879	0.381	
LengthG:Consonantd	1.405	18.979	188.873	0.074	0.941	
LengthG:Consonantr	14.732	16.657	188.919	0.884	0.378	
LengthG:Consonantn	-1.222	21.646	188.999	-0.056	0.955	
LengthG:Consonants	-9.34	21.915	188.873	-0.426	0.67	

Table A.47: Fixed effects coefficients table for the model of the Word duration for each consonant, for S4.

S4 Word duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	433.695	18.547	147.104	23.384	< 2e-16	***
LengthG	143.695	24.411	180.845	5.886	1.88e-08	***
Consonantd	23.616	22.304	184.498	1.059	0.291	
Consonantr	34.525	19.659	175.381	1.756	0.081	.
Consonantn	35.618	26.037	173.872	1.368	0.173	
Consonants	43.371	25.805	203.675	1.681	0.094	.
LengthG:Consonantd	-15.454	29.897	180.845	-0.517	0.606	
LengthG:Consonantr	-32.856	26.253	180.869	-1.252	0.212	
LengthG:Consonantn	-16.779	34.523	180.845	-0.486	0.628	
LengthG:Consonants	-49.863	35.07	181.176	-1.422	0.157	

Table A.48: Fixed effects coefficients table for the model of the Word duration for each consonant, for S5.

S5 Word duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	474.389	14.824	149.49	32.001	< 2e-16	***
LengthG	83.374	17.754	177.796	4.696	5.28e-06	***
Consonantd	31.385	17.181	198.297	1.827	0.069	.
Consonantr	36.746	15.287	192.526	2.404	0.017	*
Consonantn	45.639	20.661	198.457	2.209	0.028	*
Consonants	31.725	18.638	196.345	1.702	0.09	.
LengthG:Consonantd	-14.341	21.744	177.796	-0.66	0.51	
LengthG:Consonantr	33.729	19.134	177.976	1.763	0.08	.
LengthG:Consonantn	14.951	25.512	177.936	0.586	0.559	
LengthG:Consonants	-4.745	25.108	177.796	-0.189	0.85	

Table A.49: Fixed effects coefficients table for the model of the Word duration for each consonant, for S6.

S6 Word duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	500.212	15.364	158.367	32.558	< 2e-16	***
LengthG	90.32	19.083	184.525	4.733	4.39e-06	***
Consonantd	-7.485	18.103	197.529	-0.413	0.68	
Consonantr	8.411	16.049	190.687	0.524	0.601	
Consonantn	-36.074	21.203	195.401	-1.701	0.09	.
Consonants	46.944	19.86	201.828	2.364	0.019	*
LengthG:Consonantd	46.136	23.371	184.525	1.974	0.05	*
LengthG:Consonantr	43.641	20.534	184.525	2.125	0.035	*
LengthG:Consonantn	72.751	26.987	184.525	2.696	0.008	**
LengthG:Consonants	5.94	26.987	184.525	0.22	0.826	

Table A.50: Fixed effects coefficients table for the model of the Word duration for each consonant, for S7.

S7 Word duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	510.673	13.947	159.833	36.615	< 2e-16	***
LengthG	104.866	16.928	185.635	6.195	3.67e-09	***
Consonantd	0.426	16.268	201.379	0.026	0.979	
Consonantr	-8.24	14.437	195.862	-0.571	0.569	
Consonantn	1.065	19.064	200.436	0.056	0.956	
Consonants	35.308	17.702	201.665	1.995	0.047	*
LengthG:Consonantd	11.546	20.733	185.635	0.557	0.578	
LengthG:Consonantr	33.635	18.206	185.647	1.847	0.066	.
LengthG:Consonantn	24.995	23.94	185.635	1.044	0.298	
LengthG:Consonants	-2.681	23.94	185.635	-0.112	0.911	

Table A.51: Fixed effects coefficients table for the model of the Word duration for each consonant, for S8.

S8 Word duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	498.882	14.008	159.005	35.615	< 2e-16	***
LengthG	122.691	16.868	194.478	7.274	8.37e-12	***
Consonantd	-10.562	16.101	215.356	-0.656	0.513	
Consonantr	13.745	14.277	212.384	0.963	0.337	
Consonantn	17.011	19.202	215.31	0.886	0.377	
Consonants	33.881	17.226	210.008	1.967	0.051	.
LengthG:Consonantd	11.361	20.754	194.521	0.547	0.585	
LengthG:Consonantr	-8.909	18.139	194.593	-0.491	0.624	
LengthG:Consonantn	-2.64	23.856	194.464	-0.111	0.912	
LengthG:Consonants	-34.649	23.864	194.506	-1.452	0.148	

Appendix B

Supplemental Materials: Articulatory

B.1 Mixed effects models of TT gestural duration per subject

Table B.1: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S1.

S1 TT gestural duration ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	77.413	10.249	128.496	7.553	6.98e-12	***
LengthG	64.167	12.888	149.781	4.979	1.74e-06	***
Consonantd	-7.641	12.27	166.192	-0.623	0.534	
Consonantr	-21.948	10.798	161.702	-2.033	0.044	*
Consonants	7.752	13.369	172.45	0.58	0.563	
LengthG:Consonantd	21.998	15.865	149.921	1.387	0.168	
LengthG:Consonantr	4.409	13.951	149.931	0.316	0.752	
LengthG:Consonants	-8.889	18.226	149.781	-0.488	0.626	

Table B.2: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S2.

S2 TT gestural duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	113.125	11.992	187	9.434	< 2e-16	***
LengthG	75.486	16.481	187	4.58	8.47e-06	***
Consonantd	-7.014	14.412	187	-0.487	0.627	
Consonantr	-36.181	12.849	187	-2.816	0.005	**
Consonantn	-3.681	16.481	187	-0.223	0.824	
Consonants	-0.312	16.959	187	-0.018	0.985	
LengthG:Consonantd	7.815	20.08	187	0.389	0.698	
LengthG:Consonantr	-22.643	17.816	187	-1.271	0.205	
LengthG:Consonantn	-30.764	22.962	187	-1.34	0.182	
LengthG:Consonants	-36.736	23.648	187	-1.553	0.122	

Table B.3: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S3.

S3 TT gestural duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	96.063	9.681	152.172	9.923	< 2e-16	***
LengthG	47.222	12.494	180.342	3.78	0.0002	***
Consonantd	-13.413	11.667	188.862	-1.15	0.252	
Consonantr	-32.42	10.261	181.316	-3.159	0.002	**
Consonantn	-26.237	13.563	177.301	-1.934	0.055	.
Consonants	-19.27	12.874	200.114	-1.497	0.136	
LengthG:Consonantd	9.308	15.38	180.492	0.605	0.546	
LengthG:Consonantr	21.757	13.475	180.619	1.615	0.108	
LengthG:Consonantn	19.175	17.452	180.528	1.099	0.273	
LengthG:Consonants	18.611	17.669	180.342	1.053	0.294	

Table B.4: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S4.

S4 TT gestural duration $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	93.015	13.277	140.837	7.006	9.31e-11	***
LengthG	80.855	18.464	166.731	4.379	2.10e-05	***
Consonantd	-34.826	15.723	154.794	-2.215	0.028	*
Consonantr	-28.449	14.16	151.305	-2.009	0.046	*
Consonantn	-17.159	18.75	148.621	-0.915	0.362	
Consonants	-6.048	18.024	169.958	-0.336	0.738	
LengthG:Consonantd	1.204	22.03	165.784	0.055	0.956	
LengthG:Consonantr	-23.729	19.763	166.558	-1.201	0.232	
LengthG:Consonantn	-20.723	25.669	163.669	-0.807	0.421	
LengthG:Consonants	-49.229	25.688	165.424	-1.916	0.057	.

Table B.5: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S5.

S5 TT gestural duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	87.128	12.23	140.209	7.124	5.02e-11	***
LengthG	54.139	15.03	164.959	3.602	0.0004	***
Consonantd	-1.898	14.535	177.109	-0.131	0.896	
Consonantr	-21.369	12.825	168.328	-1.666	0.098	.
Consonantn	-27.929	16.972	174.418	-1.646	0.102	
Consonants	-7.726	15.633	185.768	-0.494	0.622	
LengthG:Consonantd	7.194	18.503	165.227	0.389	0.698	
LengthG:Consonantr	-18.895	16.244	165.305	-1.163	0.246	
LengthG:Consonantn	1.883	21.255	164.887	0.089	0.93	
LengthG:Consonants	-11.084	20.931	164.693	-0.53	0.597	

Table B.6: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S6.

S6 TT gestural duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	89.167	10.774	187.005	8.276	2.35e-14	***
LengthG	38.611	15.237	187.005	2.534	0.012	*
Consonantd	-7.494	13.195	187.005	-0.568	0.571	
Consonantr	-31.324	11.686	187.005	-2.68	0.008	**
Consonantn	-31.667	15.237	187.005	-2.078	0.039	*
Consonants	-0.729	15.706	187.005	-0.046	0.963	
LengthG:Consonantd	23.05	18.661	187.005	1.235	0.218	
LengthG:Consonantr	0.195	16.579	187.005	0.012	0.991	
LengthG:Consonantn	66.389	21.548	187.005	3.081	0.002	**
LengthG:Consonants	21.285	21.882	187.005	0.973	0.332	

Table B.7: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S7.

S7 TT gestural duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	65.571	11.933	140.947	5.495	1.78e-07	***
LengthG	49.722	15.574	174.777	3.193	0.002	**
Consonantd	-20.307	14.31	176.284	-1.419	0.158	
Consonantr	-0.402	12.752	161.459	-0.032	0.975	
Consonantn	-15.247	17.197	168.965	-0.887	0.377	
Consonants	4.245	15.963	193.056	0.266	0.791	
LengthG:Consonantd	7.989	19.277	175.005	0.414	0.679	
LengthG:Consonantr	-9.715	16.836	174.988	-0.577	0.565	
LengthG:Consonantn	8.557	22.375	175.092	0.382	0.703	
LengthG:Consonants	-24.167	22.025	174.777	-1.097	0.274	

Table B.8: Fixed effects coefficients table for the model of the TT gestural duration (ms) for S8.

S8 TT gestural duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	66.891	13.427	114.984	4.982	2.24e-06	***
LengthG	86.624	16.414	145.22	5.278	4.67e-07	***
Consonantd	16.843	16.023	157.896	1.051	0.295	
Consonantr	0.506	14.244	160.246	0.036	0.972	
Consonantn	3.784	18.799	159.356	0.201	0.841	
Consonants	-3.079	16.701	162.38	-0.184	0.854	
LengthG:Consonantd	-19.83	20.434	146.047	-0.97	0.333	
LengthG:Consonantr	-17.93	18.399	147.325	-0.974	0.331	
LengthG:Consonantn	-15.792	23.215	145.26	-0.68	0.497	
LengthG:Consonants	-53.642	23.592	145.276	-2.274	0.024	*

B.2 Mixed effects models of TT plateau duration per subject

Table B.9: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S1.

S1 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	34.805	8.232	132.395	4.228	4.36e-05	***
LengthG	55.556	11.047	157.311	5.029	1.33e-06	***
Consonantd	-5.587	10.05	158.133	-0.556	0.579	
Consonantr	-16.166	8.819	154.787	-1.833	0.069	.
Consonants	4.489	11.241	175.575	0.399	0.69	
LengthG:Consonantd	11.267	13.598	157.497	0.829	0.409	
LengthG:Consonantr	-26.278	11.958	157.446	-2.198	0.029	
LengthG:Consonants	-32.5	15.623	157.311	-2.08	0.039	

Table B.10: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S2.

S2 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	52.625	8.231	142.276	6.394	2.17e-09	***
LengthG	62.54	9.885	164.47	6.327	2.28e-09	***
Consonantd	-15.684	9.506	181.009	-1.65	0.101	
Consonantr	-27.959	8.568	173.448	-3.263	0.001	**
Consonantn	-10.303	11.076	177.22	-0.93	0.354	
Consonants	-17.423	10.712	185.504	-1.627	0.106	
LengthG:Consonantd	2.913	12.042	164.39	0.242	0.809	
LengthG:Consonantr	-29.641	10.692	164.736	-2.772	0.006	**
LengthG:Consonantn	-29.762	13.765	164.226	-2.162	0.032	*
LengthG:Consonants	-25.582	14.208	165.107	-1.801	0.074	.

Table B.11: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S3.

S3 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	43.615	8.352	152.174	5.222	5.73e-07	***
LengthG	30	10.956	181.059	2.738	0.007	**
Consonantd	-5.96	10.12	186.345	-0.589	0.557	
Consonantr	-19.537	8.89	179.151	-2.198	0.029	*
Consonantn	-26.162	11.74	172.347	-2.229	0.027	*
Consonants	-14.708	11.233	200.506	-1.309	0.192	
LengthG:Consonantd	2.716	13.487	181.227	0.201	0.841	
LengthG:Consonantr	10.954	11.816	181.349	0.927	0.355	
LengthG:Consonantn	8.564	15.304	181.276	0.56	0.576	
LengthG:Consonants	8.889	15.495	181.059	0.574	0.567	

Table B.12: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S4.

S4 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	41.071	9.107	173.002	4.51	1.19e-05	***
LengthG	70	12.879	173.002	5.435	1.84e-07	***
Consonantd	-18.13	10.82	173.002	-1.676	0.096	.
Consonantr	-16.99	9.735	173.002	-1.745	0.083	.
Consonantn	-16.071	12.879	173.002	-1.248	0.214	
Consonants	-13.884	12.47	173.002	-1.113	0.267	
LengthG:Consonantd	-9.816	15.372	173.002	-0.639	0.524	
LengthG:Consonantr	-36.582	13.786	173.002	-2.653	0.009	**
LengthG:Consonantn	-11.562	17.926	173.002	-0.645	0.52	
LengthG:Consonants	-38.616	17.926	173.002	-2.154	0.033	*

Table B.13: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S5.

S5 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	43.481	8.329	151.394	5.22	5.80e-07	***
LengthG	32.026	11.381	174.484	2.814	0.005	**
Consonantd	-8.902	10.19	167.629	-0.874	0.384	
Consonantr	-19.414	8.926	166.422	-2.175	0.031	*
Consonantn	-17.049	11.779	152.982	-1.447	0.15	
Consonants	-14.335	11.407	186.884	-1.257	0.21	
LengthG:Consonantd	12.57	14.003	174.942	0.898	0.371	
LengthG:Consonantr	-15.385	12.292	175.156	-1.252	0.212	
LengthG:Consonantn	-6.599	16.095	174.484	-0.41	0.682	
LengthG:Consonants	-6.748	15.856	174.005	-0.426	0.671	

Table B.14: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S6.

S6 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	36.111	5.601	187.001	6.447	9.44e-10	***
LengthG	35.833	7.921	187.001	4.524	1.08e-05	***
Consonantd	-11.667	6.86	187.001	-1.701	0.091	.
Consonantr	-19.886	6.075	187.001	-3.273	0.001	**
Consonantn	-20.278	7.921	187.001	-2.56	0.011	*
Consonants	-10.486	8.165	187.001	-1.284	0.201	
LengthG:Consonantd	7.222	9.701	187.001	0.744	0.458	
LengthG:Consonantr	-18.867	8.619	187.001	-2.189	0.03	*
LengthG:Consonantn	25.556	11.202	187.001	2.281	0.024	*
LengthG:Consonants	6.042	11.376	187.001	0.531	0.596	

Table B.15: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S7.

S7 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	9.864	8.48	136.106	1.163	0.247	
LengthG	39.722	10.528	170.915	3.773	0.0002	***
Consonantd	4.051	9.992	182.445	0.405	0.686	
Consonantr	14.442	8.969	167.12	1.61	0.109	
Consonantn	7.149	12.038	179.333	0.594	0.553	
Consonants	12.859	10.931	191.066	1.176	0.241	
LengthG:Consonantd	-9.352	13.033	171.088	-0.718	0.474	
LengthG:Consonantr	-14.477	11.383	171.107	-1.272	0.205	
LengthG:Consonantn	-12.942	15.128	171.141	-0.856	0.393	
LengthG:Consonants	-20.278	14.889	170.915	-1.362	0.175	

Table B.16: Fixed effects coefficients table for the model of the TT plateau duration (ms) for S8.

S8 TT plateau duration ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	24.349	10.505	112.815	2.318	0.022	*
LengthG	75.773	13.318	145.368	5.69	6.77e-08	***
Consonantd	18.209	12.699	149.429	1.434	0.154	
Consonantr	1.403	11.305	154.107	0.124	0.901	
Consonantn	8.138	14.906	149.905	0.546	0.586	
Consonants	0.192	13.447	164.446	0.014	0.989	
LengthG:Consonantd	-23.368	16.574	146.454	-1.41	0.161	
LengthG:Consonantr	-38.059	14.917	147.719	-2.551	0.012	*
LengthG:Consonantn	-47.104	18.836	145.424	-2.501	0.014	*
LengthG:Consonants	-75.214	19.141	145.432	-3.929	0.0001	***

B.3 Mixed effects models of TT height per subject

Table B.17: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S1.

S1 TT height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.704	0.02	137.932	35.439	< 2e-16	***
LengthG	0.052	0.025	154.614	2.079	0.039	*
Consonantd	-0.035	0.023	172.724	-1.476	0.142	
Consonantr	0.055	0.021	169.77	2.633	0.009	**
Consonants	-0.032	0.025	171.525	-1.28	0.202	
LengthG:Consonantd	-0.015	0.03	154.632	-0.512	0.61	
LengthG:Consonantr	0.031	0.027	154.663	1.168	0.245	
LengthG:Consonants	-0.058	0.035	154.422	-1.685	0.094	.

Table B.18: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S2.

S2 TT height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.498	0.026	187.001	18.89	< 2e-16	***
LengthG	0.025	0.036	187.001	0.687	0.493	
Consonantd	0.05	0.032	187.001	1.565	0.119	
Consonantr	0.22	0.028	187.001	7.77	5.07e-13	***
Consonantn	0.097	0.036	187.001	2.667	0.008	**
Consonants	0.088	0.037	187.001	2.353	0.02	*
LengthG:Consonantd	-0.004	0.044	187.001	-0.084	0.933	
LengthG:Consonantr	0.064	0.039	187.001	1.645	0.102	
LengthG:Consonantn	-0.009	0.05	187.001	-0.183	0.855	
LengthG:Consonants	0.002	0.052	187.001	0.042	0.967	

Table B.19: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S3.

S3 TT height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.688	0.03	160.564	23.276	< 2e-16	***
LengthG	0.013	0.038	183.948	0.355	0.723	
Consonantd	-0.109	0.035	193.285	-3.076	0.002	**
Consonantr	0.031	0.031	186.98	0.983	0.327	
Consonantn	-0.204	0.041	185.348	-4.957	1.61e-06	***
Consonants	-0.154	0.039	199.953	-3.954	0.0001	***
LengthG:Consonantd	0.033	0.046	184.06	0.704	0.482	
LengthG:Consonantr	0.112	0.041	184.173	2.755	0.006	**
LengthG:Consonantn	0.071	0.053	183.948	1.343	0.181	
LengthG:Consonants	-0.019	0.053	183.948	-0.352	0.725	

Table B.20: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S4.

S4 TT height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.522	0.028	131.608	18.597	< 2e-16	***
LengthG	0.05	0.031	153.144	1.625	0.106	
Consonantd	-0.008	0.03	172.172	-0.265	0.792	
Consonantr	0.166	0.028	172.962	6.042	9.10e-09	***
Consonantn	0.088	0.036	171.07	2.48	0.014	*
Consonants	-0.038	0.032	166.128	-1.173	0.242	
LengthG:Consonantd	-0.025	0.036	152.771	-0.696	0.487	
LengthG:Consonantr	0.087	0.033	153.195	2.644	0.009	**
LengthG:Consonantn	-0.091	0.042	152.161	-2.152	0.033	*
LengthG:Consonants	0.005	0.042	152.269	0.12	0.905	

Table B.21: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S5.

S5 TT height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.721	0.028	146.533	25.406	<2e-16	***
LengthG	0.024	0.034	167.147	0.72	0.472	
Consonantd	0.001	0.033	183.349	0.044	0.965	
Consonantr	0.009	0.029	177.072	0.311	0.756	
Consonantn	-0.017	0.039	183.316	-0.438	0.662	
Consonants	-0.046	0.035	184.457	-1.294	0.197	
LengthG:Consonantd	-0.02	0.041	167.299	-0.486	0.628	
LengthG:Consonantr	0.058	0.036	167.422	1.601	0.111	
LengthG:Consonantn	0.014	0.047	167.07	0.286	0.775	
LengthG:Consonants	0.005	0.047	166.959	0.108	0.914	

Table B.22: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S6.

S6 TT height $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.802	0.033	139.042	24.365	< 2e-16	***
LengthG	-0.014	0.038	163.625	-0.373	0.709	
Consonantd	-0.068	0.038	186.35	-1.797	0.074	.
Consonantr	-0.083	0.033	184.548	-2.481	0.014	*
Consonantn	-0.09	0.044	186.534	-2.055	0.041	*
Consonants	-0.071	0.044	181.829	-1.629	0.105	
LengthG:Consonantd	0.038	0.047	163.625	0.82	0.413	
LengthG:Consonantr	0.125	0.041	163.984	3.006	0.003	**
LengthG:Consonantn	0.05	0.055	163.797	0.905	0.367	
LengthG:Consonants	0.054	0.056	164.237	0.965	0.336	

Table B.23: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S7.

S7 TT height $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.575	0.034	149.497	17.046	< 2e-16	***
LengthG	0.121	0.044	177.011	2.756	0.006	**
Consonantd	0.037	0.04	174.709	0.917	0.36	
Consonantr	0.018	0.036	160.27	0.502	0.616	
Consonantn	0.082	0.048	159.47	1.726	0.086	.
Consonants	0.038	0.046	193.984	0.842	0.401	
LengthG:Consonantd	-0.042	0.054	177.414	-0.783	0.434	
LengthG:Consonantr	0.014	0.047	176.974	0.302	0.763	
LengthG:Consonantn	-0.117	0.063	176.921	-1.866	0.064	.
LengthG:Consonants	-0.146	0.063	177.196	-2.329	0.021	*

Table B.24: Fixed effects coefficients table for the model of the standardized TT height at TT maximal constriction point for each consonant, for S8.

S8 TT height $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.54	0.019	157.001	27.724	< 2e-16	***
LengthG	0.017	0.031	157.001	0.553	0.581	
Consonantd	0.02	0.024	157.001	0.846	0.399	
Consonantr	0.187	0.022	157.001	8.576	8.88e-15	***
Consonantn	0.06	0.028	157.001	2.191	0.03	*
Consonants	0.044	0.027	157.001	1.626	0.106	
LengthG:Consonantd	0.00e-7	0.037	157.001	0.181	0.857	
LengthG:Consonantr	0.01	0.034	157.001	0.305	0.761	
LengthG:Consonantn	0.027	0.041	157.001	0.658	0.512	
LengthG:Consonants	-0.03	0.041	157.001	-0.722	0.471	

B.4 Mixed effects models of TT backness per subject

Table B.25: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S1.

S1 TT backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.257	0.032	122.668	8.007	7.65e-13	***
LengthG	-0.017	0.035	152.548	-0.483	0.63	
Consonantd	0.02	0.035	173.547	0.584	0.56	
Consonantr	0.199	0.031	174.991	6.381	1.52e-09	***
Consonants	0.049	0.037	163.227	1.343	0.181	
LengthG:Consonantd	0.002	0.043	152.553	0.051	0.959	
LengthG:Consonantr	-0.004	0.038	152.58	-0.101	0.92	
LengthG:Consonants	-0.014	0.049	152.461	-0.288	0.774	

Table B.26: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S2.

S2 TT backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.219	0.039	140.239	5.568	1.27e-07	***
LengthG	-0.016	0.043	163.519	-0.38	0.704	
Consonantd	0.019	0.044	186.999	0.425	0.671	
Consonantr	0.352	0.04	185.586	8.907	4.44e-16	***
Consonantn	0.085	0.051	186.936	1.662	0.098	.
Consonants	0.07	0.048	180.112	1.461	0.146	
LengthG:Consonantd	0.02	0.053	163.516	0.372	0.711	
LengthG:Consonantr	-0.058	0.047	163.67	-1.233	0.22	
LengthG:Consonantn	0.009	0.06	163.437	0.143	0.886	
LengthG:Consonants	-0.005	0.062	163.851	-0.079	0.937	

Table B.27: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S3.

S3 TT backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.152	0.036	145.486	4.232	4.08e-05	***
LengthG	0.017	0.041	177.423	0.43	0.668	
Consonantd	-0.047	0.041	201	-1.162	0.247	
Consonantr	0.295	0.036	199.789	8.146	4.02e-14	***
Consonantn	0.018	0.048	200.781	0.372	0.71	
Consonants	-0.022	0.043	193.085	-0.52	0.603	
LengthG:Consonantd	-0.007	0.05	177.478	-0.141	0.888	
LengthG:Consonantr	-0.01	0.044	177.574	-0.237	0.813	
LengthG:Consonantn	-0.055	0.058	177.423	-0.956	0.34	
LengthG:Consonants	-0.003	0.058	177.423	-0.051	0.959	

Table B.28: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S4.

S4 TT backness $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.298	0.037	133.867	7.95	6.87e-13	***
LengthG	-0.018	0.045	152.817	-0.41	0.682	
Consonantd	0.037	0.042	170.762	0.877	0.382	
Consonantr	0.23	0.038	166.871	5.982	1.30e-08	***
Consonantn	0.092	0.05	172.255	1.827	0.07	.
Consonants	0.007	0.046	171.361	0.143	0.886	
LengthG:Consonantd	-0.06	0.053	152.105	-1.14	0.256	
LengthG:Consonantr	0.08	0.048	152.926	1.67	0.097	.
LengthG:Consonantn	-0.091	0.062	151.028	-1.476	0.142	
LengthG:Consonants	0.051	0.062	151.379	0.819	0.414	

Table B.29: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S5.

S5 TT backness $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.33	0.05	126.674	6.592	1.06e-09	***
LengthG	0.01	0.062	157.812	0.16	0.873	
Consonantd	-0.053	0.06	171.228	-0.887	0.376	
Consonantr	0.25	0.053	159.56	4.752	4.46e-06	***
Consonantn	-0.005	0.07	167.88	-0.071	0.944	
Consonants	0.032	0.064	185.743	0.5	0.618	
LengthG:Consonantd	0.019	0.077	158.189	0.252	0.801	
LengthG:Consonantr	-0.021	0.067	158.377	-0.313	0.755	
LengthG:Consonantn	-0.014	0.088	157.718	-0.157	0.875	
LengthG:Consonants	-0.034	0.087	157.452	-0.389	0.698	

Table B.30: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S6.

S6 TT backness $\sim$ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.31	0.045	126.137	6.884	2.44e-10	***
LengthG	-0.013	0.056	156.804	-0.235	0.814	
Consonantd	0.014	0.053	173.635	0.271	0.787	
Consonantr	0.346	0.047	168.431	7.348	8.29e-12	***
Consonantn	0.091	0.062	171.53	1.464	0.145	
Consonants	-0.036	0.063	185.96	-0.577	0.565	
LengthG:Consonantd	-0.027	0.069	156.804	-0.399	0.69	
LengthG:Consonantr	-0.009	0.061	157.445	-0.148	0.883	
LengthG:Consonantn	-0.101	0.081	157.207	-1.246	0.215	
LengthG:Consonants	0.042	0.082	158.31	0.505	0.615	

Table B.31: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S7.

S7 TT backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.284	0.044	146.509	6.43	1.69e-09	***
LengthG	0.081	0.053	173.897	1.512	0.132	
Consonantd	0.048	0.052	182.44	0.927	0.355	
Consonantr	0.16	0.047	168.101	3.436	0.001	***
Consonantn	0.072	0.061	177.349	1.176	0.241	
Consonants	0.054	0.057	193.236	0.955	0.341	
LengthG:Consonantd	-0.03	0.066	173.925	-0.455	0.649	
LengthG:Consonantr	-0.084	0.058	174.035	-1.457	0.147	
LengthG:Consonantn	-0.109	0.077	173.637	-1.429	0.155	
LengthG:Consonants	-0.054	0.077	173.739	-0.707	0.48	

Table B.32: Fixed effects coefficients table for the model of the standardized TT backness at TT maximal constriction point for each consonant, for S8.

S8 TT backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.202	0.038	76.684	5.27	1.22e-06	***
LengthG	-0.023	0.06	150.214	-0.387	0.7	
Consonantd	0.059	0.047	104.759	1.244	0.216	
Consonantr	0.361	0.043	110.678	8.416	1.54e-13	***
Consonantn	0.132	0.054	80.898	2.437	0.017	*
Consonants	0.153	0.053	155.23	2.9	0.004	**
LengthG:Consonantd	-0.023	0.073	149.91	-0.313	0.755	
LengthG:Consonantr	-0.026	0.066	151.459	-0.397	0.692	
LengthG:Consonantn	-0.009	0.08	142.681	-0.111	0.912	
LengthG:Consonants	0.032	0.081	140.41	0.399	0.69	

B.5 Mixed effects models of TB height per subject

Table B.33: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S1.

S1 TB height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.6	0.035	130.657	17.145	< 2e-16	***
LengthG	0.171	0.039	154.539	4.348	2.48e-05	***
Consonantd	-0.047	0.039	174.814	-1.208	0.229	
Consonantr	0.061	0.034	175.743	1.776	0.077	.
Consonants	-0.007	0.041	165.378	-0.169	0.866	
LengthG:Consonantd	0.1	0.048	154.544	2.095	0.038	*
LengthG:Consonantr	-0.102	0.042	154.571	-2.407	0.017	*
LengthG:Consonants	-0.15	0.055	154.447	-2.736	0.007	**

Table B.34: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S2.

S2 TB height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.497	0.036	120.782	13.797	< 2e-16	***
LengthG	0.134	0.035	166.37	3.79	0.0002	***
Consonantd	-0.035	0.037	182.271	-0.958	0.34	
Consonantr	0.098	0.034	184.589	2.917	0.004	**
Consonantn	0.124	0.043	182.409	2.9	0.004	**
Consonants	-0.082	0.04	174.908	-2.068	0.04	*
LengthG:Consonantd	0.027	0.043	166.367	0.627	0.532	
LengthG:Consonantr	-0.009	0.038	166.431	-0.229	0.819	
LengthG:Consonantn	-0.107	0.049	166.332	-2.198	0.029	*
LengthG:Consonants	-0.098	0.051	166.5	-1.936	0.055	.

Table B.35: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S3.

S3 TB height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.593	0.035	125.454	16.85	< 2e-16	***
LengthG	0.093	0.036	178.885	2.567	0.011	*
Consonantd	-0.115	0.037	197.418	-3.088	0.002	**
Consonantr	0.143	0.033	199.65	4.297	2.71e-05	***
Consonantn	-0.019	0.044	198.136	-0.443	0.658	
Consonants	-0.046	0.039	188.683	-1.169	0.244	
LengthG:Consonantd	0.032	0.045	178.911	0.723	0.471	
LengthG:Consonantr	-0.017	0.039	178.965	-0.422	0.674	
LengthG:Consonantn	0	0.051	178.885	-0.004	0.997	
LengthG:Consonants	-0.111	0.051	178.885	-2.157	0.032	*

Table B.36: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S4.

S4 TB height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.542	0.033	135.081	16.307	< 2e-16	***
LengthG	0.028	0.038	152.997	0.724	0.47	
Consonantd	0.019	0.037	172.931	0.507	0.613	
Consonantr	0.05	0.034	171.69	1.478	0.141	
Consonantn	0.084	0.044	172.897	1.92	0.057	.
Consonants	-0.039	0.04	169.034	-0.984	0.326	
LengthG:Consonantd	-0.032	0.045	152.474	-0.708	0.48	
LengthG:Consonantr	0.125	0.041	153.076	3.067	0.003	**
LengthG:Consonantn	-0.104	0.052	151.653	-1.979	0.05	*
LengthG:Consonants	-0.03	0.053	151.851	-0.563	0.575	

Table B.37: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S5.

S5 TB height ∼ Length * Consonant + (1 ∣ VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> ∣t∣)	
(Intercept)	0.813	0.04	133.028	20.346	< 2e-16	***
LengthG	0.02	0.041	166.317	0.483	0.63	
Consonantd	-0.08	0.043	184.58	-1.865	0.064	.
Consonantr	-0.173	0.039	186.488	-4.505	1.17e-05	***
Consonantn	-0.164	0.05	184.087	-3.276	0.001	**
Consonants	-0.277	0.044	176.677	-6.267	2.74e-09	***
LengthG:Consonantd	0.046	0.05	166.341	0.912	0.363	
LengthG:Consonantr	0.047	0.044	166.418	1.064	0.289	
LengthG:Consonantn	0.074	0.058	166.263	1.276	0.204	
LengthG:Consonants	0.019	0.057	166.232	0.325	0.745	

Table B.38: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S6.

S6 TB height ∼ Length * Consonant + (1 ∣ VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> ∣t∣)	
(Intercept)	0.731	0.041	88.848	17.673	< 2e-16	***
LengthG	0.143	0.038	166.335	3.763	0.0002	***
Consonantd	-0.091	0.039	177.944	-2.306	0.022	*
Consonantr	-0.087	0.035	179.676	-2.453	0.015	*
Consonantn	-0.015	0.046	177.379	-0.333	0.739	
Consonants	-0.046	0.045	172.035	-1.035	0.302	
LengthG:Consonantd	-0.033	0.046	166.335	-0.712	0.478	
LengthG:Consonantr	-0.094	0.041	166.433	-2.281	0.024	*
LengthG:Consonantn	-0.098	0.054	166.368	-1.807	0.073	.
LengthG:Consonants	-0.108	0.056	166.453	-1.941	0.054	.

Table B.39: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S7.

S7 TB height ∼ Length * Consonant + (1 ∣ VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> ∣t∣)	
(Intercept)	0.571	0.046	138.902	12.535	< 2e-16	***
LengthG	0.221	0.046	173.525	4.798	3.44e-06	***
Consonantd	0.122	0.048	192.693	2.524	0.012	*
Consonantr	0.015	0.045	193.999	0.331	0.741	
Consonantn	0.15	0.058	192.607	2.599	0.01	*
Consonants	0.124	0.051	184.389	2.433	0.016	*
LengthG:Consonantd	-0.124	0.057	173.394	-2.198	0.029	*
LengthG:Consonantr	-0.117	0.05	173.656	-2.342	0.02	*
LengthG:Consonantn	-0.263	0.066	173.353	-3.987	9.86e-05	***
LengthG:Consonants	-0.255	0.066	173.342	-3.858	0.0002	***

Table B.40: Fixed effects coefficients table for the model of the standardized TB height at TT maximal constriction point for each consonant, for S8.

S8 TB height ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.573	0.037	108.7	15.674	< 2e-16	***
LengthG	0.068	0.045	141.927	1.522	0.13	
Consonantd	-0.069	0.04	156.13	-1.7	0.091	.
Consonantr	0.101	0.036	156.196	2.794	0.006	**
Consonantn	0.052	0.047	155.583	1.103	0.272	
Consonants	-0.007	0.04	143.111	-0.164	0.87	
LengthG:Consonantd	0.061	0.054	140.199	1.132	0.259	
LengthG:Consonantr	-0.081	0.049	142.231	-1.644	0.102	
LengthG:Consonantn	-0.023	0.059	139.508	-0.388	0.699	
LengthG:Consonants	-0.057	0.06	139.556	-0.954	0.342	

B.6 Mixed effects models of TB backness per subject

Table B.41: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S1.

S1 TB backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.209	0.036	108.716	5.763	7.83e-08	***
LengthG	-0.082	0.037	153.847	-2.178	0.031	*
Consonantd	0.074	0.038	170.055	1.955	0.052	.
Consonantr	0.256	0.034	171.897	7.632	1.52e-12	***
Consonants	0.06	0.039	161.47	1.539	0.126	
LengthG:Consonantd	0.026	0.045	153.849	0.561	0.576	
LengthG:Consonantr	0.055	0.04	153.869	1.364	0.175	
LengthG:Consonants	0.056	0.052	153.787	1.077	0.283	

Table B.42: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S2.

S2 TB backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.218	0.044	136.69	4.895	2.73e-06	***
LengthG	-0.044	0.047	164.52	-0.936	0.351	
Consonantd	0.042	0.048	186.179	0.877	0.381	
Consonantr	0.373	0.044	186.997	8.523	5.11e-15	***
Consonantn	0.07	0.056	186.376	1.255	0.211	
Consonants	0.131	0.053	177.917	2.487	0.014	*
LengthG:Consonantd	0.002	0.058	164.516	0.027	0.978	
LengthG:Consonantr	-0.023	0.051	164.63	-0.454	0.651	
LengthG:Consonantn	0.043	0.065	164.457	0.668	0.505	
LengthG:Consonants	0.025	0.068	164.759	0.363	0.717	

Table B.43: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S3.

S3 TB backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.191	0.042	122.185	4.541	1.32e-05	***
LengthG	-0.013	0.043	179.469	-0.308	0.759	
Consonantd	-0.02	0.044	196.722	-0.46	0.646	
Consonantr	0.319	0.039	199.049	8.1	5.44e-14	***
Consonantn	0.043	0.052	197.415	0.841	0.402	
Consonants	0.043	0.046	188.429	0.933	0.352	
LengthG:Consonantd	0.005	0.053	179.492	0.104	0.917	
LengthG:Consonantr	0.034	0.046	179.541	0.734	0.464	
LengthG:Consonantn	-0.061	0.061	179.469	-1.004	0.317	
LengthG:Consonants	0.038	0.061	179.469	0.629	0.53	

Table B.44: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S4.

S4 TB backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.242	0.044	130.782	5.563	1.44e-07	***
LengthG	0.043	0.047	153.194	0.915	0.362	
Consonantd	0.06	0.046	171.904	1.286	0.2	
Consonantr	0.339	0.043	172.872	7.957	2.22e-13	***
Consonantn	0.152	0.055	170.718	2.755	0.007	**
Consonants	0.081	0.05	165.758	1.618	0.108	
LengthG:Consonantd	-0.08	0.056	152.837	-1.426	0.156	
LengthG:Consonantr	0.022	0.051	153.242	0.432	0.666	
LengthG:Consonantn	-0.148	0.065	152.252	-2.266	0.025	*
LengthG:Consonants	0.045	0.065	152.352	0.695	0.488	

Table B.45: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S5.

S5 TB backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.282	0.058	138.517	4.893	2.72e-06	***
LengthG	0.048	0.066	161.892	0.721	0.472	
Consonantd	-0.017	0.067	185.342	-0.255	0.799	
Consonantr	0.244	0.059	179.782	4.116	5.87e-05	***
Consonantn	0.034	0.078	185.595	0.434	0.664	
Consonants	0.119	0.07	181.968	1.7	0.091	.
LengthG:Consonantd	-0.005	0.082	162.022	-0.056	0.955	
LengthG:Consonantr	-0.079	0.072	162.164	-1.104	0.271	
LengthG:Consonantn	-0.056	0.094	161.799	-0.601	0.548	
LengthG:Consonants	-0.078	0.092	161.698	-0.841	0.401	

Table B.46: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S6.

S6 TB backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.269	0.042	138.863	6.372	2.56e-09	***
LengthG	0.001	0.051	163.17	0.021	0.983	
Consonantd	0.061	0.049	183.034	1.248	0.214	
Consonantr	0.365	0.044	179.597	8.386	1.42e-14	***
Consonantn	0.123	0.057	183.04	2.143	0.033	*
Consonants	0.056	0.058	184.253	0.965	0.336	
LengthG:Consonantd	-0.073	0.062	163.17	-1.183	0.239	
LengthG:Consonantr	-0.024	0.055	163.611	-0.441	0.66	
LengthG:Consonantn	-0.127	0.073	163.408	-1.75	0.082	.
LengthG:Consonants	0.037	0.074	164.034	0.497	0.62	

Table B.47: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S7.

S7 TB backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.27	0.049	147.921	5.543	1.33e-07	***
LengthG	0.028	0.054	172.727	0.52	0.604	
Consonantd	0	0.055	192.107	0.008	0.994	
Consonantr	0.156	0.05	184.571	3.112	0.002	**
Consonantn	0.028	0.066	191.628	0.421	0.674	
Consonants	0.017	0.059	189.797	0.279	0.78	
LengthG:Consonantd	0.002	0.067	172.592	0.024	0.981	
LengthG:Consonantr	-0.034	0.059	172.909	-0.578	0.564	
LengthG:Consonantn	-0.032	0.078	172.464	-0.412	0.681	
LengthG:Consonants	-0.013	0.078	172.479	-0.164	0.87	

Table B.48: Fixed effects coefficients table for the model of the standardized TB backness at TT maximal constriction point for each consonant, for S8.

S8 TB backness ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.318	0.037	96.126	8.516	2.26e-13	***
LengthG	-0.048	0.055	140.727	-0.88	0.38	
Consonantd	0.032	0.045	128.624	0.706	0.481	
Consonantr	0.36	0.041	137.184	8.843	4.00e-15	***
Consonantn	0.077	0.052	121.334	1.479	0.142	
Consonants	0.116	0.048	147.913	2.422	0.017	*
LengthG:Consonantd	-0.022	0.065	137.964	-0.335	0.738	
LengthG:Consonantr	-0.005	0.06	142.019	-0.09	0.928	
LengthG:Consonantn	0.021	0.072	133.474	0.287	0.775	
LengthG:Consonants	0.028	0.073	132.974	0.385	0.701	

B.7 Mixed effects models of TD backness per subject

Table B.49: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S1.

S1 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.176	0.043	107.032	4.056	9.51e-05	***
LengthG	-0.082	0.044	154.406	-1.847	0.067	.
Consonantd	0.093	0.045	169.653	2.066	0.04	*
Consonantr	0.279	0.04	171.462	6.985	6.01e-11	***
Consonants	0.073	0.046	161.525	1.572	0.118	
LengthG:Consonantd	0.017	0.054	154.408	0.317	0.752	
LengthG:Consonantr	0.067	0.048	154.426	1.391	0.166	
LengthG:Consonants	0.053	0.062	154.351	0.851	0.396	

Table B.50: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S2.

S2 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.395	0.034	122.597	11.611	< 2e-16	***
LengthG	-0.059	0.034	165.583	-1.756	0.081	.
Consonantd	0.014	0.035	182.781	0.394	0.694	
Consonantr	0.224	0.032	185.099	6.993	4.76e-11	***
Consonantn	0.017	0.041	182.942	0.423	0.673	
Consonants	0.065	0.038	174.944	1.703	0.09	.
LengthG:Consonantd	0.023	0.041	165.58	0.545	0.587	
LengthG:Consonantr	0.009	0.037	165.651	0.249	0.804	
LengthG:Consonantn	0.051	0.047	165.541	1.091	0.277	
LengthG:Consonants	0.045	0.049	165.729	0.934	0.352	

Table B.51: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S3.

S3 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.259	0.042	119.359	6.18	9.19e-09	***
LengthG	-0.02	0.042	179.663	-0.48	0.632	
Consonantd	0.013	0.044	196.213	0.298	0.766	
Consonantr	0.263	0.039	198.594	6.727	1.81e-10	***
Consonantn	0.036	0.051	196.889	0.696	0.488	
Consonants	0.039	0.046	188.161	0.854	0.394	
LengthG:Consonantd	0.01	0.052	179.685	0.188	0.851	
LengthG:Consonantr	0.067	0.046	179.731	1.472	0.143	
LengthG:Consonantn	-0.016	0.06	179.663	-0.263	0.793	
LengthG:Consonants	0.053	0.06	179.663	0.884	0.378	

Table B.52: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S4.

S4 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.175	0.042	99.807	4.119	7.86e-05	***
LengthG	0.036	0.04	152.986	0.88	0.38	
Consonantd	0.077	0.041	165.038	1.893	0.06	.
Consonantr	0.348	0.038	166.895	9.263	< 2e-16	***
Consonantn	0.171	0.048	163.639	3.544	0.001	***
Consonants	0.165	0.043	159.898	3.807	0.0002	***
LengthG:Consonantd	-0.076	0.048	152.817	-1.582	0.116	
LengthG:Consonantr	0.021	0.043	153.002	0.48	0.632	
LengthG:Consonantn	-0.116	0.056	152.523	-2.076	0.04	*
LengthG:Consonants	0.003	0.056	152.551	0.055	0.956	

Table B.53: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S5.

S5 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.219	0.045	140.549	4.924	2.34e-06	***
LengthG	0.025	0.05	163.186	0.501	0.617	
Consonantd	-0.01	0.051	186.587	-0.195	0.845	
Consonantr	0.119	0.045	183.152	2.621	0.01	**
Consonantn	0.005	0.059	186.751	0.088	0.93	
Consonants	0.079	0.053	180.978	1.472	0.143	
LengthG:Consonantd	-0.02	0.062	163.282	-0.32	0.749	
LengthG:Consonantr	-0.035	0.054	163.41	-0.641	0.523	
LengthG:Consonantn	-0.039	0.071	163.101	-0.553	0.581	
LengthG:Consonants	-0.039	0.07	163.021	-0.559	0.577	

Table B.54: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S6.

S6 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.303	0.044	134.8	6.81	2.95e-10	***
LengthG	-0.05	0.052	160.785	-0.949	0.344	
Consonantd	0.088	0.051	185.227	1.725	0.086	.
Consonantr	0.361	0.046	182.437	7.939	2.01e-13	***
Consonantn	0.129	0.06	185.468	2.146	0.033	*
Consonants	0.084	0.06	182.252	1.413	0.159	
LengthG:Consonantd	-0.027	0.064	160.785	-0.418	0.677	
LengthG:Consonantr	0.025	0.057	161.212	0.443	0.658	
LengthG:Consonantn	-0.071	0.075	160.998	-0.951	0.343	
LengthG:Consonants	0.063	0.077	161.55	0.817	0.415	

Table B.55: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S7.

S7 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.346	0.054	146.107	6.409	1.90e-09	***
LengthG	0.021	0.063	172.484	0.334	0.739	
Consonantd	-0.043	0.062	187.749	-0.7	0.485	
Consonantr	0.088	0.057	175.662	1.548	0.123	
Consonantn	-0.027	0.074	185.71	-0.369	0.713	
Consonants	-0.032	0.068	191.74	-0.473	0.636	
LengthG:Consonantd	0.027	0.077	172.402	0.343	0.732	
LengthG:Consonantr	-0.035	0.068	172.665	-0.517	0.606	
LengthG:Consonantn	-0.013	0.09	172.201	-0.146	0.884	
LengthG:Consonants	0.015	0.09	172.249	0.17	0.865	

Table B.56: Fixed effects coefficients table for the model of the standardized TD backness at TT maximal constriction point for each consonant, for S8.

S8 TD backness ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.541	0.033	58.74	16.357	< 2e-16	***
LengthG	0.015	0.052	143.985	0.286	0.775	
Consonantd	0.021	0.041	86.993	0.522	0.603	
Consonantr	0.189	0.037	95.286	5.134	1.50e-06	***
Consonantn	0.082	0.047	63.508	1.75	0.085	.
Consonants	0.125	0.045	153.158	2.771	0.006	**
LengthG:Consonantd	-0.04	0.062	143.117	-0.638	0.524	
LengthG:Consonantr	-0.059	0.057	146.041	-1.048	0.296	
LengthG:Consonantn	-0.028	0.069	132.253	-0.408	0.684	
LengthG:Consonants	-0.036	0.07	129.238	-0.513	0.608	

B.8 Mixed effects models of lateralization per subject

Table B.57: Fixed effects coefficients table for the model of the lateralization index at TT maximal constriction point for each consonant, for S1.

S1 Lateralization ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-1.132	0.398	132.228	-2.844	0.005	**
LengthG	1.603	0.465	151.958	3.446	0.001	***
Consonantd	-0.157	0.453	175.967	-0.347	0.729	
Consonantr	0.758	0.401	175.724	1.889	0.061	.
Consonants	0.618	0.478	166.398	1.291	0.199	
LengthG:Consonantd	1.452	0.564	151.967	2.573	0.011	*
LengthG:Consonantr	-0.825	0.501	152.002	-1.645	0.102	
LengthG:Consonants	-1.766	0.648	151.827	-2.726	0.007	**

Table B.58: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S2.

S2 Lateralization ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	3.406	0.602	110.819	5.659	1.21e-07	***
LengthG	2.559	0.572	166.362	4.472	1.43e-05	***
Consonantd	-0.593	0.596	180.511	-0.994	0.321	
Consonantr	1.517	0.546	182.921	2.776	0.006	**
Consonantn	2.178	0.697	180.606	3.126	0.002	**
Consonants	-1.855	0.644	173.714	-2.879	0.004	**
LengthG:Consonantd	0.201	0.701	166.359	0.286	0.775	
LengthG:Consonantr	-0.78	0.619	166.412	-1.26	0.209	
LengthG:Consonantn	-2.508	0.787	166.329	-3.185	0.002	**
LengthG:Consonants	-1.667	0.823	166.469	-2.026	0.044	*

Table B.59: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S3.

S3 Lateralization ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-1.192	0.573	135.267	-2.081	0.039	*
LengthG	1.12	0.612	178.757	1.83	0.069	.
Consonantd	-0.245	0.622	199.207	-0.394	0.694	
Consonantr	2.39	0.556	200.77	4.299	2.68e-05	***
Consonantn	0.379	0.731	199.859	0.518	0.605	
Consonants	-0.292	0.655	190.204	-0.446	0.656	
LengthG:Consonantd	-0.183	0.753	178.79	-0.243	0.808	
LengthG:Consonantr	-0.652	0.66	178.855	-0.989	0.324	
LengthG:Consonantn	0.405	0.865	178.757	0.468	0.64	
LengthG:Consonants	-1.673	0.865	178.757	-1.933	0.055	.

Table B.60: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S4.

S4 Lateralization ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-0.135	0.49	132.697	-0.276	0.783	
LengthG	-0.202	0.59	152.644	-0.343	0.732	
Consonantd	0.27	0.555	169.474	0.487	0.627	
Consonantr	-0.239	0.505	164.754	-0.474	0.636	
Consonantn	-0.007	0.661	171.443	-0.011	0.991	
Consonants	-0.648	0.611	171.893	-1.062	0.29	
LengthG:Consonantd	-0.049	0.702	151.862	-0.07	0.944	
LengthG:Consonantr	1.508	0.631	152.762	2.39	0.018	*
LengthG:Consonantn	0.522	0.815	150.687	0.641	0.523	
LengthG:Consonants	-0.87	0.818	151.105	-1.064	0.289	

Table B.61: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S5.

S5 Lateralization ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	2.535	0.601	131.631	4.216	4.59e-05	***
LengthG	-0.015	0.616	165.488	-0.024	0.981	
Consonantd	-1.059	0.646	184.545	-1.64	0.103	
Consonantr	-2.876	0.58	186.505	-4.962	1.56e-06	***
Consonantn	-2.216	0.752	184.035	-2.946	0.004	**
Consonants	-4.25	0.665	176.301	-6.386	1.47e-09	***
LengthG:Consonantd	0.569	0.759	165.514	0.749	0.455	
LengthG:Consonantr	0.916	0.666	165.594	1.374	0.171	
LengthG:Consonantn	0.903	0.872	165.432	1.036	0.302	
LengthG:Consonants	0.124	0.858	165.4	0.144	0.886	

Table B.62: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S6.

S6 Lateralization ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	2.339	0.439	187	5.331	2.79e-07	***
LengthG	0.925	0.62	187	1.491	0.138	
Consonantd	0.441	0.537	187	0.821	0.413	
Consonantr	0.155	0.475	187	0.326	0.745	
Consonantn	0.14	0.62	187	0.226	0.822	
Consonants	0.368	0.663	187	0.555	0.58	
LengthG:Consonantd	-1.158	0.76	187	-1.523	0.129	
LengthG:Consonantr	-0.997	0.674	187	-1.48	0.141	
LengthG:Consonantn	-0.421	0.891	187	-0.473	0.637	
LengthG:Consonants	-1.528	0.908	187	-1.683	0.094	.

Table B.63: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S7.

S7 Lateralization ~ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	4.078	0.943	144.524	4.323	2.85e-05	***
LengthG	2.918	0.98	173.826	2.979	0.003	**
Consonantd	2.797	1.019	193.64	2.745	0.007	**
Consonantr	0.834	0.941	193.575	0.887	0.376	
Consonantn	2.747	1.218	193.619	2.254	0.025	*
Consonants	1.969	1.077	185.87	1.829	0.069	.
LengthG:Consonantd	-2.34	1.203	173.688	-1.944	0.053	.
LengthG:Consonantr	-1.728	1.058	173.968	-1.633	0.104	
LengthG:Consonantn	-3.494	1.401	173.635	-2.493	0.014	*
LengthG:Consonants	-3.319	1.402	173.626	-2.368	0.019	*

Table B.64: Fixed effects coefficients table for the model of the lateralization index at maximal constriction point for each consonant, for S8.

S8 Lateralization ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	0.946	0.508	96.267	1.863	0.065	.
LengthG	0.278	0.587	141.177	0.474	0.636	
Consonantd	-0.207	0.536	153.395	-0.386	0.7	
Consonantr	-0.812	0.479	153.704	-1.694	0.092	.
Consonantn	-0.488	0.618	152.546	-0.789	0.431	
Consonants	-2.199	0.52	141.928	-4.232	4.14e-05	***
LengthG:Consonantd	0.624	0.699	139.819	0.893	0.373	
LengthG:Consonantr	-0.436	0.645	141.375	-0.676	0.5	
LengthG:Consonantn	0.289	0.767	139.352	0.377	0.706	
LengthG:Consonants	-0.226	0.777	139.394	-0.291	0.771	

B.9 Mixed effects models of tongue curling per subject

Table B.65: Fixed effects coefficients table for the model of the tongue curling index at maximal constriction point for each consonant, for S1.

S1 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-1.574	0.689	115.425	-2.286	0.024	*
LengthG	-1.904	0.726	154.551	-2.624	0.01	**
Consonantd	0.149	0.728	171.318	0.205	0.838	
Consonantr	0.464	0.648	173.033	0.716	0.475	
Consonants	-0.499	0.755	162.601	-0.66	0.51	
LengthG:Consonantd	-2.279	0.88	154.554	-2.588	0.011	*
LengthG:Consonantr	2.541	0.782	154.574	3.249	0.001	**
LengthG:Consonants	1.371	1.01	154.487	1.357	0.177	

Table B.66: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S2.

S2 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-7.539	0.72	138.295	-10.472	< 2e-16	***
LengthG	-2.113	0.757	166.261	-2.791	0.006	**
Consonantd	1.341	0.772	185.893	1.736	0.084	.
Consonantr	1.82	0.705	186.971	2.582	0.011	*
Consonantn	-0.822	0.903	186.087	-0.911	0.364	
Consonants	3.036	0.845	178.165	3.595	0.0004	***
LengthG:Consonantd	-0.574	0.928	166.257	-0.619	0.537	
LengthG:Consonantr	1.31	0.819	166.357	1.598	0.112	
LengthG:Consonantn	2.193	1.042	166.205	2.105	0.037	*
LengthG:Consonants	1.944	1.089	166.469	1.785	0.076	.

Table B.67: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S3.

S3 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-3.002	0.661	126.095	-4.542	1.29e-05	***
LengthG	-1.505	0.684	178.988	-2.199	0.029	*
Consonantd	0.196	0.7	197.504	0.28	0.78	
Consonantr	-2.174	0.627	199.708	-3.467	0.001	***
Consonantn	-3.215	0.824	198.219	-3.903	0.0001	***
Consonants	-1.759	0.735	188.797	-2.393	0.018	*
LengthG:Consonantd	-0.034	0.842	179.014	-0.041	0.968	
LengthG:Consonantr	2.192	0.738	179.068	2.971	0.003	**
LengthG:Consonantn	1.2	0.968	178.988	1.24	0.217	
LengthG:Consonants	1.74	0.968	178.988	1.799	0.074	.

Table B.68: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S4.

S4 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-4.956	0.601	137.086	-8.251	1.15e-13	***
LengthG	0.671	0.681	154.313	0.986	0.326	
Consonantd	-0.56	0.66	172.996	-0.848	0.397	
Consonantr	3.163	0.604	172.208	5.239	4.68e-07	***
Consonantn	0.485	0.784	172.763	0.619	0.537	
Consonants	-0.142	0.717	168.901	-0.198	0.843	
LengthG:Consonantd	0.035	0.811	153.845	0.043	0.966	
LengthG:Consonantr	-0.456	0.729	154.383	-0.626	0.533	
LengthG:Consonantn	-0.106	0.941	153.105	-0.112	0.911	
LengthG:Consonants	0.751	0.944	153.275	0.796	0.427	

Table B.69: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S5.

S5 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-3.739	0.637	130.77	-5.872	3.35e-08	***
LengthG	0.041	0.649	165.668	0.063	0.95	
Consonantd	1.371	0.681	184.289	2.012	0.046	*
Consonantr	3.025	0.612	186.347	4.946	1.68e-06	***
Consonantn	2.556	0.794	183.766	3.22	0.002	**
Consonants	3.698	0.702	176.151	5.271	3.94e-07	***
LengthG:Consonantd	-1.017	0.8	165.692	-1.271	0.205	
LengthG:Consonantr	0.043	0.702	165.769	0.061	0.952	
LengthG:Consonantn	-0.961	0.918	165.614	-1.046	0.297	
LengthG:Consonants	-0.215	0.904	165.582	-0.238	0.812	

Table B.70: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S6.

S6 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-3.475	0.778	114.995	-4.469	1.85e-05	***
LengthG	-3.687	0.778	166.503	-4.738	4.59e-06	***
Consonantd	0.455	0.802	182.285	0.567	0.571	
Consonantr	-0.206	0.718	184.013	-0.287	0.774	
Consonantn	-2.062	0.937	181.702	-2.201	0.029	*
Consonants	-0.487	0.91	174.823	-0.536	0.593	
LengthG:Consonantd	1.513	0.953	166.503	1.587	0.114	
LengthG:Consonantr	4.588	0.847	166.65	5.419	2.07e-07	***
LengthG:Consonantn	3.328	1.119	166.557	2.975	0.003	**
LengthG:Consonants	3.679	1.143	166.693	3.218	0.002	**

Table B.71: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S7.

S7 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-5.852	0.878	130.786	-6.664	6.75e-10	***
LengthG	-1.941	0.859	173.788	-2.261	0.025	*
Consonantd	-2.074	0.907	191.017	-2.286	0.023	*
Consonantr	-0.151	0.842	193.35	-0.179	0.858	
Consonantn	-1.754	1.085	190.85	-1.617	0.107	
Consonants	-2.029	0.95	182.941	-2.135	0.034	*
LengthG:Consonantd	1.538	1.055	173.672	1.458	0.147	
LengthG:Consonantr	2.239	0.928	173.899	2.413	0.017	*
LengthG:Consonantn	2.862	1.228	173.643	2.33	0.021	*
LengthG:Consonants	2.181	1.229	173.631	1.775	0.078	.

Table B.72: Fixed effects coefficients table for the model of the tongue curling index (in mm) at maximal constriction point for each consonant, for S8.

S8 Tongue curling ∼ Length * Consonant + (1 | VowelEnv)						
	Estimate	Std. Error	df	t-value	Pr (> |t|)	
(Intercept)	-4.04	0.57	118.938	-7.088	1.05e-10	***
LengthG	-0.735	0.733	144.161	-1.003	0.318	
Consonantd	1.096	0.651	156.99	1.683	0.094	.
Consonantr	1.113	0.582	156.998	1.911	0.058	.
Consonantn	-0.115	0.753	156.979	-0.153	0.879	
Consonants	0.771	0.647	145.731	1.191	0.236	
LengthG:Consonantd	-0.908	0.873	142.323	-1.04	0.3	
LengthG:Consonantr	1.486	0.804	144.545	1.848	0.067	.
LengthG:Consonantn	0.785	0.959	141.439	0.818	0.415	
LengthG:Consonants	0.303	0.972	141.478	0.312	0.755	

B.10 TT horizontal trajectories per subject (restricted data)

Figure B.1: Smoothing splines of the temporal dynamics of TT horizontal movement over the VCV region, for group T, R, and Ri for singletons.

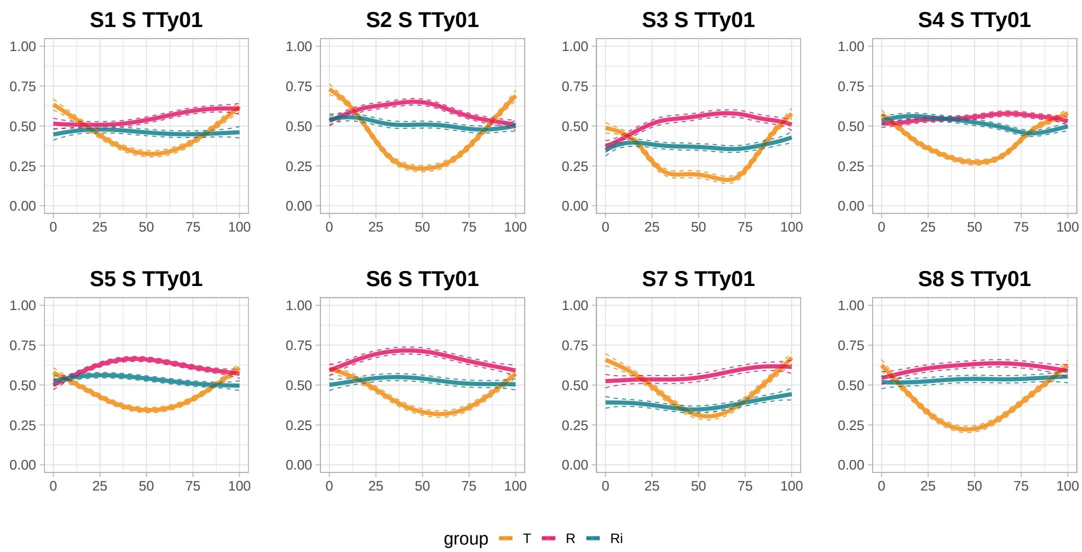
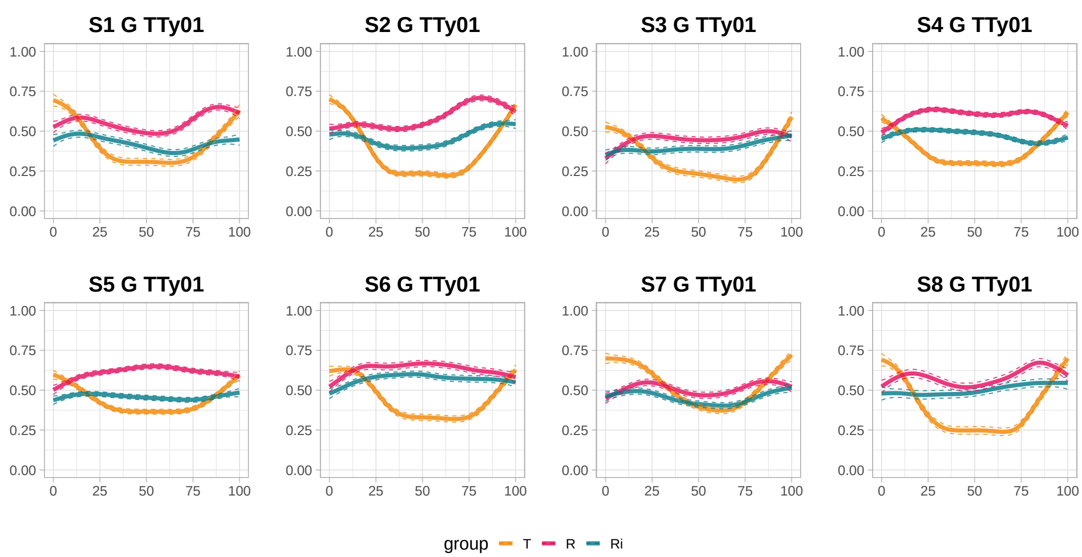


Figure B.2: Smoothing splines of the temporal dynamics of TT horizontal movement over the VCV region, for group T, R, and Ri for geminates.



B.11 TB horizontal trajectories per subject (restricted data)

Figure B.3: Smoothing splines of the temporal dynamics of TB horizontal movement over the VCV region, for group T, R, and Ri for singletons.

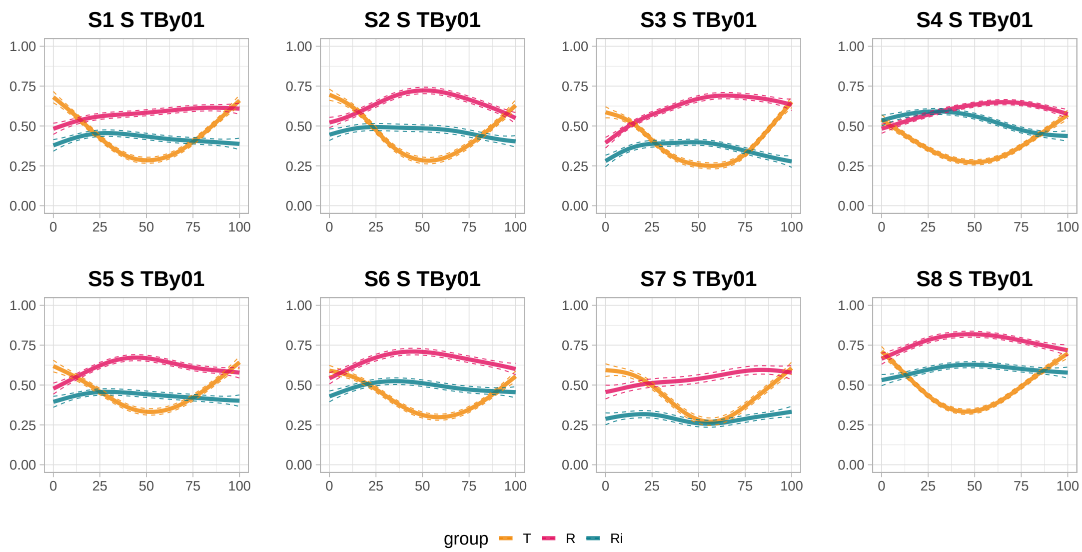
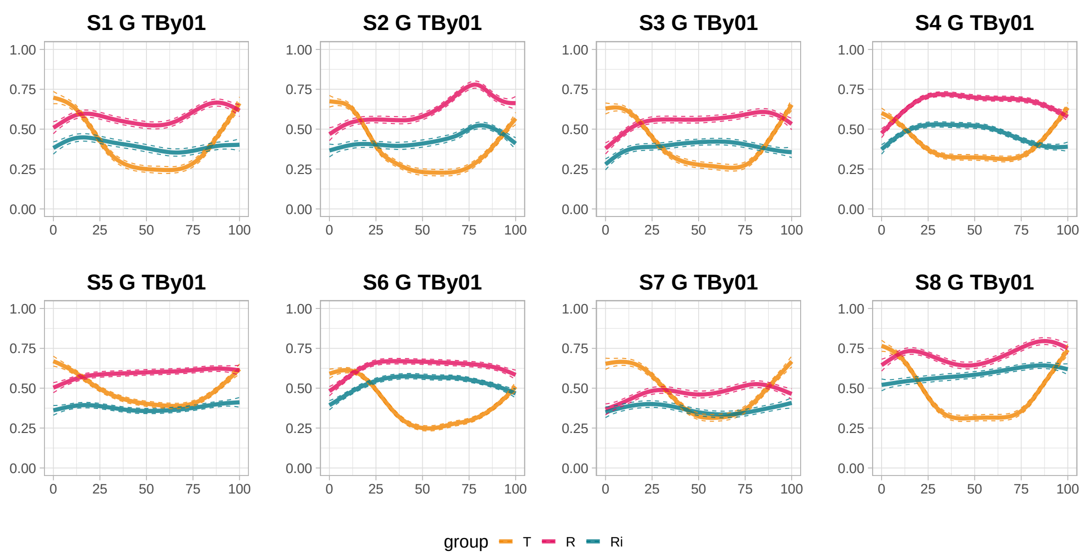
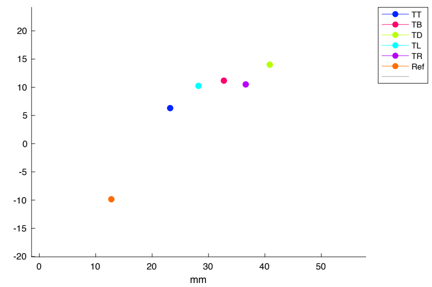


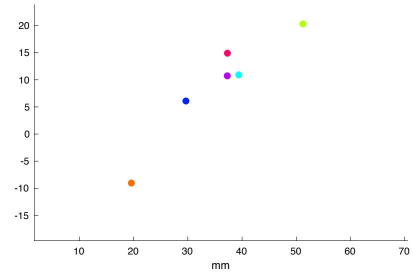
Figure B.4: Smoothing splines of the temporal dynamics of TB horizontal movement over the VCV region, for group T, R, and Ri for geminates.



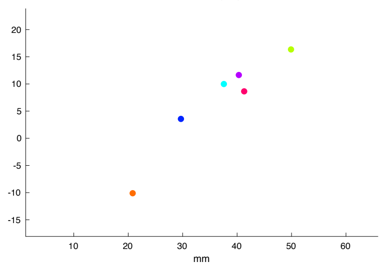
B.12 Resting position for each subject



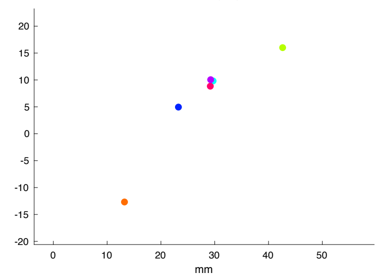
(a) S1



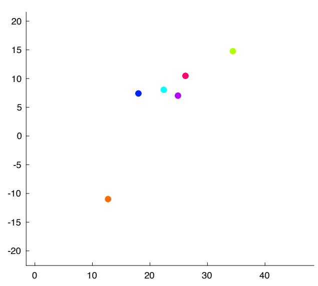
(b) S2



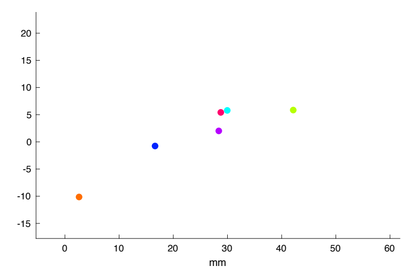
(c) S3



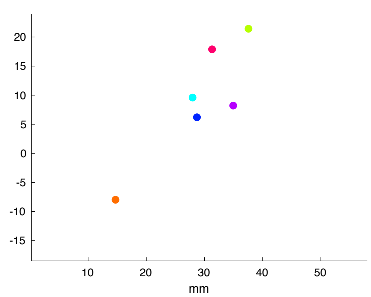
(d) S4



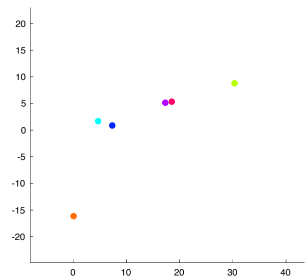
(e) S5



(f) S6



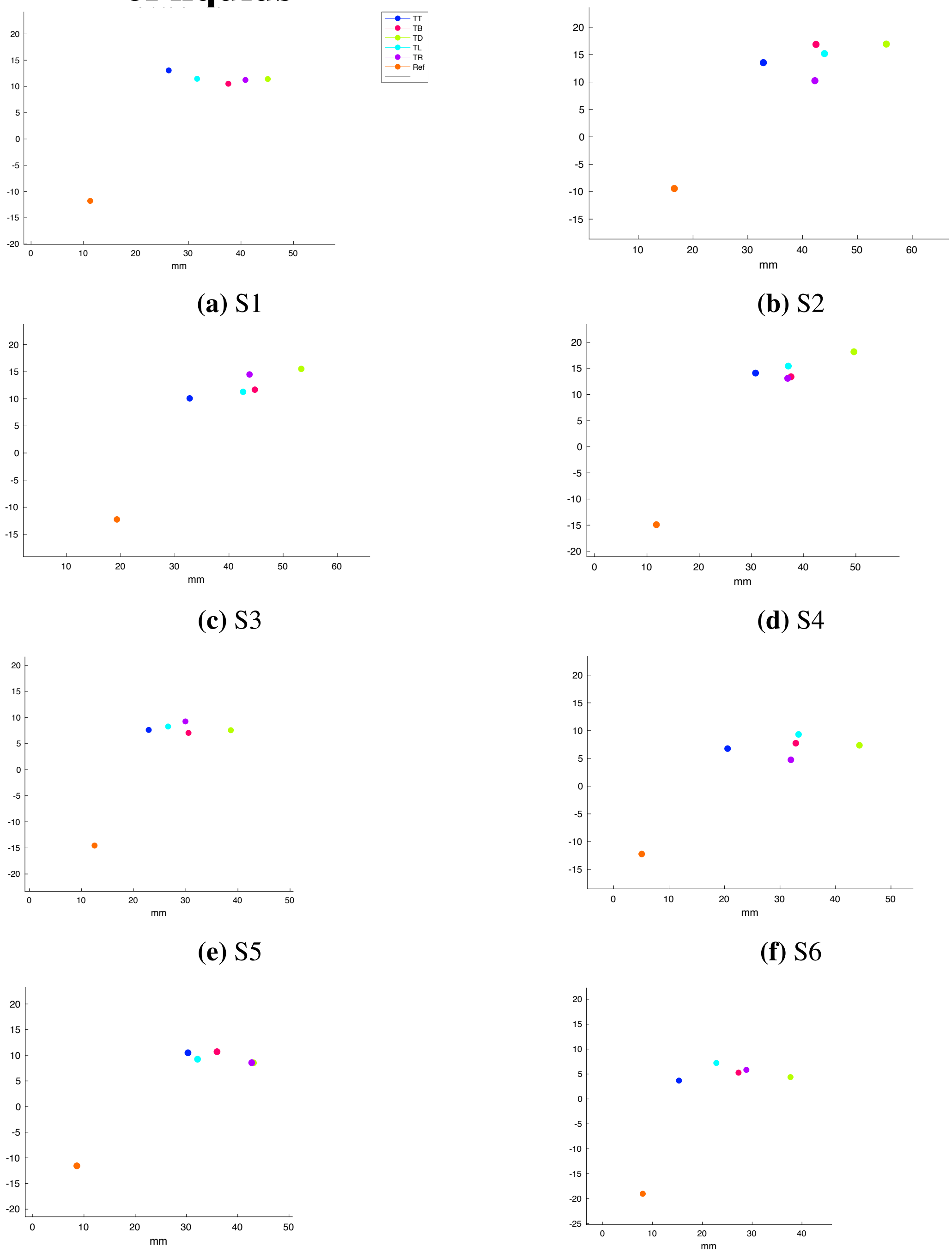
(g) S7



(h) S8

Figure B.5: Sensor configuration at resting position for each subject.

B.13 Sensor configuration at TT maximal constriction of liquids



(a) S1 **(b)** S2
(c) S3 **(d)** S4
(e) S5 **(f)** S6
(g) S7 **(h)** S8

Figure B.6: Sensor configuration at TT maximal constriction point for the geminated liquid in [garragara] for each subject.

References

Abramson, A. S. (2003). Acoustic cues to word-initial stop length in Pattani Malay. *Proceedings of ICPhS XV*, 387–390.

Aizawa, Y. (1985). Intensification by so-called “choked sounds” – long consonants – in Japanese. *The Study of Sounds*, *21*, 313–325.

Akamatsu, T. (1997). *Japanese phonetics: Theory and practice* (Vol. 3). Lincom Europa.

Akita, K. (2008). Phonosemantic evidence for the mimetic stratum in the Japanese lexicon. *Annual Meeting of the Berkeley Linguistics Society*, *34*(1), 1–12.

Akita, K., & Dingemanse, M. (2019). Ideophones (mimetics, expressives). In *Oxford research encyclopedia of linguistics.* Oxford University Press.

Alwan, A., Narayanan, S., & Haker, K. (1997). Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part II. The rhotics. *The Journal of the Acoustical Society of America*, *101*(2), 1078–1089.

Amengual, M. (2016). Acoustic correlates of the Spanish tap-trill contrast: Heritage and L2 Spanish speakers. *Heritage Language Journal*, *13*(2), 88–112.

Anand, P., Chung, S., & Wagers, M. (2011). Widening the net: Challenges for gathering linguistic data in the digital age. *Response to NSF SBE*, *2020*.

Arai, M., & Kawagoe, I. (1998). Eigo no onsetsugata to sokuon chikaku: Nansensugo niyoru chikakutesuto hōkoku [Consonant gemination and syllable types in English: a perceptual test of nonsense words]. *Journal of the Phonetic Society of Japan*, *2*(3), 87–92.

Arai, T. (2013a). Kōon no kakutoku ni hisomu onkyōteki sokumen o saguru [Acoustic properties of Japanese /r/ sounds and acquisition of their articulation]. *The Japanese Journal of Communication Disorders*.

Arai, T. (2013b). On why Japanese /r/ sounds are difficult for children to acquire. *INTERSPEECH*, 2445–2449.

Arai, T., Iwagami, E., & Yanagisawa, E. (2016). Nihongo sokuon ga kaishisita kanōsei o shiraseru chikakujō no tegakari [Perceptual cues signaling possible timing with initial geminate consonants in Japanese]. *Nihon Onkyō Gakkai [The Acoustical Society of Japan]*.

Arai, T., Warner, N., & Greenberg, S. (2007). Analysis of spontaneous Japanese in a multi-language telephone-speech corpus. *Acoustical Science and Technology*, *28*(1), 46–48.

Bates, D., Maechler, M., & Bolker, B. (2012). *lme4: Linear mixed-effects models using S4 classes*.

Beckman, M. (1982). Segment duration and the 'mora' in Japanese. *Phonetica*, *39*(2-3), 113–135.

Blevins, J. (2004). *Evolutionary phonology: The emergence of sound patterns*. Cambridge University Press.

Bloch, B. (1950). Studies in colloquial Japanese IV: Phonemics. *Language*, *26*(1), 86–125.

Boersma, P., & Weenink, D. (2001). Praat, a system for doing phonetics by computer. *Glot International 5:9/10*, 341-345.

Browman, C. P., & Goldstein, L. (1990). Tiers in articulatory phonology, with some implications for casual speech. *Papers in Laboratory Phonology I: Between The*

Grammar and Physics of Speech, 341–376.

Browman, C. P., & Goldstein, L. (1992a). Articulatory phonology: An overview. *Phonetica*, *49*(3-4), 155–180.

Browman, C. P., & Goldstein, L. (1992b). "targetless" schwa: An articulatory analysis. *Papers in Laboratory Phonology II: Gesture, Segment, Prosody*, 26–56.

Browman, C. P., & Goldstein, L. (1995). Gestural syllable position effects in American English. *Producing speech: Contemporary issues*, 19–33.

Browman, C. P., & Goldstein, L. M. (1986). Towards an articulatory phonology. *Phonology*, *3*, 219–252.

Byrd, D. (1995). Articulatory characteristics of single and blended lingual gestures. *Proceedings of the ICPhS XIII*, *2*, 438–441.

Campbell, N. (1999). A study of Japanese speech timing from the syllable perspective. *Journal of the Phonetic Society of Japan*, *3*(2), 29–39.

Dalston, R. M. (1975). Acoustic characteristics of English /w, r, l/ spoken correctly by young children and adults. *The Journal of the Acoustical Society of America*, *57*(2), 462–469.

Davidson, L. (2006). Comparing tongue shapes from ultrasound imaging using smoothing spline analysis of variance. *The Journal of the Acoustical Society of America*, *120*(1), 407–415.

Davis, S. (2011). Geminates. *The Blackwell Companion to Phonology*, 1–25.

Delattre, P. (1971). Consonant gemination in four languages: An acoustic, perceptual, and radiographic study part I. *International Review of Applied Linguistics in Language Teaching (IRAL)*, *9*(1), 31–52.

Delattre, P., & Freeman, D. C. (1968). A dialect study of American r's by x-ray motion picture. *Linguistics*, *6*(44), 29–68.

Derrick, D., & Gick, B. (2008). Quantitative analysis of subphonemic flap/tap variation in NAE. *Canadian Acoustics*, *36*(3), 162–163.

Derrick, D., & Gick, B. (2011). Individual variation in English flaps and taps: A case of categorical phonetics. *Canadian Journal of Linguistics/Revue canadienne de linguistique*, *56*(3), 307–319.

Dieth, E., & Brunner, R. (1943). Die konsonanten und geminaten des schweizerdeutschen experimentell untersucht. *Romanica Helvetica*, *20*, 757–762.

Dmitrieva, O. (2017). Production of geminate consonants in Russian. *The Phonetics and Phonology of Geminate Consonants*, *2*, 34.

Dunn, M. (1993). *The phonetics and phonology of geminate consonants* (Unpublished doctoral dissertation). Yale University, New Haven.

Espy-Wilson, C. Y. (1992). Acoustic measures for linguistic features distinguishing the semivowels /w j r l/ in American English. *The Journal of the Acoustical Society of America*, *92*(2), 736–757.

Fujimoto, M. (2013). Timing differences in articulation between single and geminate voiceless stop consonants: An analysis of cine-MRI data. *3rd International Conference on Phonetics and Phonology*.

Fujimoto, M. (2014, August). Sokuon no intōchōsetsu no kōsoku kamera to PGG niyoru kentō: Kēsusutadī [Laryngeal examination of sokuon using high-speed digital video system and PGG: A case study]. *Journal of the Phonetic Society of Japan*, *18*(2), 44–53.

Fujimoto, M., Funatsu, S., & Hoole, P. (2015). Articulation of single and geminate consonants and its relation to the duration of the preceding vowel in Japanese. *Proceedings of ICPhS XVIII*.

Fujimoto, M., Maekawa, K., & Funatsu, S. (2010). Laryngeal characteristics during the production of geminate consonants. *11th Annual Conference of the International Speech Communication Association*.

Fukui, S. (1978). Nihongo heisaon no enchō/tanshuku niyoru sokuon/hisokuon toshite no chōshu [Perception for the Japanese stop consonants with reduced and extended durations]. *Onsei Gakkai Kaihō [Phonetic Society Reports]*, *159*, 9–12.

Gafos, A. (2002). A grammar of gestural coordination. *Natural Language & Linguistic Theory*, *20*(2), 269–337.

Gafos, A., Kirov, C., & Shaw, J. (2010). *Guidelines for using Mview.* Ms., Haskins Laboratories.

Garcia, D. (2010). Robust smoothing of gridded data in one and higher dimensions with missing values. *Computational statistics & data analysis*, *54*(4), 1167–1178.

Gu, C. (2014). Smoothing spline anova models: R package gss. *Journal of Statistical Software*, *58*(5), 1–25. Retrieved from `http://www.jstatsoft.org/v58/i05/`

Guenther, F. H., Espy-Wilson, C. Y., Boyce, S. E., Matthies, M. L., Zandipour, M., & Perkell, J. S. (1998). Articulatory trade-offs reduce acoustic variability in American English /r/ productions. *The Journal of the Acoustical Society of America*, *102*.

Hagedorn, C., Proctor, M., & Goldstein, L. (2011). Automatic analysis of singleton and geminate consonant articulation using real-time magnetic resonance imaging. *Twelfth Annual Conference of the International Speech Communication Association*.

Hagiwara, R. (1994). Three types of American /r/. *UCLA Working Papers in Phonetics*, 55–61.

Hagiwara, R. (1995). Acoustic realizations of American /r/ as produced by women and men. *UCLA Working Papers in Phonetics*(90).

Hall, K. C. (2013). A typology of intermediate phonological relationships. *The Linguistic Review*, *30*(2), 215–275.

Hall, N. (2010). Articulatory phonology. *Language and Linguistics Compass*, *4*(9), 818–830.

Hall, T. A. (2000). Typological generalizations concerning secondary palatalization. *Lingua*, *110*(1), 1–25.

Ham, W. (2001). *Phonetic and phonological aspects of geminate timing*. Routledge.

Hamann, S. (2002). Retroflexion and retraction revised. In T. A. Hall, B. Pompino-Marshall, & M. Rochón (Eds.), *Papers on phonetics and phonology: The articulation, acoustics and perception of consonants* (Vol. 28, pp. 13–26).

Han, M. S. (1962). The feature of duration in Japanese. *Onsei no Kenkyū [The Study of Sounds]*, *10*, 65–80.

Han, M. S. (1994). Acoustic manifestations of mora timing in Japanese. *The Journal of the Acoustical Society of America*, *96*(1), 73–82.

Hattori, S. (1951). *Oninron to seishohō [phonemics and orthography]*. Tokyo: Kenkyūsha.

Hattori, S. (1984). *Phonetics*. Iwanami.

Hayes, B. (1989). Compensatory lengthening in moraic phonology. *Linguistic inquiry*, 253-306.

Hegedüs, L. (1959). Beitrag zur frage der geminaten. *STUF-Language Typology and Universals*, *12*(1-4), 68–106.

Hirata, Y. (2007). Durational variability and invariance in Japanese stop quantity distinction: Roles of adjacent vowels. *Journal of the Phonetic Society of Japan*, *11*(1), 9–22.

Hirata, Y., & Whiton, J. (2005). Effects of speaking rate on the single/geminate stop distinction in Japanese. *The Journal of the Acoustical Society of America*, *118*(3), 1647–1660.

Hirose, A., & Ashby, M. (2007). An acoustic study of devoicing of the geminate obstruents in Japanese. *Proceedings of ICPhS XVI*, *16*, 909–912.

Homma, Y. (1981). Durational relationship between Japanese stops and vowels. *Journal of Phonetics*, *9*, 273–281.

Hyman, L. M. (1985). *A theory of phonological weight*. Dordrecht: Foris Publications Holland.

Idemaru, K., & Guion, S. G. (2008). Acoustic covariants of length contrast in Japanese stops. *Journal of the International Phonetic Association*, *38*(2), 167–186.

Idemaru, K., & Guion-Anderson, S. (2010). Relational timing in the production and perception of Japanese singleton and geminate stops. *Phonetica*, *67*(1-2), 25–46.

Inouye, S. (1995). *Trills, taps and stops in contrast and variation* (Unpublished doctoral dissertation). University of California, Los Angeles.

International Phonetic Association. (2015). *IPA chart.* Retrieved from `http://www.internationalphoneticassociation.org/content/ipa-chart`

Ishii, T. (1999). A study of the movement of articulatory organs in Japanese geminate production: An X-ray microbeam analysis. *Journal of Otolaryngology Japan*.

Iskarous, K., & Kavitskaya, D. (2010). The interaction between contrast, prosody, and coarticulation in structuring phonetic variability. *Journal of Phonetics*, *38*(4), 625–639.

Itô, J., Kubozono, H., & Mester, A. (2017). A prosodic account of consonant gemination in Japanese loanwords. In H. Kubozono (Ed.), *The phonetics and phonology of geminate consonants* (Vol. 2, pp. 283–320). Oxford University Press Oxford.

Itô, J., & Mester, A. (1993a). Japanese phonology: Constraint domains and structure preservation. In *A Handbook of Phonological Theory.* Citeseer.

Itô, J., & Mester, A. (1995a). The core-periphery structure of the lexicon and constraints on reranking. In J. Beckman, S. Urbanczyk, & L. Walsh (Eds.), *Papers* *in Optimality Theory* (p. 181-210). Amherst, Mass.: GLSA Publications.

Itô, J., & Mester, A. (1995b). Japanese Phonology. In J. Goldsmith (Ed.), *The Handbook of Phonological Theory* (p. 817-838). Blackwell.

Itô, J., & Mester, A. (1999). The phonological lexicon. In N. Tsujimura (Ed.), *The Handbook of Japanese Linguistics* (p. 62-100). Oxford: Blackwell.

Itô, J., & Mester, A. (2003). *Japanese Morphophonemics: Markedness and word structure*. MIT Press.

Itô, J., Mester, A., & Padgett, J. (1995). Licensing and underspecification in Optimality Theory. *Linguistic Inquiry*, *26*, 571–614.

Itô, J., & Mester, R. A. (1993b). Licensed segments and safe paths. *Canadian Journal of Linguistics/Revue canadienne de linguistique*, *38*(2), 197–213.

Ji, A., Johnson, M. T., & Berry, J. (2013). Articulatory space calibration in 3D electromagnetic articulography. *2013 IEEE China Summit and International Conference on Signal and Information Processing*, 155–159.

Johnson, K. (2004). Acoustic and auditory phonetics. *Phonetica*, *61*(1), 56–58.

Katz, W. F., Mehta, S., & Wood, M. (2018). Effects of syllable position and vowel context on Japanese /r/: Kinematic and perceptual data. *Acoustical Science and Technology*, *39*(2), 130–137.

Katz, W. F., Mehta, S., Wood, M., & Wang, J. (2017). Using electromagnetic articulography with a tongue lateral sensor to discriminate manner of articulation. *The Journal of the Acoustical Society of America*, *141*(1), EL57–EL63.

Kavitskaya, D., Iskarous, K., Noiray, A., & Proctor, M. (2009). Trills and palatalization: Consequences for sound change. *Proceedings of the formal approaches to Slavic Linguistics*, *17*, 97–110.

Kawagoe, I. (2015). The phonology of *sokuon*, or geminate obstruents. In H. Kubozono (Ed.), *The Handbook of Japanese Language and Linguistics: Phonetics and*

Phonology. Mouton de Gruyter.

Kawahara, S. (2002). *Similarity among variants: Output-variant correspondence.* (International Christian University BA thesis)

Kawahara, S. (2006). A faithfulness ranking projected from a perceptibility scale: The case of [+ voice] in Japanese. *Language*, 536–574.

Kawahara, S. (2007). Sonorancy and geminacy. In *University of Massachusetts Occasional Papers in Linguistics 32: Papaers in Optimality III* (pp. 145–186). Amherst: GLSA.

Kawahara, S. (2013). Nihongo tokushuhaku no onkyō to chikaku [The acoustics and perception of Japanese special moras]. *Nihon Onkyō Gakkaishi*, *69*(4).

Kawahara, S. (2015a). Japanese /r/ is not feature-less: A rejoinder to Labrune (2014). *Open Linguistics*, *1*(1).

Kawahara, S. (2015b). The phonetics of *sokuon*, or geminate obstruents. In H. Kubozono (Ed.), *The Handbook of Japanese Language and Linguistics: Phonetics and Phonology* (pp. 43–73). Mouton de Gruyter.

Kawahara, S. (2016). *The phonetics of [voice] in singletons and geminates in Japanese: An acoustic and electroglottography study.*

Kawahara, S. (2017). Durational compensation within a CV mora in spontaneous Japanese: Evidence from the Corpus of Spontaneous Japanese. *The Journal of the Acoustical Society of America*, *142*(1), EL143–EL149.

Kawahara, S. (2018). Durational vowel-coda interaction in spontaneous Japanese utterances. *Acoustical Science and Technology*, *39*(2), 138–139.

Kawahara, S., & Braver, A. (2014). Durational properties of emphatically lengthened consonants in Japanese. *Journal of the International Phonetic Association*, *44*(03), 237–260.

Kawahara, S., & Matsui, F. M. (2017). Some aspects of Japanese consonant articulation: A preliminary EPG study. *ICU Working Papers in Linguistics (ICUWPL)*, *2*, 9–20.

Kawahara, S., & Pangilinan, M. (2017). Spectral continuity, amplitude changes, and perception of length contrasts. In H. Kubozono (Ed.), *The Phonetics and Phonology of Geminate Consonants* (Vol. 2, pp. 13–33). Oxford University Press.

Kawakami, S. (1977). *Nihongo onsei gaisetsu [Outline of Japanese phonetics]*. Tokyo: Ōfūsha.

Kelso, J., & Tuller, B. (1987). Intrinsic time in speech production: Theory, methodology, and preliminary observations. *Motor and sensory processes of language, ed. Keller E. & Gopnik M.. Erlbaum.[KGM]*.

Kent, R. D., & Read, C. (2002). Acoustic analysis of speech. 2nd. *Albany, NY: Singular/Thomson Learning*.

Kitamura, T., Nota, Y., Hashi, M., & Hatano, H. (2014). A method of measuring articulatory space using NDI Wave speech research system. *IEICE technical report*, *114*(303), 89–93.

Kochetov, A. (2012). Linguopalatal contact differences between Japanese geminate and singleton stops. *Canadian Acoustics*, *40*(3), 28–29.

Kochetov, A. (2018). Linguopalatal contact contrasts in the production of Japanese consonants: Electropalatographic data from five speakers. *Acoustical Science and Technology*, *39*(2), 84–91.

Kochetov, A., & Kang, Y. (2013). When long is tense and tense is long: An EPG study of Japanese and Korean stops. In *International conference of phonetics and phonology.*

Kochetov, A., & Kang, Y. (2017). Supralaryngeal implementation of length and laryngeal contrasts in Japanese and Korean. *Canadian Journal of Linguistics/Revue canadienne de linguistique*, *62*(1), 18–55.

Kokuritsu Kokugo Kenkyūjo [National Language Research Institute]. (1990). *Nihongo no boin, shiin, onsetsu: chōon undō no jikken onseigakuteki kenkyū [Japanese vowels, consonants and syllables: Experimental phonetics research of articulatory movements]* (Vol. 100). Tokyo: Shūei Shuppan.

Kubozono, H. (2017). Introduction to the phonetics and phonology of geminate consonants. In H. Kubozono (Ed.), *The Phonetics and Phonology of Geminate Consonants* (Vol. 2, pp. 1–10). Oxford University Press Oxford.

Kubozono, H., Itô, J., & Mester, A. (2009). Consonant gemination in Japanese loanword phonology. In T. L. S. of Korea (Ed.), *Current Issues in Unity and Diversity of Languages. Collection of Papers Selected from the 18th International Congress of Linguists [CIL 18]* (p. 953-973). Republic of Korea: Dongam Publishing Co.

Kurisu, K. (2014). The phonology of emphatic morphology in Japanese mimetics. *Japanese/Korean Linguistics*, *22*, 21–36.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. doi: 10.18637/jss.v082.i13

Labrune, L. (2012). *The Phonology of Japanese*. Oxford University Press.

Labrune, L. (2014). The phonology of Japanese /r/: A panchronic account. *Journal of East Asian Linguistics*, *23*(1), 1–25.

Ladefoged, P., & Johnson, K. (1993). *A course in phonetics* (3rd ed.). Fort Worth: Harcourt Brace Jovanovich College Publishers.

Ladefoged, P., & Johnson, K. (2006). *A course in phonetics* (5th ed.).

Ladefoged, P., & Maddieson, I. (1996). *The sounds of the world's languages* (Vol. 1012). Blackwell Oxford.

Lahiri, A., & Hankamer, J. (1988). The timing of geminate consonants. *Journal of*

Phonetics, *16*.

Lehiste, I., Morton, K., & Tatham, M. A. (1973). An instrumental study of consonant gemination. *Journal of Phonetics*, *1*, 131–148.

Lindau, M. (1985). The story of /r/. In V. A. Fromkin (Ed.), *Phonetic linguistics: Essays in honor of Peter Ladefoged.* Academic Press, Orlando.

Local, J., & Simpson, A. P. (1999). Phonetic implementation of geminates in Malayalam nouns. *Proceedings of ICPhS XIV*, *4*(92), 46.

Löfqvist, A. (2006). Interarticulator programming: Effects of closure duration on lip and tongue coordination in Japanese. *The Journal of the Acoustical Society of America*, *120*(5), 2872–2883.

Löfqvist, A. (2017). Articulatory coordination in long and short consonants: An effect of rhythm class? In H. Kubozono (Ed.), *The Phonetics and Phonology of Geminate Consonants* (Vol. 2, pp. 118–129). Oxford University Press.

Maddieson, I. (1984). *Patterns of sounds*. Cambridge University Press.

Maddieson, I. (1985). Phonetic cues to syllabification. *Phonetic Linguistics: Essays in Honor of Peter Ladefoged*, 203–221.

Magnuson, T. (2009). A pharyngeal component in Kansai Japanese /r/ variants? In *comunicación presentada en the international workshop on pharyngeals and pharyngealisation* (pp. 26–27).

Masaki, S., Akahane-Yamada, R., Tiede, M. K., Shimada, Y., & Fujimoto, I. (1996). An mri-based analysis of the English /r/ and /l/ articulations. *Proceeding of Fourth International Conference on Spoken Language Processing*, *3*, 1581–1584.

Matsui, M., Kawahara, S., & Shaw, J. (2016). EPG o mochiita nihongo shikei sokuon no chōonteki tokuchō [Articulatory characteristics of Japanese alveolar geminates using EPG]. *Proceedings of Japanese Phonetic Society*.

Matsuno, K. (1971). Some allophones of Japanese /r/ and their stylistic values. *On-*

seigakkai Kaihō, *136*, 5–8.

McCarthy, J. J., & Prince, A. (1996). *Prosodic morphology.* manuscript.

McCawley, J. D. (1968). *The Phonological Component of a Grammar of Japanese* (No. 2). Mouton.

McGowan, R. S. (1992). Tongue-tip trills and vocal-tract wall compliance. *The Journal of the Acoustical Society of America*, *91*(5), 2903–2910.

Mester, R. A., & Itô, J. (1989). Feature predictability and underspecification: Palatal prosody in Japanese mimetics. *Language*, 258–293.

Meyer, E. A., & Gombocz, Z. (1909). *Zur phonetik der ungarischen Sprache*. Uppsala: Edvard Berlings Buchdruckerei.

Miyawaki, K., Jenkins, J. J., Strange, W., Liberman, A. M., Verbrugge, R., & Fujimura, O. (1975). An effect of linguistic experience: The discrimination of [r] and [l] by native speakers of Japanese and English. *Perception & Psychophysics*, *18*(5), 331–340.

Monnot, M., & Freeman, M. (1972). A comparison of Spanish single-tap /r/ with American /t/ and /d/ in post-stress intervocalic position. *Papers in linguistics and phonetics to the memory of Pierre Delattre*, *54*, 409–416.

Moore, J., Shaw, J., Kawahara, S., & Arai, T. (2018). Articulation strategies for English liquids used by Japanese speakers. *Acoustic Science and Technology*, *39 (2)*(138–139).

Munhall, K., & Löfqvist, A. (1992). Gestural aggregation in speech-laryngeal gestures. *Journal of Phonetics*, *20*(1), 111–126.

Narayanan, S., Alwan, A., & Haker, K. (1997). Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part I. The laterals. *The Journal of the Acoustical Society of America*, *101*(2), 1064–1077.

Narayanan, S., Byrd, D., & Kaun, A. (1999). Geometry, kinematics, and acoustics of Tamil liquid consonants. *The Journal of the Acoustical Society of America*, *106*(4), 1993–2007.

Oba, R., Braun, A., & Handke, J. (2009). The perception of Japanese geminates by native and non-native listeners. *International Society of Phonetic Sciences*, 9–29.

Ofuka, E. (2003). Sokuon /tt/ no chikaku: Akusentogata to sokuon/hisokuongo no onkyōteki tokuchō niyoru chigai [Perception of a Japanese geminate stop/tt: The effect of pitch type and acoustic characteristics of preceding/following vowels]. *Journal of the Phonetic Society of Japan*, *7*(1), 70–76.

Okada, H. (1999). Japanese. In *Handbook of the international phonetic association* (Vol. 2, pp. 117–119).

Ong, D., & Stone, M. (1998). Three-dimensional vocal tract shapes in /r/ and /l/: A study of MRI, ultrasound, electropalatography, and acoustics. *Phonoscope*, *1*(1), 1–13.

Onishi, M. (1987). Dōteki jinkō kōgai ni yoru nihongo shiin no kōsatsu [a study of Japanese consonants by means of an artificial palate]. *Onsei Gakkai Kaihō [Phonetic Society Reports]*, *186*(2), 19–24.

Otsuka, N. (1997). Research on articulation development of the consonants in the /r/ and /d/ series in children. *The Japan Journal of Logopedics and Phoniatrics*, *38*(3), 243–249.

Payne, E. M. (2005). Phonetic variation in Italian consonant gemination. *Journal of the International Phonetic Association*, *35*(02), 153-181.

Payne, E. M. (2006). Non-durational indices in Italian geminate consonants. *Journal of the International Phonetic Association*, *36*(1), 83–95.

Pellard, T. (2016). Why /r/ is not a special, empty consonant in Japanese. *Journal of East Asian Linguistics*, *25*(4), 351–383.

Perkell, J. S., Cohen, M. H., Svirsky, M. A., Matthies, M. L., Garabieta, I., & Jackson,

M. T. (1992). Electromagnetic midsagittal articulometer systems for transducing speech articulatory movements. *The Journal of the Acoustical Society of America*, *92*(6), 3078–3096.

Pike, K. (1947). Phonemics: A technique for reducing languages to writing. *Ann Arbor: University of Michigan Press*, *5*.

Podesva, R. J. (2002). *Segmental constraints on geminates and their implications for typology.* Talk given at the LSA Annual Meeting.

Port, R. F., & Dalby, J. (1982). Consonant/vowel ratio as a cue for voicing in English. *Perception & Psychophysics*, *32*(2), 141–152.

Port, R. F., Dalby, J., & O'Dell, M. (1987). Evidence for mora timing in Japanese. *The Journal of the Acoustical Society of America*, *81*(5), 1574–1585.

Price, P. J. (1981). *A cross-linguistic study of flaps in Japanese and in American English* (Unpublished doctoral dissertation). University of Pennsylvania.

Prince, A., & Smolensky, P. (1993). *Optimality Theory: Constraint interaction in generative grammar*.

Proctor, M. (2009). *Gestural characterization of a phonological class: The liquids* (Unpublished doctoral dissertation). Yale University.

Proctor, M. (2011). Towards a gestural characterization of liquids: Evidence from Spanish and Russian. *Papers in Laboratory Phonology*, *2*(2), 451–485.

Pycha, A. (2009). Lengthened affricates as a test case for the phonetics–phonology interface. *Journal of the International Phonetic Association*, *39*(1), 1–31.

R Core Team. (2013). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria.

Recasens, D., & Pallarès, M. D. (1999). A study of /ɾ/ and /r/ in the light of the "DAC" coarticulation model. *Journal of Phonetics*, *27*(2), 143–169.

Ridouane, R. (2010). Geminates at the junction of phonetics and phonology. *Papers in*

Laboratory Phonology, *10*, 61–90.

Rousselot, P.-J. (1892). *Les modifications phonétiques du langage étudiées dans le patois d'une famille de cellefrouin (charente).*

Schourup, L., & Tamori, I. (1992). Palatalization in Japanese mimetics: Response to Mester and Itô. *Language*, 139–148.

Shaw, J. A., & Kawahara, S. (2018). The lingual articulation of devoiced /u/ in Tokyo Japanese. *Journal of Phonetics*, *66*, 100–119.

Shibata, S. (1968). A study of dynamic palatography. *Annual Bulletin of Research Instititute of Logopedics and Phoniatrics (RILP)*, *2*, 28–36.

Shue, Y.-L., Keating, P., Vicenik, C., & Yu, K. (2011). VoiceSauce: A program for voice analysis. *Proceedings of the ICPhS XVII*, 1846—1849.

Sievers, E. (1876). *Grundzüge der lautphysiologie zur einlührung in das studium der lautlehre der indogermanischen sprachen* (Vol. 1). Breitkopf und Härtel.

Sievers, E. (1901). *Grundzüge der phonetik zur einführung in das studium der lautlehre der indogermanischen sprachen* (Vol. 1). Georg Olms Verlag.

Smith, C. (2014). Complex tongue shaping in lateral liquid production without constriction-based goals. *Proceedings of the International Seminar on Speech Production*, 413–416.

Smith, C. L. (1992). *The temporal organization of vowels and consonants* (Unpublished doctoral dissertation). Yale University.

Smith, C. L. (1993). Prosodic patterns in the coordination of vowel and consonant gestures. In C. A. Fowler (Ed.), *Haskings laboratories status report on speech research* (pp. 45–56). Haskins Laboratories.

Smith, C. L. (1995). Prosodic patterns in the coordination of vowel and consonant gestures. In B. Connell & A. Arvaniti (Eds.), *Papers in laboratory phonology IV: Phonology and phonetic evidence* (pp. 205–222). Cambridge: Cambridge

University Press.

Smith, J. L. (2018). Stratified faithfulness in harmonic grammar and emergent core-periphery structure. In *Hana-bana: A Festschrift for Junko Itô and Armin Mester*. Santa Cruz, California.

Sproat, R., & Fujimura, O. (1993). Allophonic variation in English /l/ and its implications for phonetic implementation. *Journal of Phonetics*, *21*(3), 291–311.

Stetson, R. (1951). *Motor phonetics.* North Holland Pui,. Co., Amsterdam.

Stone, M. (2005). A guide to analysing tongue motion from ultrasound images. *Clinical linguistics & phonetics*, *19*(6-7), 455–501.

Sudo, M., Kiritani, S., & Yoshioka, H. (1982). An electro-palatographic study of Japanese intervocalic /r/. *Annual Bulletin of Research Instititute of Logopedics and Phoniatrics (RILP)*(16), 21–25.

Sugito, M. (1985). Za, da, ra gyōon no seiriteki tokuchō [Physiological features of the sounds za, da, and ra lines]. *Osaka Shoin Women's University Repository*.

Takada, S. (1985). Sokuon no chōonjō no tokuchō ni tsuite [On some articulatory charactersitsics of the mora obstruent (sokuon)]. *NINJAL Occasional Papers*, *6*, 17–40.

Tanaka, S. (2007). Itariago no jūshiin to sokuon keisei [Geminate consonants in Italian and *sokuon* in Japanese]. *Proceedings of the 134th Meeting of the Linguistic Society of Japan*, 252-257.

Tiede, M. (2005). Mview: software for visualization and analysis of concurrently recorded movement data. *New Haven, CT: Haskins Laboratories*.

Tsujimura, N. (2014). *An introduction to Japanese linguistics* (3rd ed.). John Wiley & Sons.

Tsuzuki, M., & Lee, H.-B. (1992). A phonetic study of the Korean and Japanese lateral, flap and nasal. *Proceedings of the 1992 Seoul International Conference* *on Linguistics*, 761–780.

Vance, T. J. (2008). *The Sounds of Japanese with Audio CD*. Cambridge University Press.

Walsh Dickey, L. (1997). *The phonology of liquids* (Unpublished doctoral dissertation). University of Massachusetts, Amherst.

Westbury, J. R., Hashi, M., & Lindstrom, M. J. (1998). Differences among speakers in lingual articulation for American English /r/. *Speech Communication*, *26*(3), 203–226.

Yamane, N., Howson, P., & Wei, P.-C. G. (2015). An ultrasound examination of taps in Japanese. *Proceedings of ICPhS XVIII*, 1–4.

Ying, J., Carignan, C., Shaw, J. A., Proctor, M. I., Derrick, D., & Best, C. T. (2017). Temporal dynamics of lateral channel formation in /l/: 3D EMA data from Australian English. In *Interspeech* (pp. 2978–2982).

Ying, J., Shaw, J., Kroos, C., & Best, C. T. (2012). Relations between acoustic and articulatory measurements of /l/. *Proceedings of the 14th Australasian International Conference on Speech Science and Technology*.

Zeroual, C., Hoole, P., Gafos, A. I., & Esling, J. H. (2015). Gestural coordination differences between intervocalic simple and geminate plosives in Moroccan Arabic: An EMA investigation. *Proceedings of ICPhS XVIII*.

Zwicky, A. M., & Pullum, G. K. (1987). Plain morphology and expressive morphology. *Annual Meeting of the Berkeley Linguistics Society*, *13*, 330–340.