# Influences of pellet markers on speech production behavior: Acoustical and perceptual measures

Gary Weismer and Kate Bunton
*Department of Communicative Disorders, Waisman Center, 1500 Highland Avenue, University of Wisconsin-Madison, Madison, Wisconsin 53705-2280*

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Peri- and intraoral devices are often used to obtain measurements concerning articulator motions and placements. Surprisingly, there are few formal evaluations of the potential influence of these devices on speech production behavior. In particular, the potential effects of lingual pellets or coils used in x-ray or electromagnetic studies of tongue motion have never been evaluated formally, even though a large x-ray database exists and electromagnetic systems are commercially available. The x-ray microbeam database [Westbury, J. ''X-ray Microbeam Speech Production Database User's Handbook, version 1'' (1994)] includes several utterances produced with pellets-off and -on, which allowed us to evaluate effects of pellets for the utterance, *She had your dark suit in greasy wash water all year*, using acoustic and perceptual measures. Overall, there were no acoustic or perceptual measures that showed consistent effects of pellets across speakers, but certain effects were consistent either within a given speaker or in direction across a subgroup of the speakers. The results are discussed in terms of the general goodness of the assumption that point parameterization of lingual motion does not interfere with normal articulatory behaviors. A brief screening procedure is suggested to protect articulatory kinematic experiments from those individuals who may show consistent effects of having devices placed on perioral structures. © *1999 Acoustical Society of America.* [S0001-4966(99)04005-9]

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## INTRODUCTION

Research on speech production has always relied on perioral or intraoral devices to provide information on the movements of articulators, forces exerted by articulatory structures, or to record patterns of contact between mobile articulatory structures and fixed vocal tract boundaries. Similarly, intraoral devices have been used to measure air pressures within the vocal tract, and in the case of bite blocks and transient loads to alter the normal setting and/or movement of vocal tract structures to determine effects on articulatory behavior and vocal tract acoustic output.

It is axiomatic in scientific activity that the process of observation may change the phenomenon being observed (e.g., Reichenbach, 1973), thereby requiring some understanding of the interaction between the presence of instruments and the measures being taken. It is therefore somewhat surprising to find little formal assessment of the potential effects of perioral and intraoral devices on speech production behavior. An exception to this has been the several attempts to determine the influence of pseudopalates on speech production behavior. For example, Hamlet and Stone (1976, 1978; Hamlet, 1985) showed that several temporal aspects of speech production change gradually from the time speakers first insert a pseudopalate for chronic adaptation to a point in time some two weeks later. Reports of chronic effects on articulatory timing of sibilants due to dental prostheses can be found in the literature (Hamlet *et al.*, 1979; Ichikawa *et al.*, 1995). Some of the articulatory changes induced by the presence of a pseudopalate are fairly easy to demonstrate via acoustic and perceptual analyses (see McFarland *et al.*, 1996). The demonstrated influence of the pseudopalates on articulatory behavior makes it difficult to evaluate the generalizability of findings from electropalatographic studies of speech production phenomena such as coarticulation and assimilative processes (e.g., Butcher, 1989; Recasens *et al.*, 1993; Wright and Kerswill, 1989) when the studies contain no formal assessment of the effect of the device on the measurements of interest.

Bite blocks constitute a somewhat different interaction between the intraoral modification and the observables, because in many such studies the intraoral modification is *meant* to change aspects of articulatory behavior. The classic bite block study produces a demonstration of nearly identical vowel formant frequencies for unblocked and blocked conditions (Gay *et al.*, 1981). This demonstration has been taken to show the capacity of the speech motor control system to compute and produce the correct area function for an intended vowel, even in the face of different vocal tract postures. However, not all studies have demonstrated this immediate compensation of the vocal tract area function to the presence of a bite block (e.g., McFarland and Baum, 1995), indicating another example of interference with normal articulatory behavior by an intraoral device (see also Baum and McFarland, 1997; Savariaux *et al.*, 1995). In the few studies wherein measures such as segment durations and formant transition characteristics (e.g., frequency range and duration) are compared across normal and bite-block conditions, there is evidence of a bite-block effect (Smith, 1987; Mulligan, 1986). Flege *et al.* (1988), in a palatography study, also showed effects of a bite block on obstruent and vocalic spectra. This study is interesting because the demonstrated acoustic effects were not necessarily associated with perceptual effects (see Sec. III).

Transient loads applied during speech to the lips and jaw have been used to study various aspects of articulatory coordination (Abbs and Gracco, 1984; Folkins and Abbs, 1985; Gracco and Abbs, 1988; Kelso *et al.*, 1984; Shaiman, 1989; Munhall *et al.*, 1994), but only Munhall *et al.* (1994) have examined the effect of these loads on selected aspects of speech timing; loads applied to the lower lip had a clear effect on stop closure durations and voice-onset times, but no formal perceptual measures were obtained. In other studies, the evaluation of a load's effect on vocal tract output, which is fairly critical for the interpretation of the articulatory response in terms of automatic neural pathways serving the articulatory mechanism (i.e., as compared to an interpretation of conscious compensatory adjustments to the transient load), is typically by experimenter's report: ''. . . despite some sizable movement perturbations... the intended speech motor objective was not disrupted in a discernible way (i.e., a listener could not distinguish acoustic speech patterns for loaded trials from those produced during normal, unloaded trials)'' (Abbs *et al.*, 1984, p. 204). The lesson from the available studies on pseudopalates and bite blocks would seem to suggest that formal evaluation of the effect of transient loads on vocal tract output and/or the perception of that output should be undertaken before using the technique as a window to normal articulatory processes.

One approach to speech production research that requires this kind of evaluation is the point parameterization of articulatory movement. A review of the literature suggests that, of the many studies in which pellets or electromagnetic transducers have been placed on the articulators, and especially the tongue (e.g., Kent, 1972; Kent and Moll, 1972; Perkell and Nelson, 1985; Perkell and Cohen, 1989; and see review in Perkell, 1997), none has included a formal comparison of speech production behavior with and without the intraoral devices in place. There are, however, indirect data that suggest little impact of tongue pellets on the formant frequencies of vowels. Perkell and Nelson (1985) reported vowel formant frequencies for two speakers from the Tokyo x-ray microbeam data set that are quite consistent with values reported in studies wherein speech acoustic recordings were made in the absence of any intraoral device (e.g., Peterson and Barney, 1952; Hillenbrand *et al.*, 1995). Obviously it would be useful to have such acoustic comparisons between intraoral device *versus* no intraoral device for the same speakers, producing utterances common to both conditions. Moreover, a logical hypothesis is that the articulation of sounds such as fricatives may be more susceptible than vowels to the presence of intraoral devices such as pellets or coils; there are no data in the literature, even of the indirect kind, bearing on this issue.

The purpose of the present study was to obtain formal comparisons of vocal tract output and listener judgments for utterances produced with and without pellets attached to the tongue and other articulators. This kind of comparison is important for several reasons. First, the extensive x-ray microbeam database collected at the University of Wisconsin-Madison (Westbury, 1994) will be subject to analyses for the next several years, making it necessary to interpret findings relative to possible disruptions of typical articulatory processes by the presence of pellets on articulatory structures. Second, point-parameterized observations of articulatory (and especially the tongue) motion are becoming accessible to a large pool of scientists with the advent of commercially available, relatively inexpensive (compared to the x-ray microbeam) electromagnetic tracking systems (e.g., see Tuller and Kelso, 1990). The constraints, if any, on interpretation of such point-parameterized data introduced by the process of observation should be carefully documented.

The speech sample protocol for the x-ray microbeam database project (Westbury, 1994) includes a series of utterances recorded under conditions identical to those in the main experiment, except without the pellets in place. This series of utterances, which was recorded prior to the attachment of the pellets and collection of x-ray microbeam data, represent a subset of the utterances forming the kinematic database. This allowed for a direct comparison, at the acoustic and perceptual levels of analysis, of speech production behavior with and without the pellets in place.

## I. METHOD

### A. Subjects

Acoustic data used in the present study were collected as part of the x-ray microbeam database project at the University of Wisconsin-Madison. The data base consists of 57 subjects who produced a common speech sample. Subjects passed a pure tone hearing screening and had no self-reported history of neuromotor or articulation disorders. Most subjects spoke an Upper Midwest dialect of American English. In the present report, analysis was completed for 21 subjects (11 males, 10 females). No special criteria were used to select these subjects from the total of 57, other than attaining gender balance. Age range for the subjects was 18.33 to 36.02 years (mean 22.56 years).

### B. Speech sample and pellet array

A sample of 19 tasks from the full task inventory, recorded prior to pellet placement but under identical conditions (e.g., with the subject seated in the experimental chair and with speech samples presented in exactly the same way as in the main experiment) was obtained for comparative purposes and to familiarize subjects with the tasks and experimental conditions. The subset included isolated vowels, single words, and several sentences. For the present study the sentence *She had your dark suit in greasy wash water all year* was analyzed. The sentence was useful because it contained a variety of segment types, including one exemplar each of the four corner vowels /i/ (in *she*), /æ/ (in *had*), /u/ (in *suit*), and /ɑ/ (in *wash*). This allowed a direct comparison across conditions (pellets-on vs pellets-off) of the acoustic (and by inference, articulatory) working space for vowels. The sentence was produced three times by each subject prior to pellet placement and five times during the full task inventory with the pellets in place. The five repetitions of theutterances with pellets-on were distributed throughout the entire x-ray microbeam protocol; the sequence of the entire protocol, and hence the repetitions of interest, was the same for all speakers.

The typical array for the collection of kinematic data included a total of 11 pellets, 4 of which were on the tongue, 2 on the mandible, 2 on the lips, 2 on the nose, and 1 on the buccal surface of the maxillary incisors. The four lingual pellets, the effects of which are of primary interest here, were glued to the tongue such that the most anterior pellet was placed approximately 10 millimeters (mm) posterior to the lingual apex, and the most posterior pellet approximately 60 mm from the lingual apex. The middle two pellets were then placed at approximately equal intervals between the most anterior and posterior pellets, creating three inter-pellet distances of roughly equal length from front to back (additional details can be found in Westbury, 1994).

### C. Data collection

The sound pressure wave was recorded with a directional microphone (SHURE SM81 Condenser) placed at mouth level. The microphone signal was fed into a 15-bit-resolution A/D converter programmed to sample at 21 739 times per second and to store the resulting digital stream synchronously with pellet position histories on SMD computer disks. Prior to digital conversion, an anti-aliasing filter (−3 dB at 7500) was applied to the microphone signal. For two subjects (JW7 and JW8) recorded early in database collection, recordings were made at 16 129 samples/s. Further details regarding recording procedures can be found in Westbury (1994).

### D. Acoustic measures

The acoustic variables were chosen to sample a range of measures used extensively in the literature (e.g., segment durations and vowel formant frequencies), and to reflect articulatory behaviors that may on logical analysis be likely candidates for disruption by the pellets (e.g., formant trajectory measures and spectral moments for fricatives). Acoustic analyses for the present study were completed using Cspeech (Milenkovic, 1994). To measure segment duration a combined digital spectrogram/waveform display was used. Most segment durations were measured according to conventional criteria in the literature (Umeda, 1975, 1977; Crystal and House, 1988a, b, c), but in some cases several phonetic segments were combined as a single measured interval because of the absence of reliable boundaries. Examples of the latter include /yɔr/ (in *your*), /ri/ (in *greasy*), and /ɔlyir/ (in *all year*).

LPC formant analysis was used to generate $F1$-$F2$-$F3$ data for each of the corner vowels noted above. The automatic formant tracking option in CSpeech yielded formant trajectories that were superimposed on the digital spectrogram. Formant tracks were individually inspected and manually corrected for tracking errors. These tracks were generated from data files containing frequency values sampled at 5-ms intervals. $F1$-$F2$-$F3$ frequency values at the temporal midpoint of each vowel were recorded from these output files, and served as the vowel target values.

Consonant spectra for the /ʃ/ in *she* and *wash* and the /s/ in *suit* and *greasy* were measured by computing spectral moments (Forrest *et al.*, 1988) from a 50-ms segment taken from the midpoint of each fricative. Moments were computed for consecutive 20-ms windows stepped at 10-ms increments throughout this middle 50-ms interval and then averaged across the analyzed windows. The moments were compared across conditions to evaluate the influence of pellets on fricative production.

### E. Perceptual measures

An audiotape, including 8 repetitions (3 with pellets-off, 5 with pellets-on) of the utterance for each of the 21 subjects, was prepared for perceptual tests. The tape consisted of 167 randomly sequenced repetitions of the utterance with a 6-s pause between each item; one token was omitted from this sequence because the original recording was cut off before the end of the utterance. Ten listeners who had worked with data from the x-ray microbeam project were selected to make a series of judgments about the recorded utterances. It was reasoned that listeners who were familiar with the database would be more sensitive to the potential effects of pellets on articulatory structures because of their familiarity with both the speakers and task materials. Listeners sat individually in a sound proof booth and heard the tape twice at a comfortable listening level. During one presentation the listeners were asked to make the simple, dichotomous judgment about whether the speaker had pellets-on or -off. Instructions for this task were as follows: ‘‘You will hear a series of speakers repeat the sentence, *She had your dark suit in greasy wash water all year*; Please listen carefully and decide if you think the speaker has pellets-on, or pellets-off, then circle the appropriate selection next to the utterance number.’’ During the other presentation, listeners were asked to scale the articulatory precision of each utterance using a free-modulus variation of the method of magnitude estimation. No standard was presented, and the experimenter prescribed no standard scale value; instead listeners were instructed to select the number he or she found appropriate for the first and every subsequent repetition of the utterance. For the present experiment, the listeners were told that ‘‘articulatory precision is defined as the clear articulation of both vowels and consonants: The most precise articulation is that in which the consonants and vowels appear to be ‘perfectly’ articulated, and the least precise articulation is that in which the consonants and vowels are clearly distorted and perceived as ‘sloppy.’ ’’ Listeners were told to assign low numbers to the ‘sloppy’ end of the scale and high numbers to the precise end of the scale. A procedure described by Engen (1971) was used to eliminate inter- and intra-listener variance in the data cause by differing choice of moduli. This procedure provided an exponent of the function with invariant individual slopes as well as an average of the individual intercepts. The order of listening tasks was controlled across subjects to eliminate any biases.

## II. RESULTS

### A. Segment durations

Mean segment durations for the two speaking conditions (pellets-on and pellets-off) are presented in Appendix A for individual speakers. Data averaged across the speakers and repetitions are presented in Fig. 1. Data for the final segment (/ɔlyir/) are not included in the chart for scaling reasons. This figure shows that for 17 of the 24 segments slightly longer

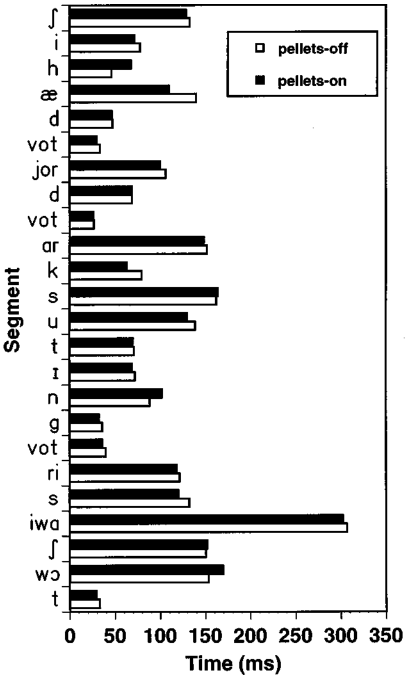

FIG. 1. Group mean segment durations, shown by speaking condition (unfilled bars=pellets-off, filled bars=pellets-on.

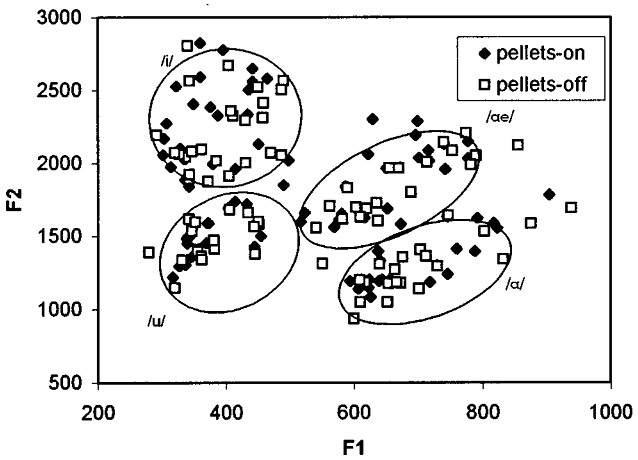

FIG. 2. $F1$-$F2$ plot for pellets-off (unfilled boxes) and pellets-on (filled diamonds). Each plotted point represents a mean for a single subject; sigma ellipses are shown for each vowel category.

durations were produced in the pellets-off condition. Statistically significant differences were found between conditions for several individual segments, most frequently in the /h/ and /æ/ segments in *had* and /ɪ/ and /n/ in the word *in*; these occurred for no more than half the speakers, with the magnitude of the effect ranging between 4 and 57 ms. The segment duration effects for the word *in* were typically in the 20–30 ms range. The direction of these significant effects, however, was not consistent between conditions.

### B. Formant frequencies and trajectories

The average formant frequencies ($F1, F2, F3$) are reported by speaker gender group for each vowel and condition in Table I; average data for individual speakers, vowel, and condition are reported in Appendix B. Between-conditions differences in formant frequencies of 75, 150, and 200 Hz for $F1$, $F2$, and $F3$, respectively, are bolded in Appendix B. These difference values were chosen based on considerations of typical measurement error for formant values (e.g., Lindblom, 1962; Monsen and Engebretson, 1983) and difference limen data for formant frequencies (e.g., Kewley-Port and Watson, 1994). Part of the data from Appendix B is shown in Fig. 2 as an $F1$-$F2$ plot where it can be seen that, taken as a whole, the distributions of coordinates appear to be roughly similar for the pellets-on and pellets-off conditions. Among the male speakers, 1 (JW07) of the 11 speakers had very large formant frequency differences between the conditions. Most of the other differences for the male speakers that met the 150-Hz criterion for $F2$ showed lower values in the pellets-on condition.

Among the female speakers there were six $F1$ comparisons (derived from four of the ten speakers) that met the 75-Hz criterion, and all but one (JW16, /a/) involved a higher $F1$ in the pellets-on condition. Seven $F2$ comparisons (derived from five of the ten speakers) met the 150-Hz criterion for the female speakers, and six of these were consistent with the pattern seen for the males of lower $F2$'s in the pellets-on condition.

There was no obvious pattern for any of these between condition differences to favor a specific vowel, for either gender. Although the direction of the $F2$ effect is very consistent across speakers, the articulatory interpretation is not straightforward. The lowering of $F2$ with pellets-on may suggest a less fronted tongue for /i/ and /æ/ (four effects for males, two for females), but the lowering for /u/ (two effects for males, one for females) is more difficult to interpret. One possibility for /u/ is that the tongue does not move as far back and up in the pellets-on condition as it does with pellets-off, which induces an over compensating lip-rounding gesture (see Perkell *et al.*, 1993). The lip rounding

TABLE I. Mean target formant frequency values for male and female groups across speaking conditions.

| | | /i/ | | | /ae/ | | | /u/ | | | /a/ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pellets | $F1$ | $F2$ | $F3$ | $F1$ | $F2$ | $F3$ | $F1$ | $F2$ | $F3$ | $F1$ | $F2$ | $F3$ |
| Males-mean | off | 339 | 2087 | 2729 | 601 | 1706 | 2482 | 358 | 1476 | 2278 | 647 | 1242 | 2345 |
| SD | off | 41 | 198 | 285 | 70 | 163 | 274 | 49 | 213 | 232 | 61 | 135 | 282 |
| Males-mean | on | 351 | 1991 | 2589 | 585 | 1663 | 2374 | 344 | 1412 | 2205 | 631 | 1168 | 2272 |
| SD | on | 38 | 145 | 162 | 55 | 79 | 143 | 27 | 133 | 92 | 37 | 117 | 174 |
| Females-mean | off | 391 | 2553 | 3098 | 701 | 2100 | 2891 | 431 | 1814 | 2726 | 765 | 1543 | 2581 |
| SD | off | 44 | 155 | 154 | 49 | 117 | 142 | 31 | 278 | 134 | 62 | 240 | 45 |
| Females-mean | on | 425 | 2503 | 2987 | 742 | 2032 | 2752 | 436 | 1784 | 2699 | 772 | 1435 | 2493 |
| SD | on | 51 | 150 | 144 | 58 | 108 | 145 | 30 | 275 | 132 | 82 | 164 | 107 |

would produce lower $F2$'s in the pellets-on condition. The same explanations may account for the lower $F2$'s for /ɑ/ (three effects for males, three for females) in the pellets-on condition.

The articulatory interpretation of the $F1$ effects in female speakers, where the $F1$ was higher in the pellets-on condition for five of the six cases meeting the 75-Hz criterion, is most likely a more open jaw. This adjustment would move the lingual pellets away from the hard tissue boundaries of the vocal tract. For males, only one $F1$ effect was produced by a speaker other than JW07 (JW41, /i/), and it also involved a higher $F1$ in the pellets-on condition. The remaining $F1$ effects were produced by JW07, who consistently produced *lower* values of $F1$ in the pellets-on condition.

The magnitude of between-conditions differences are certainly not large for the group comparisons reported in Table I, and this would follow from the relatively small proportion of large effects described above for the individual subject comparisons. The consistency of these relatively few individual-subject effects, however, is mirrored in the group means, where all four vowel comparisons for the female speakers show higher $F1$ in the pellets-on condition, and all comparisons for $F2$ show lower values in the pellets-on condition.

Vowel formant trajectories, either of the CV or VCV type, were plotted for the speakers who showed differences in target frequencies for any of the four vowel segments. The formant plots for all vowels and subjects plotted showed no remarkable differences in shape and slope. An example of a trajectory with between-conditions differences only in target frequency is shown in Fig. 3 for a male speaker (JW07). Similar vowel trajectory plots were made for the subjects who showed significant changes in segment duration related to speaking condition. These plots showed differences only in timing of the trajectories (Fig. 4); target frequency, shape, and slope remained unchanged. Additional trajectory plots were completed based on differences found in consonant spectra analysis (see below); plots of /iwɑ/ from *greasy wash* were completed for 11 speakers. It was reasoned that significant changes in fricative spectra might reflect differences in neighboring vowel trajectories; however, no trajectory differences were noted between the pellets-on and pellets-off repetitions of this segment.

### C. Consonant spectra

A complete table of the spectral moments for each speaker can be found in Appendix C. No general patterns that distinguish pellets-on *versus* pellets-off emerge from these data, but there is at least one noteworthy trend for the mean (i.e., the first moment). Average values for the first spectral moment of the /s/ frication in *suit* and *greasy* and the /ʃ/ frication in *she* and *wash* are reported for the two conditions in Table II. Using a minimum difference of at least 1.0 kHz between conditions as significant, 18 of the complete set of 84 pellets- on vs pellets-off comparisons (4 fricatives×21 subjects) are significant; moreover, 13 of these comparisons are for either the /s/ in *suit* or *greasy*, and among these 12 have the higher mean in the pellets-on condition (for /ʃ/, 3 of the 4 comparisons meeting the criterion—all for men—also showed a higher mean in the pellets-on condition). This would suggest a tendency among speakers to create the vocal tract constriction for /s/ (or /ʃ/) somewhat more forward with the pellets-on, as compared to off; it is also possible that the higher means in the pellets-on condition reflect greater overall effort in utterance production, with higher flows through the fricative constriction and consequently greater energy in the higher frequencies of the source spectrum (Shadle, 1990). A final possibility is that the pellets act like obstacles in the path of the flow, increasing the high frequency energy in the turbulent source and thus contributing to first spectral moment differences between the pellets-on versus pellets-off condition.

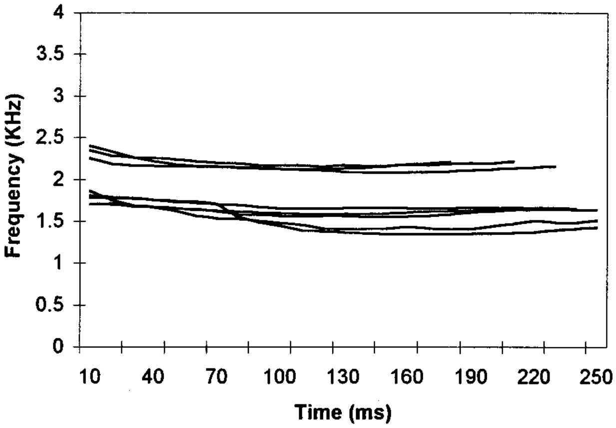

FIG. 3. $F2$ formant trajectories for /æ/, produced by subject JW07; the higher group of three trajectories are for the pellets-off repetitions, the lower group of five trajectories are for the pellets-on repetitions.

### D. Perceptual judgments

#### 1. Dichotomous judgments

The results from the dichotomous judgments are summarized in Figs. 5 and 6 for pellets-off and -on, respectively. For judgments of either 'pellets-off' or 'pellets-on,' when at least 80% inter-listener agreement was used as a criterion of consistency only 53 of the 167 tokens were judged consistently; the remaining 115 utterances were judged uniformly

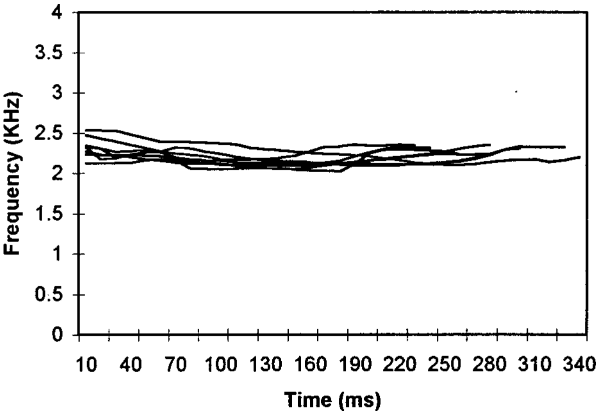

FIG. 4. $F2$ format trajectories for /æ/, produced by subject JW18; the trajectories for both conditions are superimposed, with some between-conditions differences in overall duration.

TABLE II. Mean Moment values for the fricatives across speaking conditions.

| Male speakers | Pellet | JW07 | JW08 | JW11 | JW12 | JW18 | JW19 | JW28 | JW32 | JW40 | JW41 | JW43 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHE | off | 3.49 | 3.313 | 4.062 | 3.159 | 3.224 | 4.654 | 3.575 | 3.775 | 3.452 | 3.799 | 3.105 |
|  | on | 5.208 | 3.229 | 3.834 | 3.916 | 3.481 | 3.893 | 3.591 | 3.709 | 3.105 | 3.430 | 2.94 |
| SUIT | off | 5.377 | 5.569 | 6.366 | 4.091 | 5.170 | 5.941 | 4.77 | 5.94 | 5.539 | 5.452 | 5.32 |
|  | on | 7.225 | 5.695 | 7.672 | 7.867 | 7.44 | 8.515 | 6.355 | 6.958 | 7.424 | 4.509 | 4.86 |
| GREASY | off | 5.229 | 5.749 | 5.96 | 4.441 | 5.153 | 6.044 | 5.126 | 6.182 | 5.352 | 5.864 | 5.77 |
|  | on | 6.81 | 5.3 | 6.232 | 3.137 | 5.29 | 6.043 | 6.284 | 5.479 | 5.559 | 7.329 | 5.382 |
| WASH | off | 3.415 | 4.23 | 3.906 | 2.807 | 3.196 | 4.651 | 3.984 | 4.022 | 2.725 | 3.595 | 2.868 |
|  | on | 4.697 | 3.926 | 4.203 | 4.35 | 3.894 | 3.875 | 3.546 | 4.16 | 2.672 | 3.693 | 2.704 |
| Female speakers | Pellet | JW14 | JW16 | JW27 | JW29 | JW31 | JW36 | JW37 | JW48 | JW50 | JW52 |  |
| SHE | off | 3.944 | 4.503 | 4.110 | 4.222 | 4.935 | 4.914 | 4.271 | 4.523 | 3.982 | 3.795 |  |
|  | on | 4.067 | 4.184 | 4.448 | 4.155 | 4.787 | 4.799 | 4.334 | 5.19 | 3.92 | 3.663 |  |
| SUIT | off | 7.311 | 6.604 | 6.553 | 6.588 | 6.68 | 7.357 | 5.954 | 5.421 | 7.398 | 5.385 |  |
|  | on | 7.225 | 5.695 | 7.672 | 7.867 | 7.44 | 8.515 | 6.355 | 6.958 | 7.424 | 4.509 |  |
| GREASY | off | 7.652 | 7.006 | 6.613 | 7.58 | 7.188 | 6.556 | 6.639 | 5.916 | 7.224 | 4.995 |  |
|  | on | 7.414 | 6.581 | 7.83 | 7.74 | 7.485 | 8.090 | 7.003 | 7.568 | 7.557 | 5.321 |  |
| WASH | off | 3.626 | 4.543 | 4.108 | 3.918 | 4.711 | 4.122 | 4.191 | 3.733 | 3.977 | 4.43 |  |
|  | on | 3.073 | 3.731 | 4.09 | 3.52 | 3.939 | 4.107 | 3.138 | 3.944 | 4.15 | 3.458 |  |

by the 10 listeners less than 60% of the time. There were 5 speakers (3 males and 2 females) of the original 21 speakers for whom no repetitions met the criterion of 80% agreement. These speakers are not included in Figs. 5 and 6.

Figure 5 shows for each speaker (excepting the five noted above) the percentage of pellets-off utterances that were judged consistently. Unfilled bars show utterances that were judged correctly (i.e., utterances with 'pellets-off' judged consistently [8 of 10 judges] as 'off'), and filled bars show utterances that were judged incorrectly (i.e., utterances with 'pellets-off' judged consistently as 'on'). Of the 28 utterances displayed in this figure, 22 were judged accurately (i.e., as having the pellets-off) and 6 were judged incorrectly (i.e., as having the pellets-on when they were off). For example, of the three utterances produced with pellets-off by subject JW12, one was not judged consistently, one was judged consistently and correctly, and the other was judged consistently yet incorrectly. JW40 had all three of his pellets-off utterances judged consistently, but incorrectly. JW27 and JW37 have the opposite situation, where all of their pellets-off utterances were judged correctly.

The percentage of pellets-on utterances that were judged consistently is shown in Fig. 6. As in the case of the pellets-off utterances, the majority of consistently identified pellets-on utterances were correct judgments (21 correct, 4 incorrect). No subject had all pellets-on utterances judged consistently. In general, there were proportionately fewer

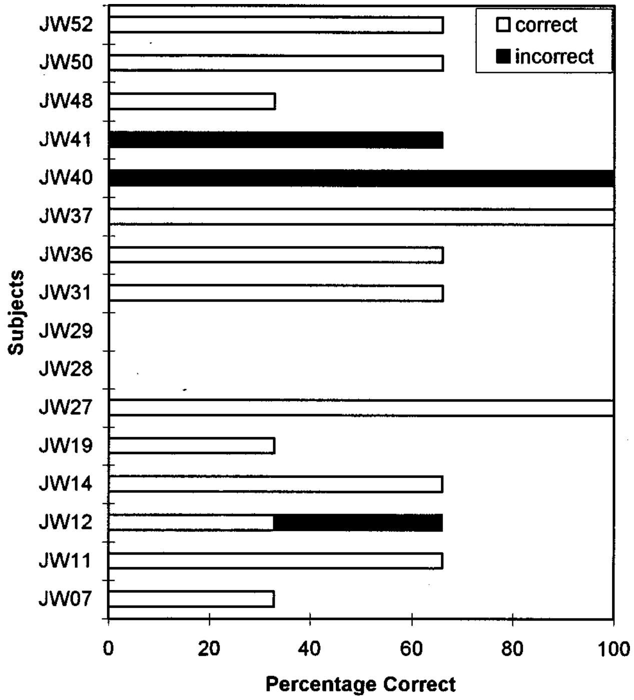

FIG. 5. Percentage of pellets-off utterances identified consistently (at least eight of ten listeners in agreement), shown by individual speakers; five speakers are not shown because none of their pellets-off utterances were identified consistently by the criterion. Correctly identified utterances are shown by unfilled bars, incorrectly identified utterances by filled bars.

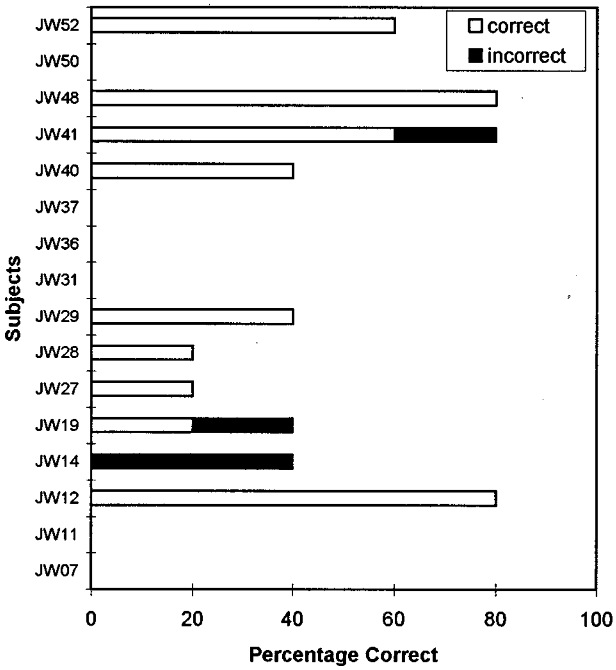

FIG. 6. Percentage of pellets-on utterances identified consistently (at least eight of ten listeners in agreement), shown by individual speakers; five speakers are not shown because none of their pellets-on utterances were identified consistently by the criterion. Correctly identified utterances are shown by unfilled bars, incorrectly identified utterances by filled bars.

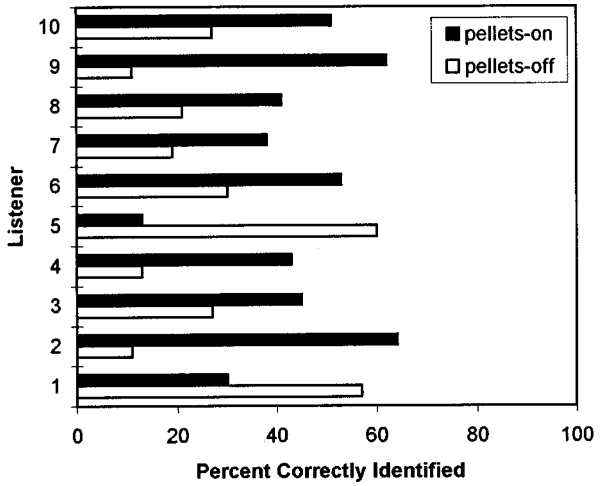

FIG. 7. Percentage of utterances identified correctly by each listener. Pellets-off utterance are shown as unfilled bars, pellets-on utterances as filled bars.

pellets-on utterances (25 of 104 utterances) judged consistently as compared to the pellets-off judgments shown in Fig. 5 (28 of 63 utterances).

Figure 7 shows the percentage of correctly identified utterances for each of the ten listeners broken down by pellets-on versus pellets-off. In this figure, there are no *a priori* criteria of consistency and the percentages are based on an item-by-item count. Eight of the ten listeners were more successful in the identification of pellets-on utterances, as compared to pellets-off utterances. Across listeners, 44% of the pellets-on utterances were identified correctly, and 28% of the pellets-off utterances were identified correctly.

### *2. Articulatory precision*

Mean articulatory precision ratings for each subject in both speaking conditions were calculated. One-way ANOVA was used to test whether the mean ratings for each of the eight utterances (three off/five on) differed for any single speaker ($\alpha = 0.05$). Results of the omnibus tests were not significant for any speakers. These findings were interesting given that roughly 35% of the utterances were identified consistently in the dichotomous listening task. Based on acoustic measures completed for this group of subjects, it might have been expected that subjects who showed differences in either timing or consonant spectra across speaking conditions would receive lower articulatory precision ratings; this was not the case, as no between-conditions differences were found.

## III. DISCUSSION

There are a large number of studies in the literature on speech production that are based on point-parameterized estimates of articulatory motion. The findings from many of these studies are often used to address certain theoretical issues, many of which are associated with temporal and spatial aspects of articulatory behavior. It is likely that the volume of published point-parameterized data, especially from the tongue, will increase in the next few years as a result of commercially available, electromagnetic systems for collecting and analyzing such data, and the existence of at least one public database of point-parameterized articulatory motion (Westbury, 1994). It seems important to know how the presence of the point markers might affect articulatory behavior, and how the interpretation of such data might be constrained by such effects.

In the present study, we selected acoustic and perceptual measures to evaluate the possibility of such effects. The findings for each of these measures will be discussed in turn.

### A. Temporal measures

Measures of segment durations revealed some between-conditions differences for individual subjects, but generally there was little consistency across subjects with respect to the direction of these effects. To the extent that segment durations reflect variation in speaking rate, it seems safe to conclude from the present findings that the presence of pellets on the articulators had little effect on global speech timing. And, there was no evidence of consistent segment-level effects for specific sound types, such as fricatives.

### B. Formant frequencies

Although the $F1$-$F2$ plot (Fig. 2) showed a great deal of between-conditions overlap in the coordinate points, there were some subtle group trends and some interesting patterns in the individual subject data. Using frequency-difference criteria based on measurement error and difference limens for formant frequencies, 6 of the 40 $F1$ comparisons exceeded 75 Hz for individual female subjects (Appendix B), all of which involved a higher $F1$ with the pellets-on, as compared to off. For $F2$ 11 of the 44 individual-subject comparisons for males and 7 of the 40 individual subject comparisons for females met the criterion of a 150-Hz difference; in 16 of these comparisons, the $F2$ value was lower with the pellets-on. Thus when formant frequency differences were observed across multiple subjects, they had a strong tendency to be consistent in direction. The $F1$ effect in females seems to reflect a greater mouth opening with the pellets-on, and the $F2$ effect in both males and females is most likely the result of a more retracted tongue. Both effects seem to be amenable to a common sense interpretation of how a speaker might react to the presence of pellets on articulatory structures, and especially on the tongue. Specifically, the effects seem to reflect an articulatory adjustment to avoid making contact between a pellet (or pellets) and the bony upper and anterior boundary of the vocal tract. The more open mouth (the $F1$ effect) would keep the anterior pellets away from the hard palate, and a more retracted tongue (the $F2$ effect) would pull the anterior pellet away from the inferiorly protruding alveolar ridge. Whereas these appear to be reasonable interpretations of these patterns, the data of one subject (JW07) consistently showed the opposite trend for $F1$, with lower values in the pellets-on condition, indicating a more closed vocal tract. Why this subject would have brought the pellets closer to the upper boundary of the vocal tract is not clear.

The fact that there was a relatively small proportion of cases in which these effects were observed indicates a differential rate of adaptation or tolerance across subjects to the presence of pellets, but the relative consistency of the effect direction (excepting JW07), when it occurred, suggests a common response when the adaptation or tolerance was incomplete. All speakers were given a short period of pre-experiment talking time after the pellets were attached to the articulatory structures, but it is impossible to know if the effects would disappear with a more extended adaptation period. A sampling of some older (Gay, 1974; Nearey, 1978; Wood, 1979) and more recent (Perkell and Nelson, 1985; Perkell and Cohen, 1989) studies in which point-parameterized articulatory positions for vowel production are reported reveals little information on the time period between attachment of pellets and collection of data. It is certainly possible, then, that some of the tongue positions and formant frequencies reported in the studies cited here (and in others) reflect an articulatory adjustment to the presence of the pellets. It is also fairly clear that in experiments of this type (e.g., Flege *et al.*, 1988; Savariaux *et al.*, 1995; and the present one) there is a good deal of intersubject variability in reaction to the presence of an intra- or perioral device.

### C. Fricative articulation

Spectral moments analysis failed to reveal a pervasive effect of pellets on fricative articulation. As noted in the Introduction, fricatives would seem to be the most rigorous test of the effects of pellets on articulatory behavior. The absence of frequent effects would seem to be a strong endorsement of the notion that point parameterization of lingual motion does not interfere, at least in any pervasive way, with production of the lingual fricatives studied here.

Approximately 20% of the possible comparisons (17/84) for the moments did show a between-conditions effect, and in the great majority of these cases (15/17) there was a higher mean in the pellets-on condition. Thus even though the effects were relatively infrequent, they were systematic when they occurred. Among the potential interpretations of these effects, two would seem to have important consequences for studies of fricative articulation. The first spectral moment could have been increased in the pellets-on condition by either a more forward point of constriction or a deepening of the midline lingual groove (Fant, 1960), either of which would be a distortion of typical articulatory patterns for fricatives. The present data do not permit a clear choice between these two adjustments, but the more forward point of constriction seems counterintuitive because it would probably create greater contact between at least the frontmost pellet (and, perhaps, the pellet immediately posterior) and the bony roof of the vocal tract. As in the case of vowel effects, discussed above, a more natural articulatory response would seem to be one in which the pellets were moved away from contact with bony structures. A deeper lingual groove would accomplish this, and may be the more reasonable interpretation of the systematic effects for the first moments of /s/ and /ʃ/.

The increase in the value of the first moment could also have occurred in the absence of the kind of lingual adjustments described above, and therefore may not reflect distortions of typical fricative articulation. For example, the first moment could increase as a result of increased high frequency energy due to greater subglottal pressure (and hence trans-constriction flows) or from higher frequency source energy associated with interruption of laminar flow streams by the pellets (see Shadle, 1990). The acoustic effects resulting from either or both of these mechanisms would be more like epiphenomena of the presence of pellets, rather than true articulatory effects.

### D. Perceptual findings

Listeners were not able to make reliable identifications of utterances spoken with pellets-on vs pellets-off, nor could they scale articulatory precision differentially across conditions. Even when listeners were consistent among themselves, they were as likely to be correct as incorrect in making the simple dichotomous judgment of ‘on’ vs ‘off.’ The listeners’ poor performance extended to speakers for whom consistent acoustic differences between pellets-on and pellets-off had been demonstrated. For example, JW07 had very dramatic acoustic differences between conditions for vowels (Appendix B) and fricatives (Appendix C), but his utterances could not be identified reliably as being produced with or without pellets, and were not distinguished by scalings of articulatory precision. This particular case, as well as that of several other subjects who had between-conditions acoustic effects that did not translate to consistent perceptual effects, raises an important caveat about the use of either formal or informal perceptual measures in experiments using point parameterization of articulatory motions. This finding is consistent with the report of Flege *et al.* (1988), who found that reliable acoustic effects produced by a bite block did not translate to reliable perceptual judgments of the presence versus absence of the block during utterance production.

As noted in the Introduction, the typical experiment using point parameterization of articulatory motion or any type of perioral or intraoral measurement device, relies on informal listening and a subject’s own report for evidence that the markers or devices are not interfering with normal speech production. Many of these same studies employ a small number of speakers because of the technical challenge of collecting and analyzing a large amount of complex data which often exist in multiple streams and are not amenable to fully-automated processing. The use of small numbers of subjects in these experiments is understandable, but a subject such as JW07 exposes a potential danger for a speech production experiment in which a few subjects are used to test a model’s prediction, or the validity of a theoretical axiom. If JW07 was one of the few speakers in such an experiment (or, for example, JW27 and JW36 in experiments dealing with /s/ articulation: see Table II; or JW31 and JW41 in experiments dealing with vowel articulation: see Appendix B), the articulatory behavior observed in the experiment would very possibly be different from the speaker’s ‘normal’ articulatory behavior, and thus not be a fair test of the model or theory. The present results suggest that even formal, apparently simple perceptual tests may not identify these speakers. It is possible, of course, that a more sensitive perceptual test of a segment’s vulnerability to the presence of pellets may have revealed listeners’ ability to make reliable identifications of speaking condition. For example, listeners might have been able to identify the pellets-on vs pellets-off conditions if only presented with excised /s/ or /ʃ/ waveforms (but see Flege *et al.*, 1988); we chose not to do this in our experiment because we were interested in formal perceptual judgments similar to the informal evaluations found most frequently in the literature and used for our own x-ray microbeam database.

If formal perceptual judgments may miss those subjects who are affected by the presence of pellets, what options exist for eliminating speakers who are likely to adjust their typical articulatory behavior when pellets, coils, or other devices are placed on their oral structures? We would suggest a fairly simple screening protocol to eliminate potential subjects who show large effects due to the placement of pellets-on the articulators. The protocol should consist of a small group of utterances produced first with no pellets attached to the articulators, and then with the pellets attached. The speech sample should include lingual fricatives as well as high vowels, and speech acoustic measures such as those used in the present investigation should be used to evaluate a potential subject's speech production sensitivity to the presence of pellets on articulatory structures in general, but especially on the tongue. The criteria for rejecting a potential subject for participation in an experiment obviously will depend on the purposes of the experiment and the hypothesis under evaluation; the criteria used in the present experiment, especially in the case of fricative spectra, may actually be overly liberal for certain experimental questions. Whereas it is possible that formal adaptation periods could be built into articulatory kinematics experiments as a way to circumvent such a screening protocol, the small number of speakers who do show acoustic effects in the present experiment argue for the screening as a more efficient and rigorous approach to the problem. Formal adaptation periods could not ensure the elimination of effects in the absence of some analytical demonstration of complete adaptation. Finally, the use of perceptual evaluation of 'normal' speech with pellets or coils in place does not seem to be an acceptable way to validate the absence of unwanted influences from the markers. Many of the perceptual evaluations in the present experiment were 'normal' for specific subjects who showed large acoustic effects of the pellets. This finding suggests that acoustic measures are the preferred indices of a subject's ability to produce typical articulatory behavior with pellets or coils attached to the tongue.

## ACKNOWLEDGMENTS

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## APPENDIX A

Segment durations for individual subjects across speaking conditions.

| Subject Pellets | Segment 1 /ʃ/ | Segment 2 /i/ | Segment 3 /h/ | Segment 4 /æ/ | Segment 5 /d/ | Segment 6 vot | Segment 7 /ɔ/ | Segment 8 /d/ | Segment 9 vot | Segment 10 /ar/ | Segment 11 /k/ | Segment 12 /s/ | Segment 13 /u/ | Segment 14 /t/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 off | 129.67 | 84.67 | 42.00 | 157.67 | 66.67 | 46.00 | 163.00 | 68.67 | 17.33 | 201.00 | 82.67 | 130.67 | 179.00 | 63.67 |
| 7 on | 119.40 | 88.60 | 48.20 | 125.20 | 51.80 | 30.20 | 121.00 | 63.40 | 17.20 | 165.80 | 77.00 | 111.80 | 153.80 | 56.20 |
| 8 off | 130.67 | 90.00 | 23.67 | 174.00 | 58.33 | 29.00 | 111.33 | 91.00 | 22.33 | 175.67 | 97.33 | 189.00 | 162.67 | 49.33 |
| 8 on | 134.40 | 76.80 | 61.20 | 120.20 | 53.00 | 31.20 | 99.00 | 60.20 | 28.00 | 158.40 | 50.00 | 181.20 | 141.60 | 45.00 |
| 11 off | 138.00 | 67.00 | 18.67 | 137.33 | 64.00 | 26.33 | 90.00 | 84.33 | 19.67 | 158.67 | 77.67 | 141.00 | 133.00 | 53.67 |
| 11 on | 133.00 | 46.20 | 59.60 | 100.20 | 49.80 | 31.20 | 82.20 | 58.60 | 28.00 | 174.20 | 75.60 | 145.20 | 112.20 | 55.80 |
| 12 off | 170.67 | 113.33 | 25.00 | 181.67 | 39.00 | 27.00 | 162.00 | 55.33 | 18.33 | 152.67 | 69.33 | 166.67 | 121.67 | 59.67 |
| 12 on | 178.80 | 141.80 | 53.00 | 157.60 | 52.20 | 25.60 | 114.80 | 63.20 | 30.20 | 135.20 | 60.00 | 185.20 | 127.80 | 42.40 |
| 14 off | 127.33 | 77.67 | 32.00 | 152.67 | 63.33 | 37.33 | 80.33 | 50.67 | 16.00 | 135.67 | 80.33 | 119.67 | 122.00 | 36.33 |
| 14 on | 117.40 | 63.00 | 61.20 | 119.60 | 51.40 | 43.20 | 66.60 | 52.40 | 13.80 | 149.40 | 47.00 | 149.20 | 119.00 | 27.00 |
| 16 off | 137.67 | 105.00 | 31.33 | 167.33 | 56.33 | 24.00 | 116.67 | 93.00 | 20.00 | 159.33 | 97.67 | 163.00 | 146.33 | 84.67 |
| 16 on | 118.20 | 97.20 | 62.80 | 128.60 | 48.20 | 32.00 | 101.80 | 72.60 | 21.40 | 155.20 | 87.60 | 168.60 | 144.00 | 71.60 |
| 18 off | 179.50 | 81.50 | 40.50 | 185.00 | 22.00 | 43.50 | 168.50 | 43.00 | 49.00 | 138.00 | 85.00 | 189.00 | 163.00 | 52.50 |
| 18 on | 151.75 | 72.50 | 77.50 | 108.00 | 33.75 | 33.25 | 124.50 | 62.00 | 32.50 | 132.00 | 77.75 | 180.75 | 167.25 | 55.50 |
| 19 off | 136.33 | 92.33 | 25.33 | 133.00 | 37.67 | 23.33 | 109.00 | 65.00 | 23.33 | 139.33 | 63.67 | 169.33 | 135.67 | 37.67 |
| 19 on | 138.40 | 95.60 | 69.40 | 115.20 | 47.40 | 25.80 | 94.40 | 82.80 | 21.20 | 141.60 | 54.40 | 172.60 | 129.80 | 44.60 |
| 36 off | 142.00 | 75.00 | 19.67 | 194.67 | 30.50 | 12.50 | 147.00 | 71.00 | 14.67 | 175.67 | 76.00 | 167.00 | 186.67 | 25.67 |
| 36 on | 124.20 | 93.60 | 66.40 | 122.40 | 15.00 | 21.40 | 143.40 | 62.80 | 34.60 | 162.40 | 69.20 | 138.60 | 146.40 | 26.20 |
| 37 off | 115.33 | 63.67 | 16.00 | 136.00 | 25.00 | 24.67 | 90.67 | 76.67 | 15.00 | 153.67 | 64.67 | 154.33 | 135.67 | 65.33 |
| 37 on | 118.40 | 61.60 | 50.20 | 123.20 | 26.00 | 20.00 | 88.60 | 67.40 | 13.40 | 146.60 | 56.00 | 141.80 | 119.80 | 50.20 |
| 48 off | 129.33 | 85.67 | 29.00 | 190.33 | 48.67 | 29.67 | 94.33 | 61.00 | 19.67 | 181.33 | 80.33 | 157.33 | 147.00 | 49.33 |
| 48 on | 139.00 | 82.60 | 62.40 | 173.00 | 39.20 | 27.00 | 109.80 | 64.60 | 17.00 | 170.60 | 72.60 | 176.80 | 146.20 | 19.20 |
| 27 off | 127.67 | 66.00 | 77.33 | 77.33 | 44.67 | 40.67 | 95.67 | 53.00 | 20.33 | 156.33 | 64.00 | 178.67 | 123.67 | 68.00 |
| 27 on | 130.40 | 66.00 | 86.00 | 83.80 | 55.60 | 26.60 | 124.80 | 59.40 | 18.60 | 151.60 | 53.00 | 204.40 | 117.80 | 54.60 |
| 28 off | 144.33 | 89.33 | 82.67 | 137.67 | 75.33 | 38.33 | 64.33 | 82.00 | 16.67 | 133.00 | 75.33 | 161.67 | 118.00 | 84.33 |
| 28 on | 138.20 | 92.60 | 69.20 | 129.00 | 71.60 | 20.80 | 81.60 | 85.80 | 17.60 | 155.20 | 67.00 | 161.60 | 136.40 | 57.40 |
| 29 off | 128.00 | 47.33 | 65.33 | 142.67 | 41.00 | 37.33 | 84.33 | 86.67 | 14.33 | 151.33 | 72.33 | 171.00 | 156.33 | 75.00 |
| 29 on | 129.20 | 57.80 | 70.80 | 116.20 | 37.80 | 23.40 | 98.40 | 74.80 | 14.00 | 146.80 | 84.00 | 157.60 | 171.20 | 87.20 |

(*Continued.*)

| Subject Pellets | Segment 1 /ʃ/ | Segment 2 /i/ | Segment 3 /h/ | Segment 4 /æ/ | Segment 5 /d/ | Segment 6 vot | Segment 7 /ɔ/ | Segment 8 /d/ | Segment 9 vot | Segment 10 /ar/ | Segment 11 /k/ | Segment 12 /s/ | Segment 13 /u/ | Segment 14 /t/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 off | 122.33 | 70.00 | 70.67 | 108.00 | 44.33 | 13.00 | 127.33 | 85.67 | 19.00 | 171.00 | 70.33 | 161.00 | 152.00 | 68.33 |
| 31 on | 132.00 | 70.00 | 73.00 | 115.00 | 48.00 | 15.00 | 135.00 | 92.00 | 21.00 | 165.00 | 68.00 | 153.00 | 146.00 | 63.00 |
| 32 off | 138.33 | 57.67 | 64.33 | 99.67 | 49.67 | 35.67 | 125.33 | 95.67 | 13.00 | 144.33 | 44.67 | 200.60 | 134.00 | 109.67 |
| 32 on | 160.20 | 62.40 | 61.60 | 82.20 | 43.20 | 35.20 | 103.80 | 131.80 | 15.60 | 139.00 | 53.80 | 154.00 | 135.40 | 90.80 |
| 40 off | 108.00 | 67.67 | 81.33 | 94.67 | 34.33 |  | 123.33 | 68.67 | 18.33 | 164.67 | 64.67 | 166.67 | 120.67 | 87.67 |
| 40 on | 126.60 | 62.00 | 60.40 | 96.80 | 37.00 | 16.00 | 124.60 | 53.80 | 20.20 | 158.60 | 62.20 | 143.80 | 91.40 | 42.20 |
| 41 off | 108.00 | 52.00 | 46.67 | 50.00 | 40.67 | 23.00 | 49.33 | 95.33 | 18.33 | 122.00 | 47.33 | 154.33 | 103.00 | 53.00 |
| 41 on | 128.25 | 49.25 | 50.25 | 34.25 | 55.50 | 18.25 | 75.25 | 90.50 | 21.25 | 128.50 | 45.75 | 162.50 | 133.75 | 42.00 |
| 43 off | 144.67 | 78.33 | 62.67 | 123.00 | 54.67 | 40.67 | 79.67 | 75.00 | 22.67 | 145.33 | 71.33 | 211.67 | 142.67 | 63.00 |
| 43 on | 128.00 | 85.40 | 75.40 | 138.80 | 52.40 | 37.40 | 112.60 | 78.00 | 17.60 | 148.40 | 65.60 | 204.40 | 167.80 | 60.00 |
| 50 off | 101.33 | 67.00 | 68.33 | 121.67 | 52.33 | 16.67 | 89.00 | 54.67 | 10.67 | 151.33 | 66.67 | 156.33 | 118.33 | 65.00 |
| 50 on | 122.20 | 54.20 | 82.40 | 102.80 | 56.80 | 22.60 | 79.00 | 54.60 | 15.00 | 140.40 | 64.40 | 148.20 | 102.60 | 57.20 |
| 52 off | 133.67 | 78.67 | 68.00 | 131.33 | 50.33 | 16.50 | 131.00 | 67.33 | 12.33 | 173.67 | 77.67 | 178.33 | 144.67 | 47.67 |
| 52 on | 130.50 | 48.50 | 56.75 | 103.75 | 33.25 | 15.00 | 105.75 | 73.00 | 15.00 | 160.00 | 72.00 | 165.00 | 119.00 | 22.00 |

(*Continued.*)

| Segment 15 /i/ | Segment 16 /n/ | Segment 17 /g/ | Segment 18 vot | Segment 19 /ri/ | Segment 20 /s/ | Segment 21 /iwa/ | Segment 22 /ʃ/ | Segment 23 /w9/ | Segment 24 /t/ | Segment 25 /ɔ/yir/ |
|---|---|---|---|---|---|---|---|---|---|---|
| 91.33 | 133.00 | 30.00 | 41.33 | 131.00 | 110.67 | 367.67 | 140.00 | 187.00 | 23.33 | 860.33 |
| 90.20 | 89.20 | 28.80 | 28.80 | 126.60 | 109.20 | 325.00 | 122.60 | 193.00 | 29.00 | 797.20 |
| 125.00 | 69.00 | 33.67 | 34.67 | 119.67 | 121.00 | 327.67 | 150.67 | 223.33 | 22.67 | 862.67 |
| 53.20 | 136.20 | 35.40 | 27.20 | 117.80 | 110.00 | 303.20 | 153.60 | 194.60 | 32.20 | 862.00 |
| 84.67 | 112.00 | 33.00 | 25.00 | 122.00 | 130.33 | 285.33 | 137.33 | 140.67 | 22.33 | 788.00 |
| 55.20 | 123.60 | 47.60 | 34.00 | 109.40 | 125.20 | 308.00 | 146.80 | 150.00 | 21.20 | 750.60 |
| 92.67 | 87.33 | 21.00 | 45.67 | 123.33 | 114.33 | 320.33 | 133.00 | 172.00 | 19.67 | 658.00 |
| 31.20 | 159.00 | 13.60 | 28.00 | 125.00 | 115.40 | 299.40 | 134.20 | 159.20 | 30.20 | 650.80 |
| 55.00 | 136.33 | 35.00 | 27.00 | 115.67 | 125.67 | 335.33 | 146.00 | 166.00 | 19.00 | 744.33 |
| 48.40 | 124.40 | 34.00 | 32.20 | 125.20 | 107.60 | 317.20 | 138.20 | 159.40 | 17.80 | 743.80 |
| 59.00 | 86.67 | 30.67 | 30.00 | 145.00 | 105.33 | 351.67 | 124.33 | 150.00 | 22.67 | 844.00 |
| 79.00 | 121.40 | 28.00 | 30.40 | 158.40 | 126.40 | 360.60 | 149.40 | 175.40 | 25.20 | 804.60 |
| 37.50 | 96.50 | 34.50 | 48.00 | 98.50 | 138.00 | 328.50 | 197.00 | 158.50 | 24.00 | 806.00 |
| 81.33 | 92.00 | 36.50 | 47.25 | 116.00 | 124.25 | 334.50 | 173.50 | 168.00 | 23.75 | 727.25 |
| 51.00 | 66.33 | 43.67 | 51.00 | 105.00 | 122.33 | 271.00 | 149.00 | 139.33 | 18.00 | 577.00 |
| 32.00 | 96.00 | 45.80 | 44.20 | 115.60 | 126.20 | 282.00 | 150.80 | 146.80 | 20.00 | 673.80 |
| 63.67 | 111.67 | 30.67 | 28.33 | 143.00 | 102.33 | 329.33 | 126.00 | 174.33 | 18.00 | 724.67 |
| 92.60 | 83.60 | 23.00 | 24.20 | 152.60 | 112.00 | 336.80 | 109.20 | 199.20 | 23.20 | 697.80 |
| 54.33 | 76.67 | 23.00 | 33.00 | 96.33 | 106.33 | 251.67 | 128.33 | 122.67 | 11.33 | 602.00 |
| 50.20 | 67.60 | 32.50 | 31.60 | 107.80 | 121.40 | 274.20 | 139.20 | 147.80 | 11.60 | 651.40 |
| 81.00 | 69.00 | 32.67 | 30.00 | 141.00 | 131.33 | 332.33 | 146.67 | 170.67 | 15.67 | 676.33 |
| 66.20 | 112.40 | 21.40 | 25.20 | 148.00 | 141.00 | 367.00 | 147.20 | 180.00 | 14.40 | 752.80 |
| 45.33 | 77.00 | 29.00 | 50.33 | 96.33 | 145.33 | 316.33 | 152.00 | 146.33 | 38.33 | 814.67 |
| 55.20 | 99.60 | 26.40 | 38.00 | 101.40 | 152.80 | 313.60 | 168.40 | 140.00 | 31.40 | 801.80 |
| 95.67 | 118.00 | 38.33 | 31.00 | 146.67 | 136.00 | 348.00 | 177.00 | 153.33 | 29.67 | 655.00 |
| 66.40 | 101.60 | 39.00 | 41.60 | 129.40 | 132.40 | 312.80 | 166.00 | 160.20 | 36.80 | 696.40 |
| 52.67 | 74.00 | 26.00 | 34.33 | 114.67 | 143.00 | 281.00 | 167.67 | 151.67 | 20.00 | 715.00 |
| 87.60 | 90.80 | 24.00 | 25.20 | 113.80 | 139.80 | 271.20 | 159.40 | 149.80 | 19.40 | 738.60 |
| 59.67 | 74.00 | 47.67 | 23.33 | 147.33 | 134.67 | 269.00 | 154.67 | 161.00 | 26.33 | 734.33 |
| 55.00 | 70.00 | 48.00 | 25.00 | 148.00 | 135.00 | 280.00 | 142.67 | 152.00 | 32.00 | 730.00 |
| 79.67 | 99.67 | 50.67 | 36.00 | 86.67 | 135.00 | 308.33 | 142.67 | 129.00 | 19.67 | 655.00 |
| 77.00 | 54.40 | 28.40 | 28.80 | 91.80 | 127.60 | 307.80 | 224.60 | 126.60 | 22.20 | 663.60 |
| 76.00 | 106.00 | 23.00 | 31.00 | 125.67 | 141.33 | 287.00 | 136.33 | 157.00 | 23.00 | 652.33 |
| 83.75 | 109.50 | 32.60 | 33.60 | 121.80 | 146.20 | 290.80 | 154.60 | 211.60 | 28.00 | 679.40 |
| 61.33 | 57.00 | 40.33 | 37.67 | 89.33 | 121.00 | 283.67 | 119.00 | 138.67 | 21.33 | 592.67 |
| 40.75 | 90.50 | 29.25 | 45.50 | 115.50 | 108.25 | 283.00 | 130.50 | 121.25 | 22.75 | 572.50 |
| 80.00 | 125.67 | 40.67 | 41.00 | 115.67 | 125.00 | 390.33 | 207.00 | 154.00 | 20.00 | 684.33 |
| 82.20 | 97.40 | 37.60 | 39.60 | 117.40 | 122.20 | 337.20 | 186.40 | 154.20 | 21.20 | 708.80 |
| 55.00 | 73.67 | 39.67 | 27.67 | 100.67 | 118.33 | 260.67 | 174.00 | 132.00 | 23.33 | 623.67 |
| 65.00 | 84.00 | 17.20 | 19.40 | 108.80 | 122.20 | 295.40 | 170.40 | 127.80 | 24.60 | 630.40 |
| 88.00 | 104.00 | 39.00 | 32.00 | 139.67 | 121.67 | 350.67 | 124.33 | 199.00 | 21.33 | 708.00 |
| 70.25 | 100.25 | 19.75 | 29.25 | 128.50 | 119.75 | 342.25 | 132.50 | 189.50 | 19.75 | 709.50 |

## APPENDIX B

Mean formant values for the four vowels in ‘pellets-off’ and ‘pellets-on’ conditions, male speakers.

| | | /i/ | | | /ae/ | | | /u/ | | | /ɛ̈/ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 |
| JW07 | off | 442 | **2561** | **3515** | **777** | **2146** | **3209** | **498** | **2018** | **2910** | **823** | **1554** | **3079** |
| | on | 372 | **1874** | **2509** | **582** | **1616** | **2359** | **347** | **1534** | **2191** | **618** | **1185** | **2264** |
| JW08 | off | 328 | 2100 | **2619** | 652 | 1686 | 2422 | 338 | 1487 | 2222 | 641 | 1333 | 2318 |
| | on | 337 | 2042 | **2446** | 635 | 1724 | 2399 | 355 | 1410 | 2186 | 664 | 1271 | 2378 |
| JW11 | off | 342 | 2076 | 2774 | 581 | 1654 | 2460 | 373 | **1590** | 2293 | 624 | **1205** | 1945 |
| | on | 362 | 2092 | 2674 | 610 | 1687 | 2313 | 356 | **1395** | 2318 | 652 | **1048** | 1964 |
| JW12 | off | 314 | 1975 | 2776 | 606 | 1676 | 2497 | 339 | 1451 | 2244 | 638 | 1397 | 2308 |
| | on | 327 | 2061 | 2764 | 620 | 1686 | 2500 | 361 | 1361 | 2156 | 640 | 1307 | 2294 |
| JW18 | off | 307 | **2274** | 2658 | 608 | 1694 | 2501 | 369 | 1455 | 2381 | 623 | 1149 | 2536 |
| | on | 347 | **2079** | 2462 | 603 | 1696 | 2467 | 382 | 1414 | 2328 | 654 | 1176 | 2625 |
| JW19 | off | 303 | 2169 | 2645 | 587 | 1840 | 2636 | 343 | 1497 | 2319 | 639 | 1192 | 2275 |
| | on | 291 | 2193 | 2736 | 590 | 1829 | 2567 | 342 | 1618 | 2314 | 609 | 1200 | 2133 |
| JW41 | off | **342** | **1840** | 2492 | 517 | 1598 | **2420** | 327 | 1296 | 2031 | 607 | **1139** | 2303 |
| | on | **435** | **1660** | 2359 | 444 | 1565 | **2027** | 279 | 1391 | 2067 | 600 | **935** | 2172 |
| JW32 | off | 380 | 1996 | 2615 | 523 | 1662 | 2167 | 337 | 1306 | 2153 | 656 | 1205 | 2279 |
| | on | 385 | 2015 | 2714 | 562 | 1705 | 2289 | 331 | 1335 | 2113 | 673 | 1179 | 2279 |
| JW40 | off | 336 | 1888 | 2483 | 569 | 1563 | 2375 | 347 | 1560 | 2241 | 594 | 1195 | 2238 |
| | on | 342 | 1891 | 2495 | 541 | 1557 | 2330 | 352 | 1595 | 2292 | 551 | 1313 | 2261 |
| JW28 | off | 301 | 2056 | 2860 | 577 | 1614 | 2401 | 317 | 1220 | 2124 | 626 | 1084 | 2151 |
| | on | 320 | 2068 | 2851 | 610 | 1631 | 2404 | 320 | 1146 | 2129 | 610 | 1047 | 2170 |
| JW43 | off | 335 | 2027 | 2585 | 617 | 1628 | **2215** | 346 | 1360 | 2135 | 644 | 1204 | 2368 |
| | on | 343 | 1921 | 2468 | 638 | 1602 | **2460** | 362 | 1338 | 2164 | 667 | 1185 | 2448 |

Mean formant values for the four vowels in ‘pellets-off’ and ‘pellets-on’ conditions, female speakers.

| | | /i/ | | | /ae/ | | | /u/ | | | /a/ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 | *F*1 | *F*2 | *F*3 |
| JW14 | off | 322 | 2525 | 3030 | 622 | 2061 | 2676 | 371 | 1589 | 2706 | 746 | 1241 | **2583** |
| | on | 343 | 2564 | 3041 | 655 | 1965 | 2539 | 381 | 1471 | 2722 | 730 | 1296 | **2296** |
| JW16 | off | 436 | 2502 | 3130 | 696 | 2193 | 3033 | 414 | **1737** | 2516 | **792** | **1622** | 2611 |
| | on | 459 | 2410 | 3020 | 740 | 2141 | 2887 | 405 | **1910** | 2649 | **676** | **1356** | 2499 |
| JW36 | off | 465 | 2580 | **3382** | **699** | 2286 | 3000 | 451 | 2132 | 2808 | **745** | 1632 | 2586 |
| | on | 490 | 2564 | **2990** | **774** | 2205 | 2891 | 470 | 2070 | 2710 | **875** | 1586 | 2432 |
| JW37 | off | 396 | 2777 | 3272 | 777 | 2034 | 3042 | 434 | 2333 | 2851 | 817 | 1588 | 2692 |
| | on | 404 | 2669 | 3076 | 790 | 2048 | 3036 | 430 | 2294 | 2819 | 803 | 1531 | 2626 |
| JW48 | off | 442 | 2647 | 3113 | 740 | 2130 | **2996** | 445 | 1430 | 2830 | 701 | **2036** | 2584 |
| | on | 450 | 2521 | 3020 | 753 | 2082 | **2765** | 446 | 1377 | 2828 | 747 | **1641** | 2454 |
| JW52 | off | **360** | **2591** | 2818 | 651 | 1966 | **2866** | 455 | 1501 | 2519 | 718 | 1188 | 2558 |
| | on | **458** | **2310** | 2680 | 670 | 1965 | **2627** | 452 | 1582 | 2572 | 701 | 1138 | 2661 |
| JW29 | off | 387 | 2327 | 3103 | 742 | 1957 | 2747 | 433 | 1722 | 2674 | 788 | 1396 | 2548 |
| | on | 411 | 2324 | 2905 | 782 | 1990 | 2692 | 451 | 1599 | 2587 | 832 | 1342 | 2503 |
| JW27 | off | **349** | 2403 | 3026 | **716** | 2085 | 2776 | 415 | 1961 | 2779 | 673 | **1583** | 2578 |
| | on | **487** | 2503 | 3042 | **855** | 2119 | 2794 | 431 | 2002 | 2611 | 704 | **1405** | 2599 |
| JW31 | off | 360 | 2824 | 3210 | 629 | **2299** | **3075** | 490 | **2052** | 2942 | 903 | 1783 | 2593 |
| | on | 340 | 2805 | 3253 | 689 | **1800** | **2620** | 487 | **1850** | 2971 | 938 | 1692 | 2475 |
| JW50 | off | 376 | 2383 | 2950 | 717 | 2017 | 2763 | 404 | 1693 | 2643 | 760 | 1415 | 2520 |
| | on | 408 | 2356 | 2845 | 714 | 2007 | 2670 | 406 | 1682 | 2524 | 712 | 1364 | 2381 |

## APPENDIX C

Mean values for the first four moments (mean (1), standard deviation (2), skewness (3), and kurtosis (4)) for individual speakers and speaking condition (pellets-off versus pellets-on).

| Male speakers<br>Pellets-off | Moment | JW07 | JW08 | JW11 | JW12 | JW18 | JW19 | JW28 | JW32 | JW40 | JW41 | JW43 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHE | 1 | 5.21 | 3.23 | 3.83 | 3.92 | 3.48 | 3.89 | 3.59 | 3.71 | 3.11 | 3.43 | 2.94 |
| | 2 | 1.91 | 1.06 | 1.27 | 1.48 | 1.14 | 0.98 | 1.31 | 1.26 | 0.64 | 1.00 | 0.85 |
| | 3 | 1.34 | 2.64 | 2.01 | 1.63 | 2.47 | 2.62 | 2.37 | 2.14 | 5.08 | 1.87 | 3.70 |
| | 4 | 1.11 | 7.93 | 4.19 | 2.00 | 7.03 | 10.92 | 5.99 | 4.67 | 40.80 | 4.51 | 17.90 |
| SUIT | 1 | 7.23 | 5.24 | 6.06 | 4.63 | 5.14 | 4.93 | 6.20 | 5.51 | 5.98 | 7.11 | 4.86 |
| | 2 | 1.76 | 1.39 | 1.64 | 1.62 | 1.50 | 1.11 | 1.35 | 1.73 | 1.53 | 1.29 | 0.88 |
| | 3 | 0.66 | 0.90 | 0.18 | 1.22 | 1.47 | 2.11 | 0.49 | 0.84 | −0.15 | −1.40 | 3.47 |
| | 4 | −0.20 | −0.41 | −0.96 | 0.26 | 1.65 | 5.80 | −0.27 | −0.23 | −0.14 | 2.29 | 20.05 |
| GREASY | 1 | 6.81 | 5.30 | 6.23 | 3.14 | 5.29 | 6.04 | 6.28 | 5.48 | 5.56 | 7.33 | 5.38 |
| | 2 | 1.59 | 1.15 | 1.83 | 1.44 | 1.51 | 1.48 | 1.27 | 1.71 | 1.52 | 1.27 | 1.27 |
| | 3 | 0.61 | 0.85 | 0.18 | 2.35 | 0.89 | 0.51 | 0.37 | 0.90 | 0.00 | −0.58 | 1.57 |
| | 4 | 0.83 | 0.44 | −1.08 | 6.06 | 0.84 | 0.20 | −0.24 | −0.02 | −0.13 | 0.79 | 3.63 |
| WASH | 1 | 4.70 | 3.93 | 4.20 | 4.35 | 3.89 | 3.88 | 3.55 | 4.16 | 2.67 | 3.69 | 2.70 |
| | 2 | 2.68 | 1.74 | 1.96 | 1.40 | 2.28 | 1.40 | 1.91 | 2.14 | 0.74 | 1.68 | 0.91 |
| | 3 | 1.02 | 1.31 | 0.99 | 1.48 | 1.37 | 2.01 | 1.46 | 0.60 | 4.55 | 0.91 | 3.83 |
| | 4 | −0.27 | 2.18 | 0.09 | 2.39 | 1.04 | 4.93 | 1.38 | −0.44 | 29.81 | 0.54 | 18.70 |

| Female speakers<br>Pellets-off | Moment | JW14 | JW16 | JW27 | JW29 | JW31 | JW36 | JW37 | JW48 | JW50 | JW52 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SHE | 1 | 4.07 | 4.18 | 4.45 | 4.16 | 4.79 | 4.80 | 4.33 | 5.19 | 3.92 | 3.66 |
| | 2 | 1.07 | 1.15 | 1.11 | 0.94 | 1.17 | 1.24 | 0.82 | 1.62 | 1.07 | 0.97 |
| | 3 | 2.04 | 1.56 | 2.20 | 2.16 | 1.16 | 1.84 | 1.89 | 1.06 | 1.52 | 1.33 |
| | 4 | 5.34 | 2.68 | 5.75 | 6.34 | 1.76 | 4.06 | 7.79 | 0.22 | 3.15 | 1.86 |
| SUIT | 1 | 7.23 | 5.70 | 7.67 | 7.87 | 7.44 | 8.52 | 6.36 | 6.96 | 7.42 | 4.51 |
| | 2 | 1.42 | 1.55 | 0.89 | 1.35 | 1.69 | 0.84 | 1.45 | 1.36 | 1.16 | 0.91 |
| | 3 | −0.21 | 1.01 | −0.99 | −0.98 | −0.07 | −1.33 | 0.38 | −0.23 | 0.01 | 1.73 |
| | 4 | −0.28 | 0.86 | 4.71 | 1.09 | 0.09 | 6.47 | 0.30 | 1.26 | 1.10 | 3.68 |
| GREASY | 1 | 7.41 | 6.58 | 7.83 | 7.74 | 7.49 | 8.09 | 7.00 | 7.57 | 7.56 | 5.32 |
| | 2 | 1.15 | 1.19 | 0.86 | 1.22 | 1.59 | 0.88 | 1.68 | 1.43 | 1.16 | 1.10 |
| | 3 | −1.06 | 0.13 | −1.14 | −1.08 | −0.55 | −1.87 | 0.11 | −0.73 | −0.30 | 0.68 |
| | 4 | 4.77 | 4.18 | 5.41 | 3.39 | 0.83 | 13.63 | −0.39 | 1.13 | 1.46 | 0.90 |
| WASH | 1 | 3.07 | 3.73 | 4.09 | 3.52 | 3.94 | 4.11 | 3.14 | 3.94 | 4.15 | 3.46 |
| | 2 | 1.20 | 1.49 | 1.39 | 1.43 | 1.12 | 1.52 | 1.15 | 1.41 | 1.39 | 1.25 |
| | 3 | 2.01 | 1.72 | 2.22 | 1.99 | 2.67 | 2.33 | 1.96 | 2.30 | 1.10 | 1.69 |
| | 4 | 5.19 | 3.18 | 4.83 | 5.16 | 8.66 | 7.24 | 6.76 | 5.51 | 1.49 | 2.28 |

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