1   Gesture-Speech Physics in Fluent Speech and Rhythmic Upper Limb Movements

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Abstract

A common understanding is that hand gesture and speech coordination in humans is culturally and cognitively acquired, rather than having a biological basis. Recently, however, the biomechanical physical coupling of arm movements to speech vocalization has been studied in steady-state vocalization and mono-syllable utterances, where forces produced during gesturing are transferred onto the tensioned body, leading to changes in respiratory-related activity and thereby affecting vocalization F0 and intensity. In the current experiment ($N = 37$), we extend this previous line of work to show that gesture-speech physics impacts fluent speech, too. Compared with non-movement, participants who are producing fluent self-formulated speech, while rhythmically moving their limbs, demonstrate heightened F0 and amplitude envelope, and such effects are more pronounced for higher-impulse arm versus lower-impulse wrist movement. We replicate that acoustic peaks arise especially during moments of peak-impulse (i.e., the beat) of the movement, namely around deceleration phases of the movement. Finally, higher deceleration rates of higher-mass arm movements were related to higher peaks in acoustics. These results confirm a role for physical-impulses of gesture affecting the speech system. We discuss the implications of gesture-speech physics for understanding of the emergence of communicative gesture, both ontogenetically and phylogenetically.

Keywords: hand gesture, speech production, speech acoustics, biomechanics, entrainment

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42   Gesture-Speech Physics in Fluent Speech and Rhythmic Upper Limb Movements

43   Communicative hand gestures are ubiquitous across human cultures. Gestures aid

44   communication by seamlessly interweaving relevant pragmatic, iconic and symbolic expressions

45   of the hands together with speech [1–3]. For such multi-articulatory utterances to do their

46   communicative work, gesture and speech must be tightly temporally coordinated to form a

47   sensible speech-gesture whole. In fact, gestures' salient moments are often timed with emphatic

48   stress made in speech, no matter what the hands depict [4,5]. For such gesture-speech coordination

49   to get off the ground, the system must functionally constrain its degrees of freedom [6]; in doing so,

50   it will have to utilize (or otherwise account for) intrinsic dynamics arising from the bio-physics of

51   speaking and moving at the same time. Here we provide evidence that movement of the upper

52   limbs constrain fluent self-generated speech acoustics through biomechanics.

53   **The gesture-speech prosody link**

54   The tight coordination of prosodic aspects of speech with the kinematics of gesture has

55   been long appreciated and is classically referred to as the beat-like quality of co-speech gesture [7].

56   As obtained from video analysis, gesture apices are often found to align with *pitch accents*—

57   accents that are acoustically predominately defined by positive excursions in the fundamental

58   frequency (F0), lowering of the second formant, longer vowel duration, and increased intensity [8–

59   10]. Pitch accents can be perceptually differentiated by sudden lowering of F0 as well, but gestures

60   do not seem to align with those events quite as much [11].

61   More recent motion-tracking studies have also found gesture-speech prosody correlations.

62   For example, gestures' peak velocity often co-occurs near peaks in F0, even when such gestures

63   are depicting something [12–16]. In pointing gestures, stressed syllables align neatly with the

64   maximum extension of the pointing movement, such that the hand movement terminates at the

65   first syllable utterance in strong-weak stressed "PA-pa" and terminates later during the second

66   syllable utterance in the weak-strong "pa-PA" [17,18]. During finger-tapping and mono-syllabic

67   utterances, when participants are instructed to alternate prominence in their utterances ("pa, PA,

68   pa, PA"), the tapping action spontaneously aligns with the syllable pattern, such that larger

69   movements are made during stressed syllables [19]. Conversely, if participants are instructed to

70   alternate stress in finger tapping (strong, weak, strong, weak force production), speech will

71   follow, with larger oral-labial apertures for stressed versus unstressed tapping movements.

72   Even when people do not intend to change the stress patterning of an uttered sentence,

73   gesturing concurrently affects speech acoustics in a way that makes it seem intentionally stressed,

74   inducing an increase in vocalization duration and a lowering of the second formant of co-

75   occurrent speech [20]. Further, gesture and speech cycle rates seem to be attracted towards

76   particular (polyrhythmic) stabilities: In-phase speech-tapping is preferred over anti-phase

77   coordination, and 2:1 speech-to-tapping ratios are preferred over more complex integer ratios

78   such as 5:2 [21–24]. This is similar to research showing rhythmic stabilities arising out upper limb

79   movement and their interactions with respiration cycles (e.g., [25,26]). Thus, the upper limb and

80   speech system naturally couples its activity, like many other living as well as non-living

81   oscillatory systems ([27]; also see [28]), requiring further study on the exact nature of this coupling.

Gesture-speech physics

83   Mainstream understanding of the gesture-prosody link holds that it is not "biologically

84   mandated" (p. 69. in [9]; [29]), requiring neural-cognitive timing mechanisms [30,31] that appear only

85   after about 16 months of age [32] (see also [33]). Recent work, however, has investigated a potential

86   physical coupling of arm movements with speech via myofascial-tissue biomechanics. This

87   works shows that hand gesturing physically impacts steady-state vocalizations and mono-syllabic

88   consonant-vowel utterances [34–37]. Specifically, hand and arm movements can transfer a force (a

89   physical impulse) onto the musculoskeletal system, thereby modulating respiration-related

90   muscle activity, leading to changes in vocalization's intensity. If vocal-fold adjustments do not

91   accommodate for gesture-induced impulses, the fundamental frequency (F0) of vocalizations is

92   affected as well. Higher-impulse arm movements or two-handed movements will induce more

93   pronounced effects on F0 and intensity than lower-impulse wrist movements or one-handed

94   movements. This is because the mass of the "object" in motion is greater in magnitude for arm

95   versus wrist movements, thereby changing the momentum of the effector (everything else—such

96   as effector speed—being equal, as effector momentum equals effector mass times effector

97   velocity). The change in momentum is the physical impulse, and physical impulse is highest

98   when the change in velocity (i.e., acceleration) is highest (everything else—such as effector

99   mass—being constant).

100   How physical impulses are absorbed by the respiratory system is likely complex and not a

101   simple linear function [38]. However, a complete understanding will involve an appreciation of the

102   body as a pre-stressed system [39,40], forming an interconnected tensioned network of compressive

103   (e.g., bones) and tensile elements (e.g., fascia, muscles) through which forces may reverberate

104   nonlinearly [41,42]. Specifically, the upper limb movements are controlled by stabilizing

105   musculoskeletal actions of the scapula and shoulder joint, which directly implicate accessory

106   expiratory muscles that also stabilize scapula and shoulder joint actions (e.g., the serratus anterior

107   inferior; see [37] for an overview).

108   Peripheral actions also play a role, as performing an upper-limb movement recruits a

109   whole kinetic chain of muscle activity around the trunk (e.g., rector abdominus) to maintain

110   posture [43–45]. Indeed, when people are standing versus sitting, for example, the effects of peak

111   physical impulse of gestures onto vocalization acoustics are more pronounced [34]. We reasoned

112   that this is because standing involves more forceful anticipatory postural counter adjustments [46],

113   which reach the respiratory system via accessory expiratory muscles also implicated in keeping

114   postural integrity (see also [44,45]). Recently, more direct evidence has been found for the gesture-

115   respiratory-speech link: Respiratory-related activity (measured with a respiratory belt) was

116   enhanced during moments of peak-impetus of gesture as opposed to other phases in the gesture

117   movement, and respiratory-related activity itself was predictive of the gesture-related intensity

118   modulations of mono-syllable utterances [37].

119   The evidence reviewed so far has been based on experiments on continuous vocalizations

120   or monosyllabic utterances and cannot, therefore, directly generalize to fluent, self-generated,

121   full-sentenced speech. However, recent work suggests that gesture-speech physics does

122   generalize to fluent speech. For example, Cravotta and colleagues[47] found that encouraging

123   participants to gesture during cartoon narration versus giving no instructions lead to 22Hz

124   increase in observation of max F0 and to greater F0 ranges of speech and intensity. Furthermore,

125   computational modelers have reported on interesting successes in synthesizing gesture kinematics

126   based on speech acoustics alone [48,49], indicating that information about body movements inhabits

127   the speech signal (see also [50,51]). Although such results do not necessitate a role for biomechanics,

128   they do suggest a strong connection between gesture and speech.

129   **Current experiment**

130   The current experiment was conducted as a simple test of the constraints of upper limb

131   movement on fluent speech acoustics. Participants were asked to retell a cartoon scene that they

132 had just watched, while either not moving, vertically moving their wrist, or vertically moving

133 their arm at a tempo of 80 beats per minute (1.33Hz). Participants were asked to give a stress or

134 beat in the downward motion with a sudden stop at maximum extension (i.e., sudden

135 deceleration). Participants were asked to not allow movements to affect their speaking

136 performance in any way. Similar to previous experiments [34,37], we assessed the following to

137 conclude that gesture-speech physics is present:

138   • 1) Does rhythmic co-speech movement change acoustic markers of prosody (i.e.,

139   F0 and amplitude envelope)?

140   • 2) At what moments of co-speech movement is change in acoustics observed?

141   • 3) Does degree of physical impulse (as measured by effector mass or changes in

142   speed) predict acoustic variation?

143 **Method**

144 **Participants & Design**

145 A total of 37 undergraduate students at the University of Connecticut were recruited as

146 participants (*M* age = 18.76, *SD* age = 0.95, %cis-gender female = 67.57, %cis-gender male =

147 32.43, %right-handed = 94.59).

148 The current design was fully-within subject, with a three-level movement manipulation

149 (passive vs. wrist-movement vs. arm-movement condition). Movement condition was randomly

150 assigned per trial. Taken together, participants performed 419 trials, each lasting about 40

151 seconds. The study design was approved by the IRB committee of the University of Connecticut

152 (#H18-227).

153 **Material & Equipment**

154 **Cartoon vignettes.** Twelve cartoon vignettes were created from the "Canary Row" and

155 "Snow Business" Tweety and Sylvester cartoons (M vignette duration = 59.42 seconds; *SD* =

156 32.11 seconds). These cartoons are often used in gesture research (McNeill, 1992). The videos

157 can be accessed here: https://osf.io/rfj5x/.

158   **Audio and Motion Tracking.** A MicroMic C520 cardioid condenser microphone headset

159   (AKG, Inc.) was used to record audio at 44.1 kHz. The microphone was plugged into a computer

160   that handled the recording via a C++ script. Also plugged into this computer was a Polhemus

161   Liberty motion tracking system (Polhemus, Inc.), which tracked position of the participant's

162   index finger of the dominant hand, sampling with one 6D sensor at 240 Hz. We applied a first-

163   order Butterworth filter at 30 Hz for the vertical position (z) traces and its derivatives.

Procedure

165   Upon arrival, participants were briefed that this 30-minute experiment entailed retelling

166   cartoon scenes while standing and performing upper-limb movements. A motion sensor was

167   attached to the tip of the index finger of their dominant hand, and a microphone headset was put

168   on. Participants were asked to stand upright and were introduced to three movement conditions

169   (see Figure 1). In the passive condition, participants did not move and kept their arm resting

170   alongside the body. In the wrist-movement condition, participants were asked to continuously

171   move the hand vertically at the wrist joint while keeping the elbow joint at 90 degrees. In the

172   arm-movement condition, participants moved their arm vertically at the elbow joint, without

173   wrist movement. Similar to previous studies [34], participants were asked to give emphasis in the

174   downward motion of the movement with a sudden halt—in other words, a beat—at the maximum

175   extension of their movement.

176   After introduction of the movements, participants were told that they were to move at a

177   particular tempo, indicated by visual feedback system. The feedback system consisted of a

178   horizontal bar that continually updated to report on the participant's movement speed in the

179   previous movement cycle. The participant was to keep the horizontal bar between the lower and

180   higher boundaries (a 20% region, [72-88] BPM) of the 1.33-Hz target tempo (i.e., 80 BPM).

181   Participants briefly practiced moving at the target rate before starting the experiment.

182   Critically, the participants were not exposed to an external rhythmic signal, like a visual

183   metronome. Subsequently, participants were instructed that they would watch and then retell

184   cartoon clips while making one of the instructed movements (or making no movements).

185   Participants were asked to keep their speech as normal as possible while making the

186   movements (or no movement). In the conditions requiring movement, participants were to keep

187   their movement tempo within the target range. Twelve cartoon vignettes were readied to be

188 shown before each trial. The experiment ended when the participant saw and retold all 12

189 vignettes or when the total experiment time reached 30 minutes. To ensure that all movement

190 conditions would be performed at least once within that time, we set the maximum time per trial

191 at 1 minute. In other words, when participants were still retelling the same scene after 60 seconds,

192 the experimenter would terminate the trial and move to the next trial. Mean retelling time was,

193 however, well below 1 minute ($M = 26.00$ seconds, $SD = 7.06$).

194

195   Figure 1. Graphical overview of movement conditions
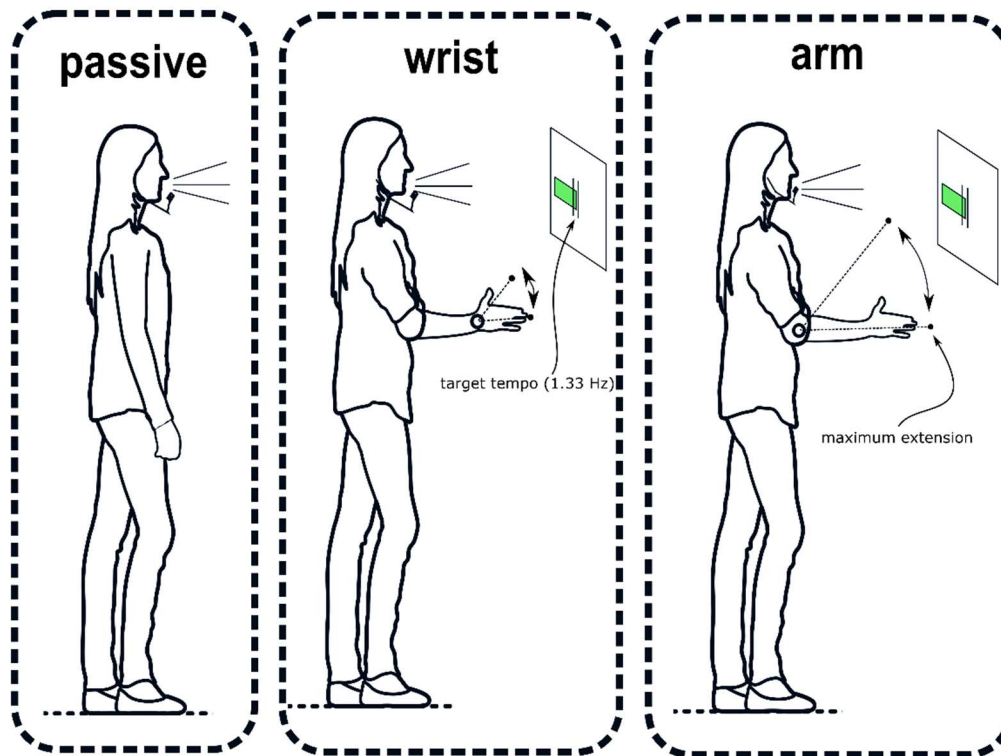
196

197   *Note*. Movement conditions are shown. Each participant performed all conditions (i.e., within-

198   subjects). To ensure that movement tempo remained relatively constant, participants were shown

199   a moving green bar, which indicated whether they moved too fast or too slow relative to a 20%

200   target region of 1.33Hz. Participants were instructed to have an emphasis in the downbeat with an

201   abrupt stop (i.e., beat) at the maximum extension.

202   **Preprocessing**

203   **Speech acoustics.** The fundamental frequency was extracted with sex-appropriate preset

204   ranges (male = 50-400Hz; female = 80-640Hz). We used a previously written R script

205   (https://osf.io/m43qy/; [52]) utilizing the R package 'wrassp' (Winkelmann, Bombien, & Scheffers,

206   2018), which applies a K. Schaefer-Vincent algorithm. It should be noted that F0 tracking is

207   always susceptible to noisy estimation. We have, however, checked multiple participants' data

208   for mistrackings of F0 algorithm (e.g., sudden jumps to higher harmonics) and did not find any.

209   Given the current sample size, we did not hand-check the F0 track for all the data, so we must

210   accept a certain range of noise that is common to F0 tracking.

211   We also extracted a smoothed (5-Hz Hann window) amplitude envelope using a

212   previously written custom-written R script (https://osf.io/uvkj6/, which reimplements a procedure

213   from He & Dellwo, 2017). The amplitude envelope was calculated by applying a Hilbert

214   transformation to the sound waveform, yielding a complex-valued analytic signal from which we

215   take the complex modulus. After smoothing and downsampling to 240Hz, this gives a one-

216   dimensional time series referred to as the amplitude envelope, tracing the extrema of the sound

217   waveform as shown in Figure 2.

218   **Data and Exclusions.** We collected 189.70 minutes of continuous data (passive condition

219   = 63.45, wrist-movement condition = 63.56, arm-movement = 62.69). However, a C++ memory

220   allocation error caused an insufficient storage to be reserved for more than 6 digits resulted in the

221   loss of the precise timing information of the sampling of the motion tracker after a certain period,

222   i.e., after a 7th digit was needed to represent time (> 1 million milliseconds or 16 minutes and 40

223   seconds), fortunately affecting only a subset of the experiment data for each participant. Full data

224   was therefore obtained for the first 16m & 40s of each trial for each participant. We limit our

225   analyses to this complete data set. This dataset consists of 124.49 minutes of continuous speech

226   and movement data (passive = 40.08, wrist-movement condition = 42.32, arm-movement

227   condition = 42.10).

228   **Baseline**

229   We created a surrogate condition as a baseline for temporal coordination between speech

230   and movement. We randomly paired the speech of the passive condition trials of participant x

231   with motion-tracking data from the movement conditions for that participant x (without

232   scrambling the order of the speech and motion time series extracted in these falsely paired trials).

233   This surrogate randomly paired condition allowed us to exclude the possibility that any effects of

234   movement were due to chance correlations inherent to the structure of speech and movement,

235   rather than the correlations arising out of the coupling of speech and movement. We only use this

236   surrogate control condition as a contrast when we are performing analysis on the temporal

237   relation between speech and movement.

238   **Manipulation Checks**

239   We computed additional measures to check whether our movement manipulation was

240   successful and whether speech rates were comparable across conditions. Figure 2 shows a

241   summary of the results for key manipulation check measures.

242   **Movement Frequency.** To ascertain whether participants moved their limbs within the

243   target 1.33-Hz range, we performed a wavelet-based analysis (using R package "WaveletComp";

244   [53]). Wrist movements were performed at slightly faster rates ($M = 1.44$ Hz, $SD = 0.24$) than arm

245   movements ($M = 1.36$ Hz, $SD = 0.19$), but in both cases the movements were distributed over the

246   target range. This confirms that our movement manipulation was successful. For our surrogate

247   control condition, the mean frequency of the artificially paired movement time series fell between

248   both arm- and wrist-movement condition frequency distributions ($M = 1.41$ Hz, $SD = 0.22$).

249   **Speech Rate.** We calculated two measures of speech rate: vocalization duration and

250   vocalization interval (see Fig. 2 for examples), which are measures derived from information in

251   the F0 track, as well as the amplitude envelope for the interval calculation. The vocalization

252   duration was defined as the length of time (in milliseconds) of an uninterrupted run of F0

253   observations. The vocalization interval was determined by identifying two consecutive runs of F0

254   observations (i.e., vocalization events) and determining the peak amplitude envelope of each of

255   those vocalization events so as to compare the relative timing between those peaks. This way we

256   have a single time point for each vocalization event that we can compare with the next

257   vocalization event's time point (i.e., the vocalization interval).

258   Figure 3 shows relatively uniform distributions for these specific speech measures. No

259   clear 1:1 frequency couplings of movement and vocalization duration or vocalization interval nor

260   any other clear signs of polyrhythmic coupling of movement and speech are observed (see e.g.,

261   [22,24]). Note though that there are other possible (acoustically defined) units of speech that might

262   entrain to movements that we do not further pursue here [54]. We restrict ourselves for the current

263   report to speech vocalization acoustics rather than speech-movement cycle dynamics, as the

264   former is the confirmatory research topic of the current study.

265   To compare vocalization rates to movement, we computed the average vocalization

266   duration and interval for each trial by tracking the time of uninterrupted runs of F0 observations

267   and then converting the time in milliseconds to Hz. For the passive condition, the average

268   vocalization duration was $M = 6.28$ Hz ($SD = 6.03$), and the vocalization interval was $M = 5.17$

269   Hz ($SD = 6.94$). For the wrist-movement condition the vocalization duration was $M = 6.24$ Hz

270   ($SD = 5.96$), and the vocalization interval was $M = 5.02$ Hz ($SD = 6.86$). For the arm-movement

271   condition, the vocalization duration was $M = 6.08$ Hz ($SD = 5.83$), and the vocalization interval

272   was $M = 4.86$ Hz ($SD = 5.76$).

273   Figure 2. Example movement, amplitude envelope, F0 time series, and time-dependent

274   movement frequency estimates

275
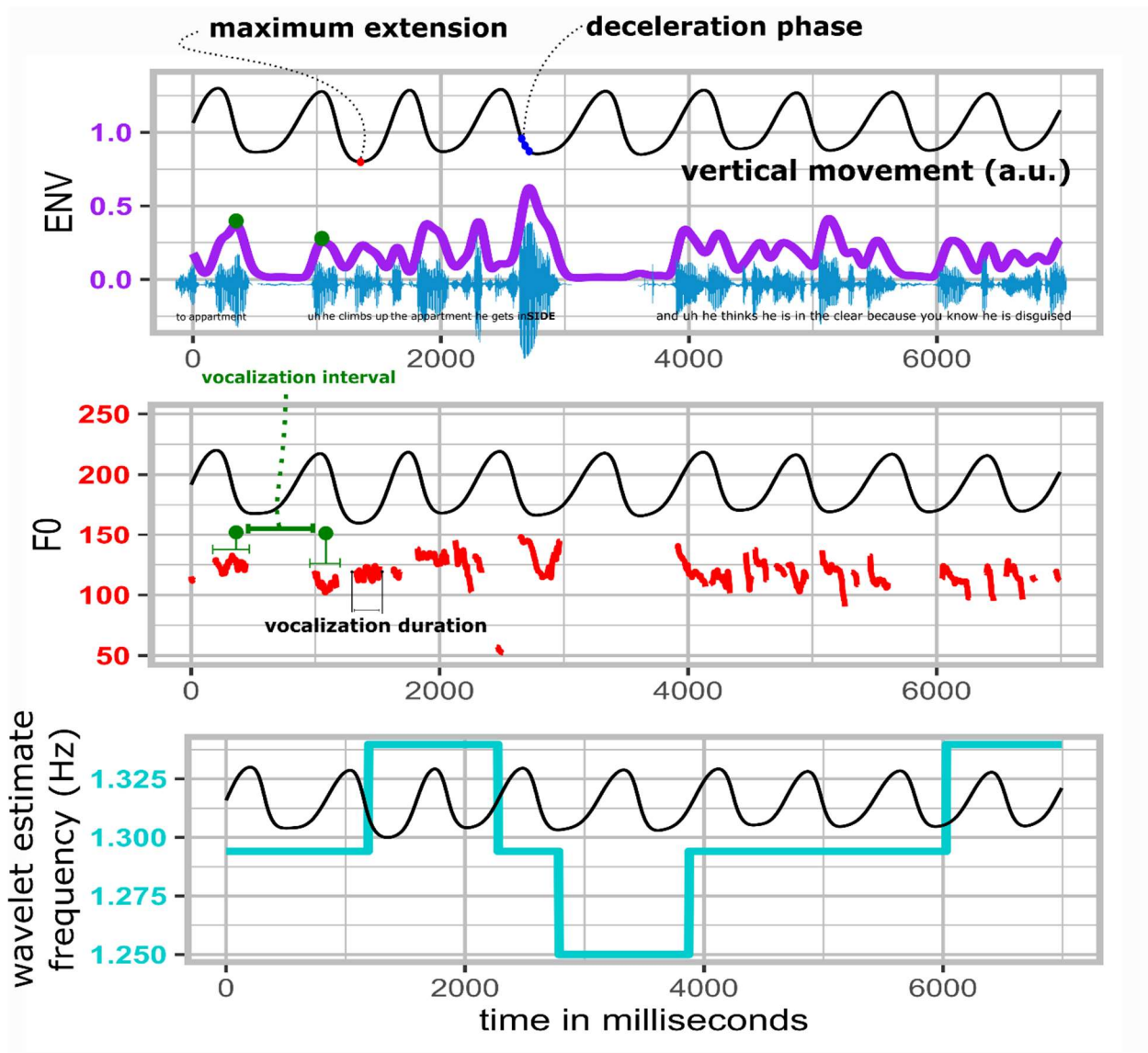
276   *Note figure 2.* A sample of about 10 seconds is shown. With the participant's permission the

277   speech sample is available at https://osf.io/2qbc6/. The smoothed amplitude envelope in purple

278   traces the waveform maxima. The F0 traces show the concomitant vocalizations in Hz, with an

279   example of vocalization interval and vocalization duration (which were calculated for all

280   vocalizations). The bottom panel shows the continuously estimated movement frequency in cyan,

281   which hovers around 1.33 Hz. In all these panels, the co-occurring movement is plotted in

282   arbitrary units (a.u.) to show the temporal relation of movement phases and the amplitude

283   envelope, F0, and the movement frequency estimate. In our analysis, we refer to the maximum

284   extension and deceleration phases as relevant moments for speech modulations. In this example,

285   a particularly dramatic acoustic excursion occurs during a moment of deceleration of the arm

286   movement, possibly an example of gesture-speech physics.

287   Figure 3. Summaries of movement frequency, vocalization duration and vocalization interval

288
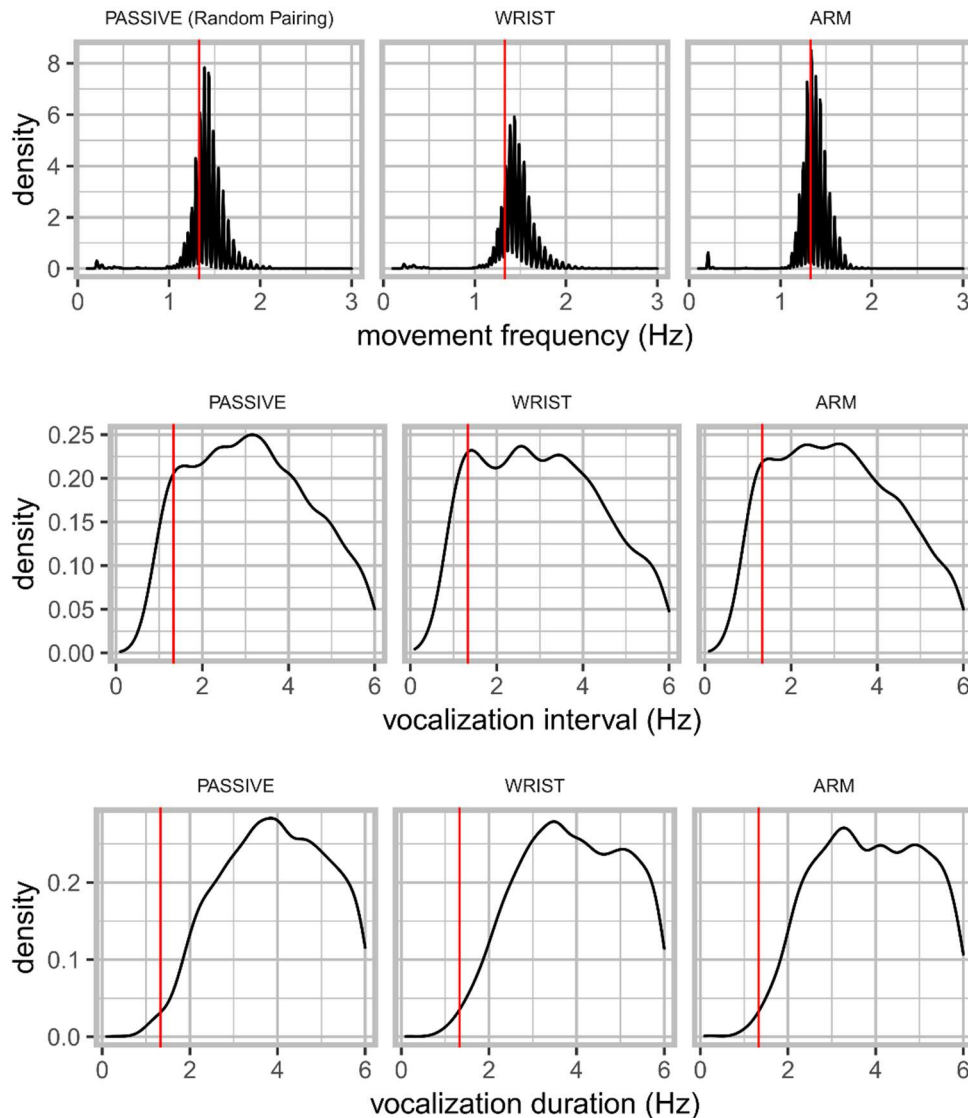
289 *Note Figure 3*. Density distributions of movement frequencies, vocalization interval, and
290 vocalization duration are shown. There was no movement for the passive condition, but we
291 display the randomly paired movement time series in the surrogate baseline pairing for which
292 frequency information is shown. The red vertical line indicates the target movement frequency
293 (1.3 Hz).

294   **Results**

295 **Overview of analyses**

296   We report three main analyses to show that gesture-speech physics is present in fluent
297 speech. Firstly, we assess overall effects of movement condition on vocalization acoustics (F0
298 and the amplitude envelope); these would support our hypothesis that upper limb movement—
299 and, especially, high-impulse movement—constrains fluent speech acoustics. Secondly, we
300 assess whether vocalization acoustic modulations are observed at particular phases of the
301 movement cycle, which gesture-speech physics holds should occur at moments of peaks in
302 deceleration. Thirdly, we assess whether a continuous estimate of upper-limb physical impulse
303 through deceleration rate predicts vocalization acoustic peaks, which would support the gesture-
304 speech physics hypothesis that physical impulses are transferred onto the vocalization system.
305 The following generally applies to all analyses. For hypothesis testing, we performed mixed
306 linear regression models (using R package "nlme"; [55]), and non-linear generalized additive
307 modeling or GAM (using R package "gam"; [56]) with random intercept for participants by default.

308 **Acousic correlates of movement condition**

309   Figure 4 shows the average F0 and amplitude envelope (*z*-scaled for participants) per trial
310 per condition. The passive condition had generally lower levels of F0 and amplitude envelope as
311 compared to the arm- and wrist-movement conditions. Furthermore, the higher-impulse arm-
312 movement condition generally had higher levels of F0 and amplitude envelope as compared to
313 lower-impulse wrist-movement condition.

314   Table 1 shows the results of mixed linear regression analysis. For the amplitude envelope,
315 the passive condition had a lower average amplitude envelope as compared to the the wrist-
316 movement condition, as well as the arm-movement condition. After accounting for differences in

317   F0 for sex (males had generally 73 Hz lower F0), wrist-movement condition had about 1.6 Hz

318   increase in average as compared to the passive condition, but this was not statistically reliable.

319   Further, the arm-movement condition increased in F0 by 3.5 Hz over the passive Condition.

320   Figure 4. Average F0 and amplitude envelope (ENV) per trial per condition

321
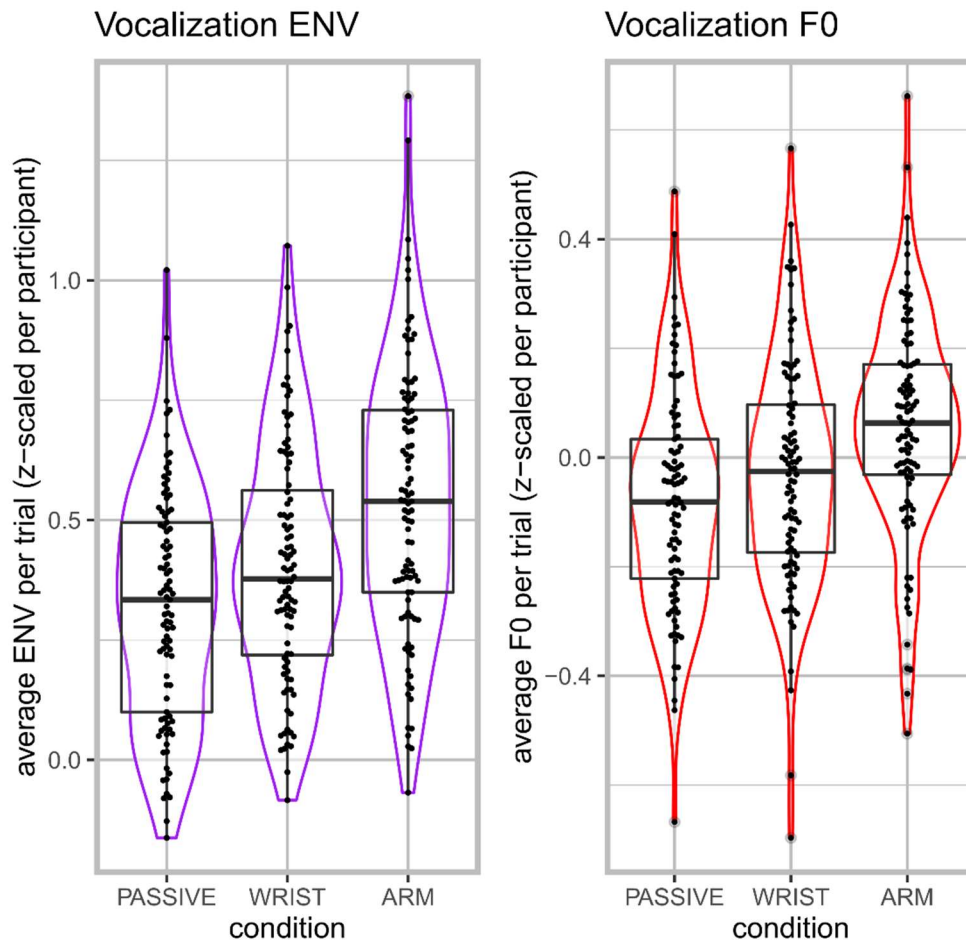
322   *Note Figure 4*. Violin and box plots are shown for average F0 (Hz) and amplitude envelope (*z*-

323   scaled) per trial. (Points are jittered to show per-trial observations).

324

325 Table 1. Linear mixed effects for effects of condition on F0 and amplitude envelope (ENV)

	contrast	b	SE	df	p
ENV (z-scaled)	intercept	0.32	0.036	251	< .0001
	Wrist vs. Passive	0.094	0.028	251	0.001
	Arm vs. Passive	0.215	0.028	251	< .0001
F0 (Hz)	intercept	186.577	3.22	251	< .0001
	Male vs. Female	-73.268	5.437	33	< .0001
	Wrist vs. Passive	1.603	0.845	251	0.0588
	Arm vs. Passive	3.504	0.828	251	< .0001

326 **Coupling of vocalization duration and movement**

327   Having ascertained in the previous analysis that acoustics were modulated for movement
328 versus no movement, we further need to confirm that such modulations occur at particular
329 moments in the movement cycle. Figure 5 shows the main results for all data, in which we model
330 over time the acoustic patterning in vocalizations around the maximum extension of the
331 movement cycle, for all movement cycles that occurred. If vocalizations are affected in particular
332 moments of the movement cycle—for example, when the hand starts decelerating (estimated
333 from the data as shown in Figure 5)—we would expect acoustic modulations (peaks) at such
334 moments of the movement cycle.

335   Just before the moment of maximum extension, the observed amplitude envelope shows a
336 clear peak, most dramatically for the arm-movement condition, but also for the wrist-movement
337 condition. For speech in the randomly paired movement- and passive condition, this was not the
338 case; this provides evidence that the results observed in the arm- and wrist-movement conditions
339 are not due to mere chance. For F0, the pattern is somewhat less clear, but positive peaks still
340 occur just before the maximum extension. These findings replicate our earlier work on steady-
341 state vocalization and mono-syllabic utterances, showing that moments of peak deceleration also
342 show peaks in acoustics [34,37].

343   To test whether trajectories are indeed non-linear and are reliably different from the
344 passive condition, we performed generalized additive modeling (GAM), a type of non-linear

345   mixed effects procedure. GAM is a popular time-series analysis in phonetics and allows the

346   automatic modeling of more (and less) complex non-linear patterns by combining a set of smooth

347   basis functions. Furthermore, GAM allows for testing whether those non-linear trajectories are

348   modulated depending on some grouping of the data (see, e.g., [57]). We assessed the trajectory of

349   acoustics around 800 milliseconds of the maximum extension of the movement. We chose 800

350   milliseconds (-400, 400), as this is about the duration of a 1.33Hz cycle (1000/1.33Hz = 752 ms)

351   with an added margin of error of about 50ms. The model results with random slopes and intercept

352   for participant are shown in Table 2.

353   Firstly, for all models, tests for non-linearity of the trajectories were statistically reliable

354   (ps < .0001), meaning that there were peaks or valleys in acoustics over the movement cycle

355   rather than a flat linear trend (Figure 6). As shown in Table 2, our results replicate the general

356   finding that the wrist movements condition led to reliably different non-linear peaks in acoustics

357   as compared to the passive condition (p < .001). Moreover, this effect—relative to the passive

358   condition—is even more extreme for the arm-movement condition (p < .001). Figure 6 provides

359   the fitted trajectories for the GAM models.

360   For readers interested in individual differences in trajectories, we have created interactive

361   graphs for each participant's average amplitude envelope trajectories (https://osf.io/a423h/) and

362   F0 trajectories (https://osf.io/fdzwj/).

363   Figure 5. Average observed vocalization acoustics relative to the moment of maximum extension
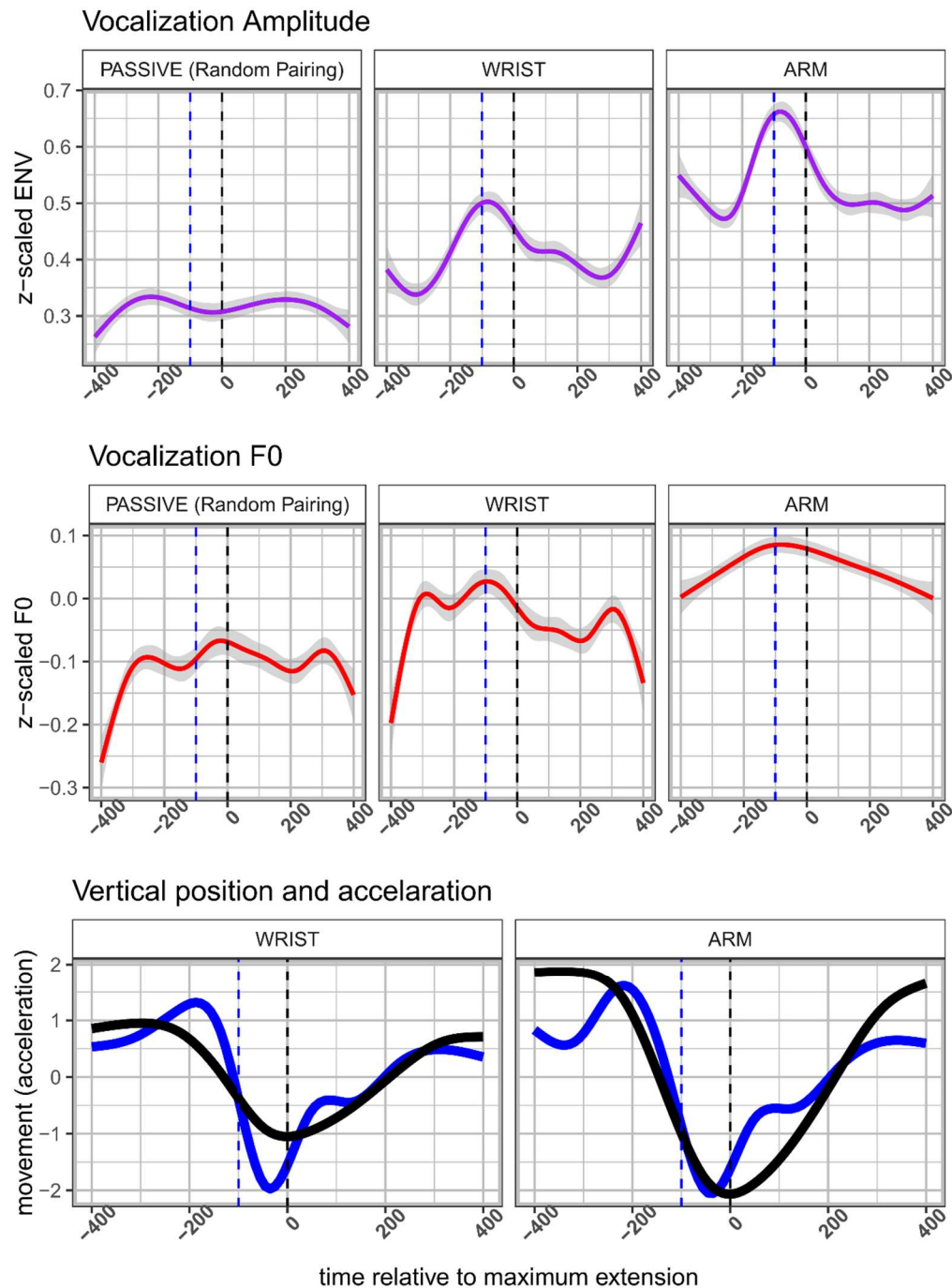
364

365   *Note Figure 5*. For the upper two panels the average acoustic trajectory is shown around the
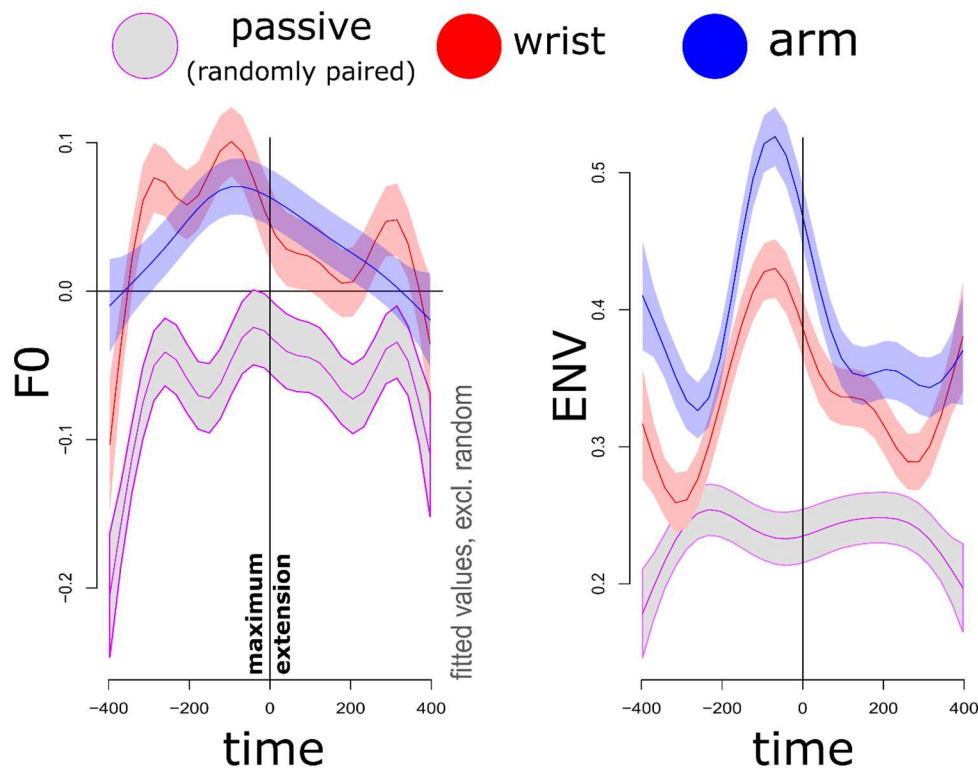
366   moment of maximum extension ($t = 0$, dashed black line). In the lower panel, we have plotted the

367   z-scaled average vertical displacement of the hand and the z-scaled acceleration trace. The blue

368   dashed vertical line marks the moment where the deceleration phase starts, which aligns with

369   peaks in acoustics.

370   Figure 6. Fitted trajectories GAM

371

372   Table 2. Model results for GAM analysis

|	contrast	b	SE	df	p
ENV (z-scaled)	intercept	0.237	0.006	36.923	< .0001
	Wrist vs. Passive	0.096	0.009	10.579	< .0001
	Arm vs. Passive	0.152	0.009	16.862	< .0001
F0	intercept	-0.061	0.006	-8.35	< .0001
	Male vs. Female	-0.019	0.009	-4.29	< .0001
	Wrist vs. Passive	0.101	0.009	10.222	< .0001
	Arm vs. Passive	0.094	0.103	9.546	< .0001

373   *Note*. Model results are shown for the amplitude envelope (ENV; *z*-scaled) and F0 (Hz). For F0,

374   we accounted for sex differences when estimating independent effects of condition.

375 **Degree of physical impetus and acoustic peaks**

376   We have confirmed that speech acoustics are modulated around moments of the
377 deceleration phase, about 0-200 ms before the maximum extension. The effect of gesture-speech
378 physics can be further examined by looking at how the forces produced by the upper-limb
379 movement predict acoustic peaks. Therefore, for all vocalizations that occurred between 200–0ms
380 before the maximum extension, we assessed whether acoustic peak (i.e., maximum F0 or
381 maximum amplitude envelope) was predicted by the maximum deceleration value (i.e., minimum
382 acceleration observation) observed in that 200 ms window. In previous research, we found that
383 higher deceleration was related to higher amplitude envelope observations but not F0 [37].

384   Figure 7 shows the general pattern of the results for the wrist- and arm-movement
385 condition. For each participant's trial in each condition, we averaged the maximum deceleration
386 values of max F0 and max ENV for each vocalization event. Table 3 shows the model results of
387 linear mixed-effects model with random intercept and slopes for participants, in which we
388 regressed the trial-averaged maximum observed deceleration against the co-occurring trial-
389 averaged vocalization acoustic peaks for amplitude envelope and F0 (separately). Higher
390 deceleration indeed predicted higher amplitude envelope. This was also the case for F0, but only
391 for arm movements (as opposed to wrist movement), as indicated by a statistically reliable
392 interaction between condition and max deceleration effect ($ps < .05$). Together, these demonstrate
393 the roles of both acceleration and effector mass in producing physical impulses.

394

395   Figure 7. Relation max deceleration and height acoustic peak
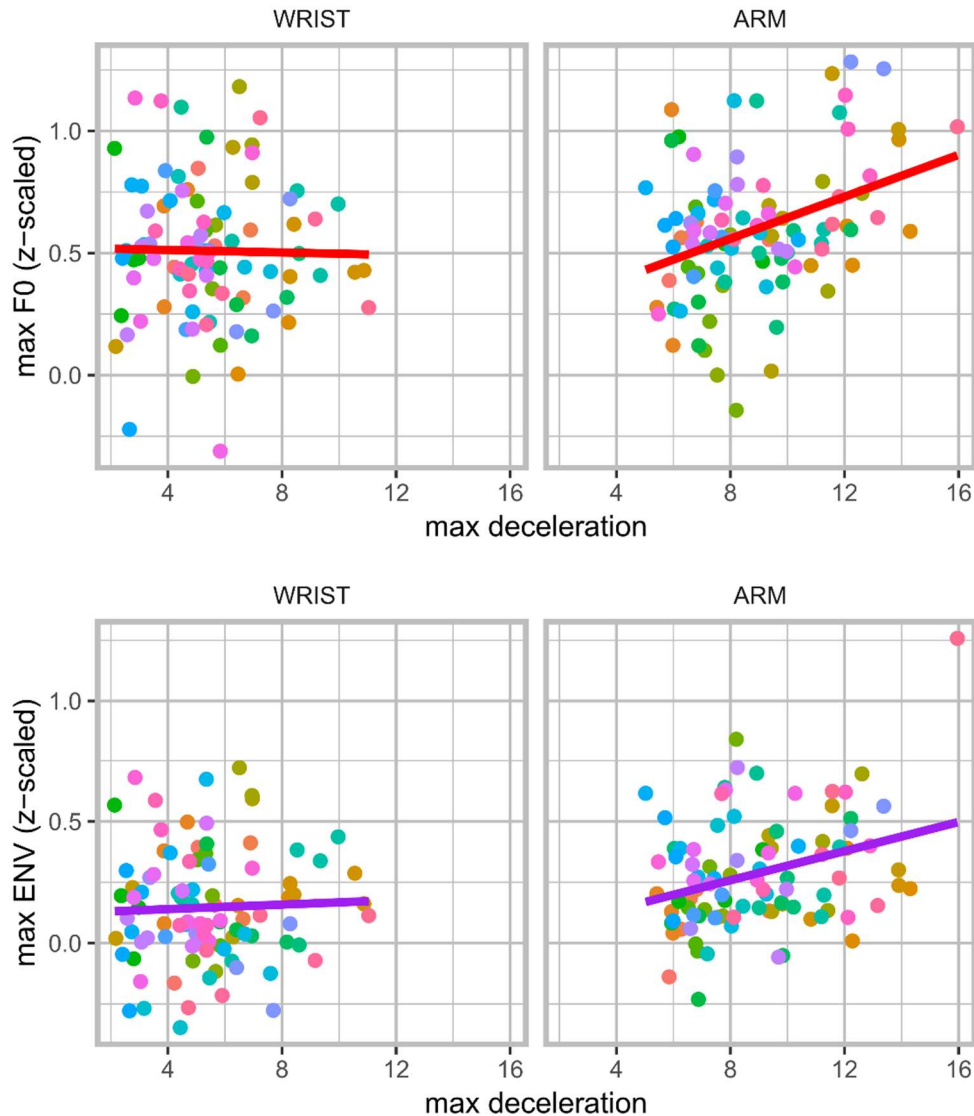
396

397   *Note Figure 7*. The *x*-axis shows the average maximum deceleration per trial (absolutized

398   negative acceleration value), where 0 indicates no deceleration (absolutized) and positive values

399   indicate higher deceleration rates in cm/s^2. Each point contains trial averaged values. It can be

400   seen that deceleration rates are more extreme for the arm versus the wrist condition. On the *y*-

401   axis, we have the average maximum observed amplitude envelope (lower panel) and F0 (upper

402   panel) for those moments of deceleration. Higher decelerations co-occur with higher peaks in

403   acoustics for arm movements (but not or less so for wrist movements).

404

405   Table 4. Linear mixed effects of deceleration and acoustic peaks

Model		contrast	b	SE	df	p
1.	ENV (z-scaled)	Intercept	0.003	0.06	153	0.9597
		Max Deceleration	0.029	0.007	153	<.001
2.	F0 (z-scaled)	intercept	0.512	0.086	151	< .0001
		Arm vs. Wrist	-0.284	0.134	151	0.0349
		Max Deceleration	-0.001	0.015	151	0.9603
		Arm x Max Deceleration	0.042	0.018	151	0.0205

406   *Note.* Wrist movement is the reference factor for model 2.

Discussion

407

408   In the current study, we demonstrated biomechanical effects of flexion-extension upper-
409 limb movements on speech by replicating in fluent speech effects obtained in steady-state
410 vocalization and mono-syllabic utterances. We showed that rhythmically moving the wrist or arm
411 affects vocalization acoustics by heightening F0 and amplitude envelope of speech vocalizations,
412 as compared to both passive-control and statistical-control conditions. We finally show that
413 higher deceleration rates observed within 200 milliseconds before the moment of the maximum
414 extension of the arm movement materializes into more extreme acoustic peaks, demonstrating a
415 role for acceleration and effector mass for gesture's effect onto speech (i.e., an effect of physical
416 impulse). Indeed, in all analyses, we observe that higher-mass arm versus wrist movements affect
417 speech more clearly.

418   Thus, stabilities in speaking may arise out of gesture-speech biomechanics in fluent
419 speech as well as more simplified speech sounds. This does not mean that speech prosody
420 necessarily requires gesture for reaching prosodic targets. Indeed, other sensorimotor solutions
421 are available for modulating F0 and intensity (e.g., vocal-fold tensioning, respiratory actions; [58]).
422 Furthermore, F0 is uniformly less (if at all) affected, in line with our previous work [37] and other
423 work on the variable and often negligible role of respiratory actions in F0 modulations [59].
424 However, we think on the basis of present work we can argue that the biomechanical coupling of
425 gesture and speech provides a 'smart' mechanism for 'timing' acoustic and movement
426 expressions—and provides a way toward understanding the phylogenetic origin of pulse or beat
427 quality of gesture.

428   We should wonder still whether the current effects of upper limb movement can be
429 produced due to the attentional guidance to move (in the sense of "I must stop my wrist here and
430 move up"), rather than the physical impulses produced by moving. In the previous studies, we
431 provided additional evidence with a respiration belt that tensioning around the trunk is involved
432 in gesture-induced effects on vocal acoustics[37] or that postural stability moderates said effects[34].
433 The additional evidential strength of these previous studies for gesture-speech physics lies in part
434 in that a cognitive control account does (a) not readily predict that trunk tensioning is involved in
435 synchronizing upper limb movement and speech and (b) equally does not predict that standing or
436 sitting matters for synchronizing two speech and gesture trajectories. It should be noted here that

437   trunk tensioning and postural control effects could be explained (in principle) with some new

438   cognitive control account, but such an account would not seem parsimonious in light of a gesture-

439   speech physics alternative.

440   This reasoning from parsimony extends to the basic kinematic-acoustic analysis of the

441   current study, too. We should therefore ask in the current context: Does a cognitive control

442   account predict that arm motion versus wrist motion should lead to heightened acoustic effects,

443   that acoustic peaks arise around the deceleration phase rather at the maximum extension phase, or

444   that the degree to which a limb in motion decelerates scales with the acoustic peak that ensues? It

445   is wholly possible that a particular cognitive control account may still account for all these effects

446   or, more likely, a subset of these effects. But to do so, one needs to invoke some new hypothesis

447   about how this cognitive control system produced these observables. This comes at the cost of

448   parsimony, as we are invoking new unobservable mechanisms to explain these observables—

449   especially if a more parsimonious explanation that explains these effects is already available.

450   To be clear, this does not mean that we can fully exclude cognitive control—neither in

451   principle nor, more forcefully, in degree. Fluid speech likely includes bidirectional interactions

452   either of amplification or counteraction of gesture-speech physics with lexical, syntactics, and

453   prosodic speech organization. In other words, complex interactions likely arise between the

454   biophysical constraints arising out of moving your upper limb while vocalizing and a speech

455   system organizing meaningful speech in the context of those constraints (see e.g., [32,60]). For

456   example, a speaker might speed up the occurrence of a physical impulse, as then it will occur

457   during a part of speech where there is a lexical stress. Or a speaker might counteract an F0 effect

458   of a physical impulse laryngeally, as its acoustic effect would lead to an inappropriate acoustic

459   marker in the syntactic context of the sentence. These potential interactions between gesture-

460   speech physics and meaningful speech organization must be studied in controlled experiments,

461   but we believe they likely exist in real-world contexts, too.

462   While future research should include controlled experiments on syntactic, lexical and

463   prosodic interactions with biophysical constraints, more research is needed on truly spontaneous

464   speech as well. In the current study, participants are retelling a cartoon, which is a very different

465   context than, say, a conversation; in part because cognitive load of having to retell something

466   accurately from recent memory while also having to move (see e.g., [26,61,62]).

467 **Wider implications**

468 Gesture-speech physics holds promise for revising our understanding of the emergence of
469 communicative gesture in anatomically modern humans, both ontogenetically and
470 phylogenetically.

471 It is well known that infants produce concurrent vocal-motor babblings. Furthermore,
472 increased rhythmicity or frequency of motor babbling predicts speech-like maturation of
473 vocalization [63,64]. Rather than a primarily neural development that instantiates gesture-speech
474 synchrony [32], we suggest that during such vocal-motor babblings gesture-speech physics is
475 discovered; this could provide the basis for infants to develop novel stable sensorimotor solutions
476 for communication, such as a synchronized pointing gesture with a vocalization. Such
477 sensorimotor solutions are, of course, likely solicited and practiced through support of caretakers,
478 yet without the biomorphological scaffolding, gesture-speech synchrony would not get off the
479 ground ontogenetically.

480 Phylogenetic accounts have been central in discussions of the drivers of the depiction and
481 referential function of gesture [65–67]. However, the current work supports the view that peripheral
482 body movements may have served as a control parameter of an evolving vocal system. Previous
483 work has proposed that the vocal system may have been evolutionarily exapted from rhythmic
484 abilities in the locomotor domain [68,69], and viewing upper limb movements as constraints on the
485 vocal system's evolution fits neatly in such views. When our species became bipedal, the
486 respiratory system was thereby liberated from upper-limb locomotary perturbations. We know
487 that breathing (and vocalization) cycles often rigidly couple 1:1 with locomotion cycles in
488 quadrupeds [70], rigidly limiting what can be done (or communicated) in one breath. Similarly to
489 how vocalization acoustics of flying bats are synchronized with their wing beats through
490 respiratory interactions [71]. Bipedalism, however, did not only free respiration from locomotion; it
491 freed the upper limbs, too, allowing these highly skilled articulators to modulate a possibly less
492 skilled respiratory-vocal system. Gestures, then, may have played a role in the complexification
493 of the control of the respiratory system in our species, which has been attributed to have occurred
494 to serve speech evolution [72,73].

495 Upper limb-vocal synchrony is not specific to human culture, as many non-human animals
496 can do it, too (e.g., bats; [71]). It can further be related to other species—including orangutans, who

497 deepen their vocalizations by cupping their hands in front of their mouth [74]. Other animals have

498 been found to be sensitive to body-related information in sound in that body size and strength can

499 be detected from vocalizations alone [75,76], and humans are able to do this with some accuracy as

500 well [77], even when they are blind from birth [78]. In a recent experiment, we found that listeners are

501 exquisitely sensitive to gesture-modulated acoustics: Listeners can synchronize their own upper

502 limb movement by simply listening to a vocalizer producing a steady-state vocalization while

503 rhythmically moving their wrist or arm [35]. Thus, bodily dynamics can imprint the (human) voice,

504 and this can be informative for listeners. Further research is needed to see if possibly other bodily

505 contexts can tune and live through the vocal system similarly as hand gestures, for example head

506 gesturing and body postures [79–81].

507   To conclude, gesture-speech physics opens up the possibility that gesture may have

508 evolved as a control parameter on vocal actions. This ecological revision [42,82] of gesture-speech

509 coupling provides a solid phylogenetic basis for a co-evolution of gesture and speech, whereby

510 peripheral bodily tensioning naturally formed coalitions with sound-producing organs that were

511 still very much under development.

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