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The Effect of Jaw Position on Perceptual and Acoustic Characteristics of Speech

Nancy Pearl Solomon, Ph.D., CCC-SLP, Matthew J. Makashay, Ph.D., and Benjamin Munson, Ph.D.

Nancy Pearl Solomon, 4954 North Palmer Road, National Military Audiology & Speech Pathology Center, Walter Reed National Military Medical Center, Bethesda, MD 20889;
Contributor Information.

Abstract

Bite blocks are used to stabilize the jaw and to isolate tongue and lip movements from that of the mandible during speech and nonspeech activities. Ten normally speaking young adults produced sentences with an unconstrained jaw and with unilateral placement of 2-mm and 5-mm bite blocks. Six listeners rated sentences spoken without either bite block as the most natural sounding. Spectral characteristics of /s/, /ʃ/ and /t/ (sibilant frication and stop bursts) differed significantly with than without bite blocks, such that mean spectral energy decreased, and variation and skew of spectral energy increased. Spectral kurtosis did not change for the group, but 2 participants exhibited highly kurtotic /s/ spectra without a bite block that normalized with bite blocks. The second formant frequency for the high vowel /i/ was lower with bite blocks; there was no systematic difference in F2 slope for diphthongs. Segmental and suprasegmental timing of speech articulation was not affected significantly by these small bite blocks. This study provides support for using small bite blocks to isolate the tongue from the jaw without large effects on speech, but cautions that speech is likely to sound less natural than when produced with an unconstrained jaw.

Keywords: speech, jaw stabilization, bite block, acoustic analysis, perceptual analysis

INTRODUCTION

Constraining jaw movements during speech has been attempted for a variety of clinical and research purposes. Therapeutically, jaw stabilization is considered facilitative for training differentiated or coordinated lingual movements for speech in children with speech sound disorders (SSD) or apraxia of speech (AOS). Jaw movements are more stable and become more adult-like earlier than lip movements in young children (Green, Moore, & Reilly, 2002). Children with SSD may produce undifferentiated coronal consonants particularly if they exhibit the phonological process of fronting. This lack of differentiation is generally considered to be a consequence of an immature pattern of moving the jaw and tongue as a unit (Edwards, 1992; Gibbon, 1999; Goozée, Murdoch, Ozanne, Cheng, Hill, & Gibbon, 2007; McAllister Byun, 2012). Children with AOS demonstrate more difficulty generating stable and coordinated movement patterns of the articulators than children with SSD or typically developing children (Moss & Grigas, 2012; Nijland, Maassen, & van der Meulen, 2003; Terband, Maassen, van Leishout, & Nijland, 2011). Therapies designed to facilitate independent actions of the tongue use a jaw-constraint approach, usually involving biting down on a tongue depressor or bite block (Marshalla, 2007). Although stabilizing the jaw with a bite block is meant to be a mechanical solution, it results in masseter muscle activation as well (Folkins & Zimmerman, 1981; Solomon & Munson, 2004). Techniques intended to stiffen the temporomandibular joint by eliciting masseteric stretch reflexes have also been used in an attempt to stabilize the jaw (Marshalla, 2007).

The use of bite blocks has been studied in adults with speech disorders as well. Bite blocks are considered to have an inhibitory influence on the spasms associated with oromandibular dystonia (Dworkin, 1996; Netsell, 1985). They have also been used as a way to either constrain jaw movement or to perturb the speech-motor system in non-therapeutic investigational studies of adults with a variety of communication disorders, including AOS (McNeil, Weismer, Adams, & Mulligan, 1990; Robin, Bean, & Folkins, 1989), dysarthria (McNeil et al., 1990; Mefford & Bissmeyer, 2016), and stuttering (Namasivayam, van Lieshout, & De Nil, 2008). These studies sought to differentiate the role of the jaw from the lips and tongue to test adaptability in the speech-motor system.

The effects of bite blocks on the normal production of vowels, consonants, and temporal aspects of speech have been investigated to deepen our understanding of speech motor control and speech motor planning (Baum, McFarland, & Diab, 1996; Flege, Fletcher, & Homiedan, 1988; Folkins, Linville, Garrett, & Brown, 1988; Gay, Lindblom, & Lubker, 1981; McFarland & Baum, 1996; Warren, Nelson, & Allen 1980). Blocks ranging in height from 2.5 mm to 22.5 mm have been used to perturb the system, and intermediate sizes (5–15 mm) have been used to stabilize the jaw for the purpose of isolating tongue and lip movements during speech tasks.

Changes in speech with a bite-block perturbation vary in terms of the degree and timing of adaptation. Some studies reported complete, instantaneous compensation (Gay et al., 1981; Kelso & Tuller, 1983), whereas other studies have revealed incomplete or delayed compensation (Flege et al., 1988; McFarland & Baum, 1995). Differences may be attributable in part to tasks, bite-block sizes, and outcome measures. For example, as jaw displacement increases, acoustic parameters such as vowel formants and spectral characteristics of consonants change predictably (Flege et al., 1988; Lindblom & Sundberg, 1971; McFarland & Baum, 1995).

Previously, we studied the use of bite blocks on nonspeech assessment of tongue function to determine the effects of isolating the tongue by stabilizing the jaw (Solomon & Munson, 2004). Results revealed that tongue strength and endurance were greatest when no bite block was used. In addition, tongue strength results did not differ significantly when measured with a very small (2 mm) or no bite block. Larger bite blocks (5, 10, and 15 mm) resulted in lower measures of tongue strength. For subsequent studies designed to examine nonspeech and speech functions of the tongue, we aimed to identify a bite block that would stabilize the jaw with as little disruption in natural speech production as possible.

The research program for which bite blocks were needed addressed the effects of tongue fatigue on speech (Solomon, 2006). For an earlier study along this line of research, normally speaking young adults exercised their tongues to the point of fatigue (Solomon, 2000). Speech invariably deteriorated, as judged perceptually by several groups of listeners. Acoustically, spectral and temporal characteristics of speech were evaluated. Consonantal acoustic energy was assessed via spectral moments. These are calculated by treating the power spectrum as a probability distribution, and calculating the statistical properties of that distribution. Spectral moments have been shown to differentiate places of articulation for stop consonants (Forrest, Weismer, Milenkovic, & Dougall, 1988) and fricatives (Jongman, Wayland, & Wong, 2000). After fatiguing the normal adult tongue, the first moment (mean) increased and the third moment (skew) decreased for /t/, /s/, and /ʃ/ in sentences; temporal characteristics of the phones did not change significantly. The spectral results indicated that consonants were produced with greater and more anterior constriction after the fatiguing exercises, contrary to our hypothesis. An interesting and unexpected observation was that high vowels and diphthongs changed (reduced F2 mean and F2 transitions) after the fatiguing tongue exercises.

The purpose of the present study was to identify which of two small bite blocks would have a lesser effect on speech, evaluated perceptually and acoustically. The eventual goal was to design a bite block that would isolate tongue function for exercise and speech without having deleterious effects on speech. The specific speech stimuli used were deemed to be sensitive to changes in speech after fatiguing the tongue according to our previous research (Solomon, 2000). Subsequently, the results of this methodologic research led to the use of an intermediate-sized bite block for a study on speech after fatiguing the tongue in adults who had dysarthria associated with Parkinson's disease (Makashay, Cannard, & Solomon, 2015).

METHOD

Participants

Ten neurologically normal speakers of American English, 8 women and 2 men, ages 20 through 38 years (*M* = 26), participated in this study. They were the same participants as in our previous study on nonspeech tongue function (Solomon & Munson, 2004). They reported normal histories of speech and language, had normal dentition and no dental appliances, and passed a hearing screening. Each provided written consent to participate in this study which was approved by the Institutional Review Board for Human Subjects Research at the University of Minnesota.

Instrumentation

Bite blocks were custom made from dental putty for each speaker, as described previously (Solomon & Munson, 2004) (Figure 1). For this study, participants used two bite blocks, designed to allow jaw separation of approximately 2 mm and 5 mm. The bite block was placed unilaterally between the lateral teeth (premolars and/or molars).

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Figure 1

Custom-made 5-mm bite block.

Speech was recorded in a quiet laboratory using a studio-quality digital workstation (Roland VS-890) at a sampling rate of 44.1 kHz, with 16-bit quantization and an anti-aliasing filter (cutoff frequency = 22.05 kHz). Participants wore a head-mounted condenser microphone (AKG-C420, Rolls phantom power source) placed 5 cm from their lips. For further analysis, the data were downloaded from the Roland VS-890 to a personal computer at 22 kHz with antialias filtering at 11 kHz. Multimedia signal-processing software (Praat v. 4.0.7, Boersma, 2001) was used to segment and randomly play the speech samples for the perceptual study, and to derive spectral and temporal measures for the acoustic analyses.

Speech Stimuli

Participants said three sentences containing five instances each of /t/, /s/, and /ʃ/, and three tokens of /i/ (referred to as "consonant sentences"), and two sentences with three tokens each of /aɪ/ and /ɔɪ/ ("diphthong sentences") (Table1). Participants were instructed to read using their typical speech, voice, and rate, with each sentence on a single, typical breath. Three sets of the sentences were produced in counterbalanced order in three bite block conditions: none, 2 mm, and 5 mm. To allow for accommodation to the bite blocks, the third set of sentences was used for perceptual and acoustic analyses. Of the 50 sentences (5 sentences × 10 participants), 12 were replaced by sentences from the second repetition because of recording errors.

Table 1

Sentence stimuli grouped according to loading with coronal consonants (and /i/) and with diphthongs. Consonantal targets are bolded; vocalic targets are underlined.

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Perceptual Study

Participants Six graduate students or post-doctoral researchers in communication disorders served as listeners. They ranged in age from 22 to 32 years ($M = 27$) and reported a normal recent audiometric evaluation or passed a hearing screening at 25 dB at 0.5, 1, 2, and 4 kHz.

Procedure Sentences were paired by bite-block condition (none vs. 2 mm, none vs. 5 mm, and 2 mm vs. 5 mm). This generated 150 unique sentence pairs (10 participants × 5 sentences × 3 comparisons). Participants listened over headphones at a comfortable loudness level, and selected the sentence in each pair that sounded more natural. They also had the option of judging the two sentences as equally natural sounding.

Analysis Individual and pooled naturalness judgments were fit to the Bradley-Terry-Luce (BTL) model. This model is designed for multiple comparisons of paired data (Agresti, 1990). Chi-square tests of goodness of fit for the binomial regression model were not significant $\chi^2(1) = 0.181$, $p = .671$, for pooled data], indicating that the data fit the BTL model.

Acoustic Analyses

Segmental durations Segmental durations of the target phones were determined using methods described previously (Solomon, 2000). Briefly, the stop-plosive consonant /t/ was measured for stop-closure duration (SCD) and voice-onset time (VOT). SCD is the duration between the reduction in signal amplitude or complexity for the preceding vowel (indicating lingual-alveolar contact) and the /t/ burst, and VOT is the duration between the burst onset and voicing onset of the subsequent vowel. Duration of the fricatives /s/ and /ʃ/ was measured from onset to offset of high frequency noise.

Spectral moments The five target tokens of /t/, /s/, and /ʃ/ were segmented from the consonant sentences in each bite-block condition. Praat acoustic-analysis software (Boersma, 2001) was used to pre-emphasize the acoustic signal and calculate the first four linear moments of the spectrum (M1: mean; M2: standard deviation; M3: skewness; M4: kurtosis).

For /t/, a 20-ms Hamming window was centered at 10 ms after the burst onset. For the fricatives, a 30-ms Hamming window was centered at 45 ms after the onset of frication. For statistical analyses, each moment was transformed according to its power (none for M 1, square root for M2, cubed root for M3, fourth root for M4). Four repeated-measures ANOVAs were conducted, one for each moment coefficient ($\alpha = .0125$). Within-subjects factors were phone and bite-block condition.

Formant frequencies and transitions Formant analysis determined the mean frequencies of F1 and F2 at the midpoint of /i/, and the F1 and F2 frequency slopes for the diphthongs /aɪ/ and /ɔɪ/. Formant values were extracted using Praat, following the 20 Hz/20 ms guideline (Weismer, Martin, Kent, & Kent,

1992) on F1 transitions that were continuously falling and F2 transitions that were continuously rising for the diphthongs.

Speech rate Sentences were analyzed for speech rate (or articulation rate) by dividing the number of syllables produced by the duration of the sentence in seconds. Each sentence was demarcated from the onset of the first phone (including prevoicing if applicable) to the offset of the last phone. No sentence productions contained pauses.

Measurement Reliability

Ten percent of the data were re-measured by the same experimenter (MJM) and by an experienced independent experimenter (NPS). One sentence was selected from each subject, counterbalanced for sentence and bite-block condition. Absolute intrarater differences for segmental durations averaged 3.14, 4.28, 1. 71, and 1.83 ms and interrater differences averaged 6.82, 9.06, 1.79, and 1.57 ms for /s/, /ʃ/, /t/ SCD and /t/ VOT, respectively. Intrarater and interrater differences were <10 ms for 97.0% and 85.8% of all tokens, respectively. For speech rate, average intrarater and interrater differences were 0.01 and 0.03 syllables/s, and intrarater and interrater agreement were < 0.05 syllables/s for 100% and 79% of the sentences, respectively.

RESULTS

Perceptual Study

Listeners rated sentences produced without a bite block as more natural sounding than those produced with a bite block. BTL modeling produced normalized propensities of .79, .13, and .08 for the none, 2-mm, and 5-mm bite-block conditions, respectively. These results indicate that there is an 86% probability that listeners would prefer a no-bite-block speech sample over one produced with a 2-mm bite block, 91% probability for none over a 5-mm block, and 64% probability for a 2-mm over 5-mm block in terms of naturalness.

Separate BTL models for sentences loaded with consonants vs. diphthongs revealed that naturalness ratings for the former were more negatively affected by bite blocks than the latter. Figure 2 illustrates the normalized propensities for each group of sentences. When converted into probabilities, listeners were 94% more likely to prefer no bite block over a 2-mm bite-block sample for consonant sentences but only 73% for diphthong sentences. Listeners have a 97% probability to prefer no bite block over a 5-mm bite-block sample for consonant sentences and 78% for diphthongs. Finally, listeners were 69% more likely to prefer 2-mm over 5-mm bite-block speech for consonant sentences and 57% for diphthong sentences.

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Figure 2

Propensities for normal listeners to rate sentences as more natural when presented in pairs. Left chart includes sentences loaded with coronal consonants and the high vowel /i/; Right chart includes sentences loaded with diphthongs. White = no bite block; Gray = 2-mm bite block; Black = 5-mm bite block.

Acoustic Analyses

Segmental durations There was no statistically significant effect of bite block on segmental durations in sentences [$F(2,18) = 0.539$, $p = .592$]. This was true for fricative duration [$F(2,18) = 0.383$, $p = .687$] as well as for stop closure and release [$F(2,18) = 3.015$, $p = .074$].

Spectral moments Figure 3 plots results for the four spectral moments according to bite-block condition and target phone. M1 decreased significantly from none to either bite block [$F(2,18) = 14.081$, $p < .001$]. Post-hoc analysis (Tukey pair-wise comparisons) revealed that M1 decreased for all consonants with the 2-mm bite block, and M1 decreased significantly for /s/ and /t/ with the 5-mm bite block. M2 increased significantly from none to either bite block [$F(2,18) = 21.042$, $p < .001$]; post-hoc testing revealed significant differences for /s/. M3 increased significantly with bite blocks [$F(2,18) = 8.623$, $p = .002$] for /s/ according to post-hoc testing. There was no significant difference across bite blocks for M4 [$F(2,18) = 2.585$, $p = .103$].

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Figure 3

Spectral moments for /s/ (black square), /ʃ/ (gray diamond), and /t/ (white triangle) in each bite-block condition. M1 = spectral mean; M2 = standard deviation; M3 = skewness; M4 = kurtosis. Error bars = SD.

Formant frequencies and transitions For the vowel /i/, F1 did not change significantly [$F(2,18) = 0.853$, $p = .442$]. F2 for /i/ lowered significantly from the no-bite-block condition to either bite block [$F(2,18) = 6.439$, $p = .008$] (Figure 4). For the diphthongs, average F2 slopes did not change significantly with bite-block condition for /aɪ/ [$F(2,18) = 1.009$, $p = .384$] or /ɔɪ/ [$F(2,18) = 0.565$, $p = .578$].

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Figure 4

Average frequency of the second formant (F2) for /i/ in each bite-block condition. Error bars = SD.

Speech rate There was no statistically significant difference in speech rate according to bite block [$F(2,18) = 0.310$, $p = .737$] or sentence type [$F(1,9) = 1.171$, $p = .307$].

DISCUSSION

This study aimed to confirm that a specific set of speech stimuli designed for a study on the effects of tongue exercises on dysarthric speech (Makashay et al., 2015) would be relatively unaffected by a small bite block. The use of a bite block was intended to exercise the tongue to the point of fatigue without a jaw assist, while simulating typical maxillary-mandibular distances during speech. The speech stimuli were modified slightly from an earlier study (Solomon, 2000) to include more repetitions of the high vowel /i/ and the diphthongs /aɪ/ and /ɔɪ/ because they appeared to be particularly susceptible to the effects of tongue fatigue.

The present study, based on 10 normally speaking young adults, revealed few statistically significant effects of 2-mm and 5-mm bite blocks on speech acoustics. These differences included decreased spectral means for the fricative noise in /s/ and /ʃ/ and burst noise in /t/ as well as increased spectral standard deviation and skew for /s/ with bite blocks. The decrease in M1 as bite-block size increased was expected because a lower M1 is associated with a larger sublingual cavity anterior to the consonant's noise source. F2 decreased with bite blocks for /i/ but formant slopes did not differ systematically for the diphthongs /aɪ/ and /ɔɪ/. Segmental and suprasegmental timing were not significantly affected by the bite blocks. These few differences assured us that a small bite block could be used in future studies that aimed to isolate tongue from jaw movements. Ultimately, we used a 3–4 mm bite block to stabilize the jaw in our tongue-exercise and disordered-speech study (Makashay et al., 2015). As we noted in the discussion of that paper, however, the bite block actually appeared to contribute to the participants' overall muscular fatigue because of the engagement of the jaw-closing muscles to hold the bite block. Furthermore, although the bite block prevented participants from approximating their teeth, it did not prevent them from opening the mouth wider. This unintended freedom of movement may have contributed to a between-group difference reported by Makashay et al. that neurologically normal talkers demonstrated larger F2 slopes for diphthong productions than did participants with Parkinson's disease.

Paired comparisons of perceived speech naturalness with and without bite blocks in the present study revealed that normal listeners preferred speech produced without a bite block, particularly when the sentences were replete with coronal consonants and the high vowel /i/ rather than diphthongs. Similarly, Baum et al. (1996) reported that small bite blocks (2.5 mm for vowels, 5 mm for consonants) had no effect on perceptual ratings of quality for vowels and stop consonants but had a significant impact on the fricatives /s/ and /ʃ/ produced in CV syllables. These results were consistent with their acoustic analyses as well (McFarland & Baum, 1995).

Individual differences provide interesting insight into these results. Specifically, the consonants differed significantly with than without bite blocks for M1–M3, but not for M4, apparently because of greater variability in the data. By examining the individual data illustrated in Figure 5, one can ascertain that two participants produced /s/ with a very strong high frequency peak, resulting in extremely high kurtosis values, with an unconstrained jaw. Perceptually, these /s/ productions sounded whistle-like, a feature that dissipated when they used bite blocks. Figure 6 displays the spectra for /s/ produced in each jaw position by the most extreme example of this phenomenon; note the flattening of the high-frequency portion of the spectra as the participant talks without a bite block and with 2-mm and 5-mm bite blocks. This may have implications for speech-sound therapy such that certain talkers might benefit from positioning the mandible to improve natural-sounding sibilants.

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Figure 5

Individual results for spectral kurtosis (M4) for /s/ in each bite-block condition.

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Figure 6

Sound spectra for /s/ produced with no bite block (top) and with 2-mm (middle) and 5-mm (bottom) bite blocks by the participant labeled with black circles in Figure 4.

Jaw position is well known to affect vowel height and also plays a role in the manner of consonantal articulation (Mooshammer, Hoole, & Geumann, 2007). Thus, for the most natural speech production, speech should obviously be produced with an unconstrained jaw. For clinical situations in which differentiation of tongue and lip movement is temporarily desired, jaw stabilization may be facilitative. However, this study was not intended to address this issue. Rather, it was designed to rule out substantial effects of fixing jaw position on speech. Although it was successful in that goal, our subsequent study had the unanticipated effect of eliciting jaw fatigue by biting on the block for an extended period of time (Makashay et al., 2015). Therefore, the use of a bite block beyond a reasonable period of time may be contraindicated.

CONCLUSION

In conclusion, this study demonstrated that speech sounds more natural when produced with an unconstrained jaw rather than with small bite blocks, but that the few acoustic consequences of using a small bite block on coronal consonants, a high vowel and diphthongs are relatively inconsequential and primarily affected the fricative /s/. The specific differences for /s/ were quite predictable given the articulatory consequences of the bite-block perturbation. There were notable individual differences in normal adults' productions of /s/ that appear to normalize when speaking with a small bite block. In the case of children or adults with SSD or AOS, individual consideration of adaptations to a bite-block perturbation may be instructive when designing therapeutic approaches. Future studies involving bite blocks and speech are needed to demonstrate validity and efficacy of using bite blocks to stabilize the jaw or isolate tongue and lip movements.

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Footnotes

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Contributor Information

Nancy Pearl Solomon, 4954 North Palmer Road, National Military Audiology & Speech Pathology Center, Walter Reed National Military Medical Center, Bethesda, MD 20889.

Matthew J. Makashay, National Military Audiology & Speech Pathology Center, Walter Reed National Military Medical Center, Bethesda, MD.

Benjamin Munson, Speech-Language-Hearing Sciences, University of Minnesota, Minneapolis.

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