Preprint to be submitted for peer review (version 1.4). For the original time-stamped pre-registration document on the OSF see (<https://osf.io/e3ukd/>).

Energy flows in gesture-speech physics: Exploratory findings and pre-registration of confirmatory analysis

Wim Pouw^{1,2}, Steven J. Harrison¹, Núria Esteve Gibert³, James A. Dixon¹

Center for the Ecological Study of Perception and Action, University of Connecticut¹

Department of Psychology, Education, & Child Studies, Erasmus University Rotterdam²

Psychology and Education Sciences, Universitat Oberta de Catalunya³

Author note: Correspondence should be addressed to Wim Pouw (wimpouw@uconn.edu).

Open data & Pre-registration: The data and code supporting this exploratory analysis and the time-stamped version of the pre-registration can be found on the OSF (<https://osf.io/e3ukd/>).

Funding: This research has been funded by The Netherlands Organisation of Scientific Research (NWO; Rubicon grant “Acting on Enacted Kinematics”, Grant Nr. 446-16-012; PI Wim Pouw).

Abstract

A well-known phenomenon of multimodal language is the synchronous coupling of prosodic contours in speech with salient kinematic changes in co-speech hand-gesture motions. Invariably, such coupling has been rendered by psychologists to require a dedicated neural-cognitive mechanism preplanning speech and gesture trajectories. Recently, in a continuous vocalization task, it was found that acoustic peaks unintentionally appear in vocalizations when gesture motions reach peaks in physical impetus, suggesting a biomechanical basis for gesture-speech synchrony (Pouw, Harrison, & Dixon, 2019). However, from this rudimentary study it is still difficult to draw strong conclusions about gesture-speech dynamics in (more) complex speech and the precise biomechanical nature of these effects. Here we assess how the timing of physical impetus of a gesture relates to its effect on acoustic parameters of mono-syllabic consonant-vowel (CV) vocalization(/pa/). Furthermore, we assess how chest-wall kinematics is affected by gesturing, and whether this modulates the effect of gestures on acoustics. In the current exploratory analysis, we analyze a subset ($N = 4$) of an already collected dataset ($N = 33$), which serves as the basis for a pre-registration of the confirmatory analyses yet to be completed. Here we provide exploratory evidence that gestures affect acoustics (amplitude envelope and F0) as well as chest-wall kinematics during mono-syllabic vocalizations. These effects are more extreme when a gesture's peak impetus occurs closer to the center of the vowel vocalization event. If the current findings can be replicated in confirmatory fashion, there is a more compelling case to be made that gesture-speech physics is important facet of multimodal synchrony.

Keywords: Gesture, Speech Acoustics, Respiration, Motion Tracking

Hand gesture and speech are said to synchronize their activity on the level of prosody (Wagner, Malisz, & Kopp, 2014). Prosody, broadly defined, entails modulations in acoustics or body motions which are employed as special linguistic devices that serve what is uttered *by way of how it is uttered* - constraining pragmatic, syntactic, semantic, and affective dimensions of communication (McNeill, 2005; Prieto & Esteve-Gibert, 2018; Shattuck-Hufnagel & Ren, 2018; Wagner et al., 2014). When quantifying gesture-speech synchrony on the side of speech, researchers have particularly looked at peaks in Fundamental Frequency (F0; perceived as pitch) and intensity contours (Krivokapic, Tiede, Tyrone, & Goldenberg, 2016; Parrell, Goldstein, Lee, & Byrd, 2014; Pouw & Dixon, 2019). With respect to gesture, researchers have defined salient peaks in kinematics of gestural motions in terms of, for example, peak velocity or onsets of a gestural stroke (Danner, Barbosa, & Goldstein, 2018; Danner et al., 2018; Loehr, 2012; Pouw & Dixon, 2019; Rochet-Capellan, Laboissière, Galván, & Jean-Luc, 2008; Wagner et al., 2014). This line of research has shown that gesture and speech are tightly and flexibly coupled with one another, raising the question how such strong coupling is established, developmentally as well as cognitively.

An information-processing perspective on gesture-speech synchrony would maintain that gesture and speech need to be pre-planned, so as to synchronize their moments of expressive contrast (McClave, 1998; Ruiter, 2000; Wagner et al., 2014). On such an account, gesture-speech synchrony is established via a developmentally advanced module which is dedicated for multimodal temporal processing (Iverson & Thelen, 2005; Ruiter, 2000). Although some have argued that such a module can developmentally emerge naturally out of basic hand-mouth linkages such as feeding-related actions, it is still understood that gesture-speech linkages emerge in late stages in development and is completely a matter of motor planning in brain (Iverson & Thelen, 2005; Wagner et al., 2014).

There are also a range of findings which suggest that there is dynamic bidirectional coupling between gesture and speech, which operates on such short time scales that a cognitively pre-

planned gesture and speech trajectory seems untenable (Chu & Hagoort, 2014; Esteve-Gibert & Prieto, 2013; Kelso & Tuller, 1984; Krahmer & Swerts, 2007; McNeill, 1992; Parrell et al., 2014; Pouw & Dixon, 2019; Rusiewicz, Susan, Iverson, & Szuminsky, 2013; Treffner & Peter, 2002). Parrell and colleagues (2014), for example, show that intentionally changing emphasis in speech (emphatic stress on a vocalization) or gesture (by making a larger amplitude gesture) automatically leads to unintended changes in the other modality. This suggests that moments of emphasis in gesture and speech are directly coupled. Indeed, a recent breakthrough in deep-learning modeling suggests a highly invariant coupling of gesture and speech prosody. A recurrent neural network trained on person-specific gesture-speech sequences (motion and audio data from talk shows), was able to produce novel speech-synchronous gestures based on novel speech from the person the neural network was trained on (Ginosar et al., 2019). These neural networks are thus showing that there must be some person-specific invariant between speech acoustics and gesture motion, although it remains unknown what the neural network in fact picked up on in speech so as to produce gesture so well (but see Kucherenko, Hasegawa, Henter, Kaneko, & Kjellström, 2019). Interestingly, recent research shows that rudimentary gesture-acoustic invariants can also be picked up by *human* listeners (Cwiek & Fuchs, 2019; Pouw, Paxton, Harrison, & Dixon, In Press; see also Wagner, Cwiek, & Samlowksi, In Press).

In a recent study, a possible candidate gesture-speech invariant was identified (Pouw, Harrison, et al., 2019). Namely, when steady-state vocalizing a vowel /a:/ (as in cinemaa), high-impetus whole-arm upper limb movements imparted positive peaks in the amplitude envelope and F0 of phonation acoustics. Such effects were exaggerated when participants were standing as opposed to sitting, suggesting a role for anticipatory muscle activations as these are more reactive when postural stability is low (Cordo & Nashner, 1982). As mentioned, changes in F0 have in fact been associated with gesture in *natural* contexts as well (Cravotta, Grazia, & Prieto, 2018; McClave, 1998; Wagner et al., 2014). Thus, it seems that this particular type of gesture-speech F0 and

intensity synchrony (excluding possibly other types), may arise naturally from gesture-speech physics. If these findings are on track, then this form of gesture-speech coupling should not be seen as an arbitrary cultural convention, but rather as an embodied innovation (e.g., Blasi et al., 2019; Cwiek & Fuchs, 2019; Hardus, Lameira, Schaik, & Wich, 2009).

The dynamics of the hypothesized gesture-induced forces on the lower vocal tract are still unknown. We hypothesized that physical impulses produced by acceleration and decelerations in gesture, are not kept locally contained at the effector muscles (Pouw, Harrison, et al., 2019). Namely, reverberations of gesture-induced forces are possible (Silva, Moreno, Mancini, Fonseca, & Turvey, 2007), because the body is characteristically pre-stressed, wherein tensioned tendon- and fascia elements are attached to compressive elements such as the bones (Turvey & Fonseca, 2014). According to this tensegrity perspective of biological systems (Ingber, 2008), it is precisely the non-local dispersal of muscle-tensioning onto the whole myofascial-skeletal network that allows biological systems to organize multiple degrees of freedom in intentional action (see Bernstein, 1967).

Applied to gesture, we reasoned that given that muscles around the respiratory system are actively engaged when moving the upper limbs for reasons described above, alveolar (lung) pressure is increased, thereby increasing F_0 and acoustic intensity (everything else being equal). In other words, gesture-induced forces lead to an energy bump to be dissipated by the gesture-respiratory-vocal system in the form of air escaping more quickly through the vocal tract.

The important role of lower vocal tract activity in speech dynamics has been argued for very early on by Stetson (Stetson, 1928). Stetson (1928) suggested based on empirical work involving a myriad of lower vocal tract measurements that production of syllables was associated with positive burst-like pulses of the chest wall. Later on, this chest-pulse thesis has been reconsidered and found to be too general, as evidence suggested that only specific prosodically stressed syllables (specifically emphatic stress) seemed to covary with respiratory kinematics, as

opposed to every syllable produced (Ladefoged, 1968; Ohala, 1990). From present-day research, we further obtain that although there is confirming evidence that lower vocal tract dynamics play a role in prosodic stress, it is also found that respiratory kinematic modulations are not always consistently recruited when performing some stressed vocalization (Fuchs, Koenig, & Petrone, 2019; Petrone, Fuchs, & Koenig, 2017). Indeed, akin to what is known about coordinative structures in general (Kugler, Scott Kelso, & Turvey, 1980), and speech specifically (Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984), chest-wall modulations are just a few of many degrees of freedom that can be utilized to successfully perform a vocal act, next to a host of other vocally equivalent solutions (Perrier & Fuchs, 2015).

Current Study and Exploratory Analysis

As reviewed above, there is evidence to suggest that gesture might affect lower vocal tract dynamics, and that this can translate in prosodic modulations. Yet, it still to be *directly* tested whether gestures affect respiratory dynamics. Furthermore, it is still difficult to translate gesture-speech physics' findings obtained in rudimentary steady-state phonation task, onto fluid speech (but see Cravotta, Busà, & Prieto, 2019). Indeed, because fluid speech does not entail continuous phonation, but intermittent closing of the glottis for pauses or consonant productions, we could wonder whether gesture's physical impulses have a chance at all to acoustically materialize. Therefore, in the current study we investigated whether gesture's physical impetus can affect mono-syllabic consonant-vowel (CV) vocalizations (/pa/) in terms of F0, acoustic intensity, and chest wall kinematics. We further assessed the role of timing for gesture-related impulses to take acoustic and respiratory effect. We directly assessed whether chest-wall kinematics is affected by gesture as participants were wearing a respiration belt that captured gross changes in chest wall-circumference kinematics.

Participants phonated a CV syllable at 1-second intervals either *passively* without body movement, or while vertically moving the wrist or arm in rhythmic fashion with an emphatic stress

at the downbeat (higher stress and sudden stop in the downbeat). We contrasted wrist- versus arm movements as the latter movement has a higher physical impetus and therefore should lead to more pronounced effects on acoustics and chest kinematics (Pouw et al., 2019). We further trained participants to either coincide the vocalization with the downbeat or 90 degrees out-of-phase wherein participant initiated vocalization when moving the effector upward (moment of lowest deceleration/acceleration). With this phasing manipulation we can assess how speech acoustics is affected by timing of physical impetus, as well as excluding the possibility that acoustics is affected when any movement is present. For the CV vocalizations, we deliberately chose a voiceless stop as the releasing consonant as it provides an interesting situation for gesture-speech physics. Namely, we could reason that when a vowel is preceded by a consonant, acoustic effects on phonation may be neutralized, or at least diminished in magnitude, as physical impulses meet a resisting obstacle in the form of a /p/-induced closed glottis. On the other hand, /p/ as a plosive is actually successfully performed because closing the glottis allows for build of sub-glottal pressures (Stetson, 1928). If the timing is right, gesture-related impulses on the body can provide additional energy build up during preparation of the release of the plosive and the following vowel.

Method

Participants and Design

We examined the first 4 participants in the current exploratory analysis (2 females, ages = 21, 19, 18, 18, all right-handed), drawn from a larger scale study (total $N = 33$, age $M [SD] = 19.39 [1.10]$, all right-handed). The study design consisted of two within-subjects' factors, a two-level phasing condition (in-phase beat vs. 90° out-of-phase beat) and a 2-level movement type condition (wrist vs. arm). There was also a passive (no movement) control condition. We performed four blocks of five trials containing all conditions. Thus, each condition (in-phase wrist beat, in-phase arm beat, 90° out-of-phase wrist beat, 90° out-of-phase arm beat, and the passive condition) were performed for four trials resulting in 20 of trials per participant (a total of 80 trials for the current

dataset). Each trial consists of mono-syllable CV speech for 8 seconds (8 beats), thus resulting in $80 \times 8 = 640$ vocalizations.

Measurements and equipment

Respiration Belt

We used a NeuLog Respiration Belt (type NUL-236). The respiration belt outputs in arbitrary units of measurement and reflects absolute pressure measurements from a pressure sensor. We scaled the raw measurements by minima and maxima of a respiration baseline trial (see procedure). We sampled at ~ 30 Hz per second. The belt uses an air bladder similar to blood-pressure measurement systems. The belt was filled with air using a hand-held pump, wherein the experimenter increased pressure up to the point that the belt fitted tightly but comfortably around the participant's lower ribs. Although the respiration belt is marketed for monitoring respiration phases, it should be noted that any chest circumference adjustments such as tensioning of the back muscles will be registered as increased pressure readings by the belt. Indeed, we use the respiration belt readings as an overall physical measure of muscular activity around the respiratory system.

Motion tracking

Motion-tracking was performed with a Polhemus Liberty (Polhemus, Inc., Colchester, VT, USA), which contained a wired sensor that was attached to the index finger of the dominant hand. The same sampling rate was set as the respiration belt (~ 30 Hz).

Audio recording

Audio was recorded with a headset MicroMic C520 (AKG, Inc.), which is high-performance condenser cardioid microphone.

Synchronizing recording

A custom written c++ script was used (see <https://osf.io/u2q4f/>) which requested input from the respiration belt via its API (<https://neulog.com/software/>), the motion tracker (using

modified code from Richardson, 2009), and audio was sampled using toolbox SFML package for c++ (<https://www.sfm-dev.org/>). The c++ script ensured that all devices were sampling at the same time and observations were time stamped, ensuring synchronization across data modalities.

Audio extraction

We used PRAAT (Boersma & Weenink, 2019) to extract F0 time series from the audio, with suitable ranges for males (75-450Hz) and females (100-500Hz). We used a PRAAT script by He & Dellwo (2017) to generate a smoothed amplitude envelope, which serves as a measure of gross changes in intensity. The amplitude envelope was scaled from 0 (minimum value observed for the participant) to 1 (highest value observed). All acoustic measures were extracted at 200Hz intervals.

Data Aggregation and post-processing

A custom written R script (<https://osf.io/96cmz/>) aggregated acoustic data together with motion tracking + respiration data. This script also up sampled the motion tracking and respiration data at 200Hz so as to match acoustic data. We used a 30Hz low-pass first order Butterworth filter to smooth vertical movement traces and its time derivatives. The script also automatically determined vowel vocalization onsets/offsets by start/end of a run of F0 observations.

Procedure

Participants were asked to sit on a chair without arm rests and without their backs touching the back rest. A Polhemus Motion tracker sensor was attached to the tip of the index finger of the dominant hand, and the respiration belt was applied to the participant's lower rib cage area. Subsequently we performed several respiratory function control measurements (respiratory baseline trial). For the first measurement, we obtained the maximum inspiration level, wherein participants were asked to maximally inspire and hold their breaths for 2 seconds (maximum inspiration). Then we asked participants to take a deep breath and exhale until they were completely out of breath (maximum expiration).

Participants were introduced to the visual metronome, which showed tiles numbered from 1 to 8, which were each visually highlighted in 1-second intervals (see <https://osf.io/qr65j/>). Participants were instructed that a trial lasted 8 seconds, wherein they needed to vocalize 8 times with the 1-second rhythm of the visual metronome. Participants decided themselves when to start the next trial, by waiting for the visual metronome to reset to the first tile. One practice trial was performed wherein the participant practiced vocalizations with the visual metronome. Participants were instructed to keep their phonations as monotonic as possible throughout the whole experiment, with no variation between vocalizations in terms of intensity or pitch. Importantly, participants were also instructed to take one deep breath before the start of each trial and not inhale air intermittently. This way we kept breathing strategies controlled, making respiration belt observations more interpretable.

Participant were then introduced to the movement-type conditions, ignoring vocalizations for a moment. For the no-movement condition, participants were asked to rest their hands on their legs. For the wrist-movement condition, participants were asked to continuously move their hand up and down along the sagittal plane around the wrist joint, while the lower arm and upper arm were kept in a 90-degree angle and were kept stationary. In the arm-movement condition, participants were asked to move the lower arm around the elbow joint up and down, while not producing any movement around the wrist joint. In both the wrist- and arm-movement conditions participants were asked to give an energetic contrast in the down-beat extension phase, such that the arm was moved downward more quickly (than the upward movement) and was stopped with a sudden complete halt (a “beat”) shortly followed by the up-ward stroke (flexion phase).

Participants were then introduced to the phasing conditions, wherein they either produced the CV production at the downward beat (in-phase) or they produced it during the flexion phase (90° out-of-phase). By producing the vocalization around the moment of stopping (the beat), we ensured that the phonation phase was occurring during the moment when the physical impetus is

highest; participants were explicitly instructed to stop phonating after initiating the upward flexion phase. In the 90° out-of-phase condition, participants were asked to start vocalizing directly after the down-beat was reached, during the flexion phase. This ensured that phonation-phase was performed during the movement phase with relatively lower physical impetus. Note, participants were instructed to move in the same way in the in-phase and 90° out-of-phase condition, with a beat in the downward phase. As can be imagined, this was a difficult task for the participants, as it required learning two different gesture-speech timing regimes which they needed to adopt flexibly during the experiment. Therefore, we trained the participants until they could flexibly alternate between timing regimes, whereby the experimenter only gave instructions on whether the timing of the vocalization was too late or too early relative to the vocalization. After practice of about 5 to 10 minutes, all participants were able to learn the timing (we will also assess timing relationships as a manipulation check).

Figure 1. Example trials for phasing conditions

Note. Key measurements are shown for the current experiment for different phasing condition trials. **a)** It can be seen that for the in-phase condition the vocalization is close to the maximum extension of the vertical movement (z time series), whereas for the 90° out-of-phase condition the vocalization is occurring during the flexion phase. **b)** The z-movement time series is shown, showing the vertical movement for the conditions. **c)** The Fundamental Frequency is shown in red, showing short bursts of observations which coincide with the voiced portion of the vocalizations. **d)** In pink the smoothed amplitude envelope is shown, superimposed on the raw audio waveform in green. It can be seen that there are some higher peaks for the amplitude envelope in the in-phase condition as compared to the 90° out-of-phase condition. **e)** In blue the respiration belt observations are shown (rescaled for

minima and maxima). The time series has a negative trend indicating air capacity diminishing over the trial. **f)** If we look at the spectral properties of the movement relative to the respiration belt time series, we can see that in each condition there is a peak at 1 second, suggesting that for the vocalizations some chest activity is recruited regardless of movement. However, in this case, for the in-phase condition the respiration activity is most strongly defined by 1 second periods, while for the other conditions the periodicities having to do with movement and speech activity. In the in-phase conditions these speech and gesture activities are fully aligned, thus yielding a more pure 1-second periodicity.

Results

Descriptives and manipulation checks

From Table 1 we obtain, as to be expected, that participants moving their wrists (as opposed to arms) had lower negative vertical velocity (velocity in the extension phase) and a smaller vertical amplitude for the movement phase when the vocalization was occurring (in-phase or 90° out-of-phase). Further note that the positive velocity (velocity of the flexion motion) is less extreme than the negative velocity (velocity of the downward motion), as participants were indeed instructed to provide an emphatic beat (i.e., maximum physical impulse) at the downward motion (leading to higher negative velocities). There is an overall lack of differences between phasing conditions in terms of movement kinematics, with the exception of slightly faster upward motions in the 90° out-of-phase condition as compared to the in-phase condition. The overall lack of large differences shows that the movements were not particularly different when moving in-phase or 90° out-of-phase, suggesting any movement effects that arise on lower vocal tract are due to the timing (i.e., phasing) of movement relative to the vocalization.

Table 1. Descriptives upper limb movement

		Wrist Beat	One-Arm Beat
Duration (ms)		Mean (SD)	Mean (SD)
Movement period		[95%CI: lower, upper]	[95%CI: lower, upper]
	In-phase	945 (199) [911, 980]	947 (179) [915, 978]
	Out-of-Phase	990 (139) [966, 1015]	1001 (168) [972, 1031]
Max negative velocity z (cm/s)		Mean (SD)	Mean (SD)
		[95%CI: lower, upper]	[95%CI: lower, upper]
	In-phase	-89 (30) [-84, -94]	-154 (41) [-146, -161]
	Out-of-Phase	-88 (23) [-84, -92]	-149 (45) [-141, -156]
Max positive velocity z (cm/s)		Mean (SD)	Mean (SD)
		[95%CI: lower, upper]	[95%CI: lower, upper]
	In-phase	41 (16) [38, 43]	74 (31) [69, 79]
	Out-of-Phase	50 (16) [47, 52]	78 (24) [74, 81]
Amplitude (cm)		Mean (SD)	Mean (SD)
		[95%CI: lower, upper]	[95%CI: lower, upper]
	In-phase	17 (5) [17, 18]	32 (12) [30, 34]
	Out-of-Phase	19 (6) [18, 20]	32 (11) [31, 34]

Note. Duration of the movement period (give in ms) indicates the average duration of a cycle of the rhythmic arm movement (calculated from moment of maximum extension to the next). The duration of movement period should be around 1000 ms as this was the speed at which the participants were guided to move. Both max negative velocity z and max amplitude are given to provide an indication about how participants were moving. The maximum vertical (z) negative velocity (given in centimeters per second) gives the maximum negative velocity of each downbeat averaged for condition. The max amplitude (given in centimeters) gives the difference of the maximum and minimum z value within each movement period (indicating size of the movement), averaged for each condition.

Participants sometimes found the timing of the movement and vocalization difficult to perform. Therefore, it is important to provide a manipulation check as to whether phasing timing was overall performed correctly. As can be seen in Figure 2, the timing of the midpoint of the vocalization (vocal midpoint) was on average closely aligned with the moment of maximum extension in the in-phase condition. As instructed, in the 90° out-of-phase condition the timings of the maximum extension were close to just short of half a period (ca. 450 milliseconds) removed from the vocal midpoint. This indicates that the phasing instructions were successful and we can assume that vocalizations were more often timed with the moment of peak physical impetus in the in-phase condition as opposed to the 90° out-of-phase condition. Note however, gesture-speech timing is variable, so movement timing relative to vocalization should be taken into account when assessing effects on acoustics.

Figure 2. Timing distributions for the movement and phasic condition

Note. Density distributions of the temporal differences of the vocal mid-point compared to the moment when the maximum extension was reached for movement condition (upper panel = arm movement, lower panel = wrist movement) and phasing condition (solid lines = in-phase, dashed lines = 90° out-of-phase). Negative values mean that the maximum extension followed the vocal midpoint, and positive values indicate that midpoint was following the maximum extension. The bimodal distribution of 90° out-of-phase condition simply indicates that sometimes the downbeat is leading or following the next vocalization depending on how the participant started the trial.

Table 2 provides a detailed overview of key acoustic markers of phonation: duration, maximum F0, minimum F0, and amplitude envelope (z-scaled per participant). It can be seen that vowel vocalization events lasted for about 230-250 milliseconds, with trivial differences between conditions.

Table 2. Detailed descriptives Acoustics

	Passive	Wrist In-phase	Wrist Out-of-phase	Arm In-phase	Arm Out-of-phase
Duration phonation (ms)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PPN1 (male)	187 (30)	181 (22)	181 (30)	177 (22)	190 (27)
PPN2 (female)	374 (61)	346 (84)	340 (51)	363 (51)	356 (54)
PPN3 (female)	183 (85)	210 (54)	189 (42)	211 (37)	206 (45)
PPN4 (male)	254 (70)	253 (70)	228 (67)	243 (66)	232 (54)
Total	246 (101)	248 (88)	232 (80)	248 (84)	245 (79)
Max F0 (Hz)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PPN1 (male)	122 (14)	118 (6)	117 (7)	115 (3)	114 (4)
PPN2 (female)	195 (15)	195 (12)	195 (14)	201 (13)	194 (11)
PPN3 (female)	202 (14)	203 (9)	202 (10)	210 (11)	206 (11)
PPN4 (male)	110 (20)	113 (23)	111 (8)	109 (6)	112 (8)
Total	168 (42)	167 (42)	164 (42)	170 (46)	166 (42)
Midpoint F0 (Hz)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PPN1 (male)	109 (4)	109 (3)	110 (4)	108 (3)	108 (2)
PPN2 (female)	178 (7)	178 (8)	177 (8)	181 (7)	179 (6)
PPN3 (female)	180 (9)	178 (5)	182 (6)	194 (9)	181 (5)
PPN4 (male)	103 (53)	111 (73)	93 (4)	91 (4)	94 (3)
Total	144 (45)	144 (50)	139 (40)	140 (42)	140 (40)
Min F0 (Hz)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PPN1 (male)	106 (4)	105 (3)	107 (4)	104 (3)	105 (3)
PPN2 (female)	174 (8)	174 (9)	172 (8)	176 (8)	174 (9)
PPN3 (female)	171 (14)	168 (9)	173 (7)	174 (11)	174 (6)
PPN4 (male)	97 (54)	107 (74)	88 (3)	86 (3)	88 (3)
Total	138 (39)	138 (50)	133 (39)	134 (41)	135 (40)
Max Amplitude Envelope (z-scaled)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PPN1 (male)	2.71 (0.55)	3.30 (0.65)	2.31 (0.40)	2.80 (0.81)	2.14 (0.23)
PPN2 (female)	1.88 (0.44)	1.90 (0.41)	1.79 (0.48)	2.11 (0.44)	1.84 (0.33)
PPN3 (female)	1.87 (0.62)	2.12 (0.48)	2.01 (0.62)	2.96 (0.84)	1.98 (0.55)
PPN4 (male)	2.06 (0.57)	1.96 (0.53)	1.82 (0.60)	1.91 (0.54)	1.99 (0.60)
Total	2.12 (0.64)	2.31 (0.77)	1.99 (0.56)	2.44 (0.81)	1.98 (0.57)

Note. Duration vowel vocalization is given in milliseconds (ms), and indicates the average phonation length when uttering /pa/. The maximum/minimum F0 shows the max/min F0 for each vowel vocalization averaged for condition and or participant.

Main Results

For the main results, we use z-scaled values of maximum F0, amplitude envelope and respiration activity. The measurements are z-scaled per participants, such that individual differences in acoustic-respiratory ranges are not of influence to our analysis.

Passive versus moving in-phase or 90° out-of-phase

Figure 3 shows all acoustic-respiratory trajectories for each vocalization made, grouped by conditions.

Figure 3. Trajectories during vocalization for acoustics and chest kinematics per condition

Note. The green in-phase trajectories show higher arcs for the amplitude envelope of phonation as compared to the 90° out-of-phase (blue) trajectories. Such patterns are less clear for F0 trajectories, which show high peaks at the beginning of phonation and falling at the end of phonation. These higher peaks at the start of the vowel is a characteristic phenomenon referred to as “pitch skip” which is caused by articulatory constraints that emerge due to a voiceless plosive that precedes the utterance of the vowel (Hanson, 2009). For the respiration trajectories we do see higher observed values for the in-phase conditions, suggesting higher chest muscle activity at moments of vowel vocalizations.

For our first analyses, we will assess whether phonation properties for the in-phase versus out-phase movement was different than the passive control condition. We performed mixed regression analysis using R-package `nlme` (Pinheiro, Bates, DebRoy, Sarkar, & R Team, 2019), with random intercept for participant for each model. For the z-scaled maximum amplitude envelope (max ENV) per vocalization we obtain that indeed in-phase movement lead to higher amplitude peaks (as can be seen in Figure 3), as compared to the passive condition. Interestingly, 90° out-of-phase movement had a weakly lower max amplitude envelope than the passive condition. For the z-scaled max fundamental frequency (max F0) we find no reliable differences between passive versus movement conditions. For the z-scaled max respiration (i.e., chest muscle activity) we obtain that any type of phased movement (in-phase or 90° out-of-phase) was associated with higher levels during vocalization as compared to the passive condition. However, the effect size for the in-phase condition (vs. passive condition) was twice as high as compared to the 90° out-of-phase condition (vs. passive condition). For the next analysis we will drop the passive condition and look more closely whether type of movement matters next to phasing conditions.

Table 3. Mixed regression passive versus phasing condition

Max ENV (z-scaled)	<i>b</i>	<i>t</i>(647)	<i>p</i>
Passive (intercept)	2.12	13.62	< .001
Passive vs. In-phase movement	0.26	4.17	<.001
Passive vs. Out-of-phase movement	-0.13	-2.06	.040
Max F0 (z-scaled)	<i>b</i>	<i>t</i>(647)	<i>p</i>
Passive (intercept)	1.80	9.45	<.001
Passive vs. In-phase movement	0.05	0.25	.80
Passive vs. Out-of-phase movement	-0.31	-1.53	.13
Max Respiration Belt (z-scaled)	<i>b</i>	<i>t</i>(647)	<i>p</i>
Passive (intercept)	-0.16	-1.24	0.21
Passive vs. In-phase movement	0.98	12.13	< .001
Passive vs. Out-of-phase movement	0.42	5.42	<.001

Contribution of movement condition and phasing condition

We further examined whether movement type (wrist vs. arm movement) and phasing conditions (in-phase vs. 90° out-of-phase) showed differences in phonation properties. For this analysis we only compare movement and phasing conditions as the passive condition could not be crossed with the movement and phasing condition. Table 4 provides the results of these analysis. Note, that for each dependent variable we tested whether the interaction between movement-type condition and phasing condition was reliable, but only in the case of respiration kinematics did we obtain a significant interaction.

Table 4 shows that for the max amplitude envelope as well as max F0, in-phase movement had higher peaks as compared to 90° out-of-phase movements, with type of movement being statistically inconsequential (wrist vs. arm movement showed no differences). For respiration similar effects are obtained, with additional interaction for movement type and phasing condition. This shows that for respiration kinematics, arm movement did obtain higher max respiration observations as compared to wrist movement, but only for the in-phase movements.

Table 4. Mixed regression passive versus phasing condition

Max ENV (z-scaled)	<i>b</i>	<i>t</i>(510)	<i>p</i>
Intercept	2.41	15.58	< .001
Phase (Out-of-phase vs. In-phase)	-0.39	-7.43	<.001
Movement (Wrist vs. Arm)	-0.07	-1.27	.205
Max F0 (z-scaled)	<i>b</i>	<i>t</i>(510)	<i>p</i>
Intercept	1.79	8.99	<.001
Phase (Out-of-phase vs. In-phase)	-0.36	-2.43	.015
Movement (Wrist vs. Arm)	0.13	0.85	.40
Max Respiration Belt (z-scaled)	<i>b</i>	<i>t</i>(510)	<i>p</i>
Intercept	-0.16	-1.24	0.21
Phase (In-phase vs. Out-of-phase)	-0.79	-8.02	< .001
Movement (Arm vs. Wrist)	-0.56	-5.44	<.001
<i>Phase x Movement</i>	0.45	3.21	.001
<i>Phase x Movement Posthoc</i>	Estimated Diff.	<i>t</i>(510)	corrected <i>p</i>
<i>In-phase: Arm vs. Wrist</i>	0.56	5.44	< .001
<i>Out-of-phase: Arm vs. Wrist</i>	0.10	1.10	.270

Note. The post-hoc analysis (performed with `lsmeans`) pertains to the Phase x Movement interaction for Max respiration, wherein it is found that arm movement had higher respiration belt readings during vocalizations as compared to wrist movement, but only for the in-phase condition.

Role of timing during in-phase wrist or arm movement

We know from the descriptives and Figure 2 that even in the in-phase condition there is variability in timing of the moment of a physical impetus and the vocal mid-point. If indeed the moment of physical impetus matters, we could obtain additional evidence for the idea that physical impetus is crucial for acoustic-respiratory modulations when we estimate the exact timing of physical impetus relative to vocalizations.

To assess this, we determined for all in-phase trials, the absolute timing of the peak in deceleration of the downbeat movement relative to the vocal midpoint (see Figure 5). The peak in deceleration is also a peak in a physical impetus, as the body is then maximally absorbing forces that were produced in accelerating the arm/hand for the downbeat.

Figure 5. Peak deceleration-Vocalization and the peaks in acoustics and respiration

Note. Note that participants individual slopes may be different than population slopes. As can be seen especially for the amplitude envelope there is a clear linear relationship such that the further away the peak deceleration (in absolute terms in ms) from the vocalization the lower the maximum observed amplitude envelope for that vocalization.

We ran three different mixed regression models (participant as random intercept) to see whether absolute timing of peak impetus versus vocal midpoint was predictive for the height of the maximum observations in: 1) amplitude envelope, 2) F0, 3) respiration kinematics. Simple main effects were tested, showing across the board that the further the arm or wrist movement's physical impetus (peak deceleration) was removed in time from the moment of vocalization, the lower the observed maximum amplitude envelope, F0 and Respiration. However, for respiration this was not as reliable a relation as compared to acoustics.

Table 5. Effects vocalization-physical impetus timing on acoustics and respiration

Max ENV (z-scaled)	<i>b</i>	<i>t</i>(257)	<i>p</i>
Intercept	2.89	14.89	< .001
Timing Peak Dec	-0.002	-4.29	<.001
Max F0 (z-scaled)	<i>b</i>	<i>t</i>(257)	<i>p</i>
Intercept	3.60	5.66	<.001
Timing Peak Dec	-0.008	-4.87	<.001
Respiration	<i>b</i>	<i>t</i>(257)	<i>p</i>
Intercept	1.17	3.62	<.001
Timing Peak Dec	-0.002	-1.92	.055

Preliminary Quantification of Biomechanical Synergies: Is cross-wavelet coherence between movement and respiration predictive of height acoustic peaks?

Finally, we want to assess whether the degree to which movement is entraining respiratory activity predicts the height of the acoustic peaks (max amplitude envelope, max F0) for in-phase movements trials. This would indicate that synergy between movement and respiratory kinematics is modulating changes in acoustics. Similar to earlier research (Pouw & Dixon, 2019; Pouw, Paxton, Harrison, & Dixon, Under Review) we determined the coupling strength between two time series (in this case vertical movement and respiration) with cross-wavelet analysis (with R-package `WaveletComp`, Rosch & Schmidbauer, 2014). Cross-wavelet analysis allows for the assessment of whether two time series have correlated periodic activity within some period range. The period

range that we focus on is around 1 second as this is the rate at which vocalizations were produced (the period range was set at 0.8 - 1.2 seconds). Cross-wavelet analysis then determines, using a Morlet wavelet as its daughter wavelet, at which moments of the time series (thus in a time-dependent way) whether similar periodicities are obtained (at the 0.8 – 1.2 second range) and quantifies the strength of periodicity coupling, from perfectly correlated (coherence = 1) to no correlation (coherence = 0). Since we have a time-dependent measure of coherence, we can determine the maximum observed respiratory-limb movement coherence *for when the participant was vocalizing*. This is very convenient as we can determine on a vocalization-by-vocalization basis whether respiration and gesture was indeed entrained and whether this predicts acoustic properties. Figure 6 does not clearly indicate higher acoustic peaks (amplitude envelope or F0) when respiration-movement coherence is higher, although this trend is clearly present for arm movements. We tested for F0 and amplitude envelope separately whether peak height in acoustics was associated with respiration-movement coherence, but we did not find reliable relationships (p 's > .112). However, given interesting trends for the arm movement condition, and the higher-powered sample to be examined, we predict that in the confirmatory analysis we will obtain reliable modulation of acoustic peak height by the coherence between respiration activity and upper limb movement.

Figure 6. Cross-wavelet coherence for respiration and movement and its relationship with peaks in acoustics

Note. The time series for respiration and movement from Figure 2 are shown here again, with an example of cross-wavelet output which ascertains common periodicities between the time series along the time axis. We only assess the middle 4 vocalizations per trial, as coherence estimates at the beginning and end time points are less reliable due to indeterminacies (a common characteristic of wavelet analysis). We determined for each of these four middle vocalizations the maximum observed coherence (coherence closely correlates with cross-wavelet power as shown here). The right panel shows the correlations between coherence (horizontal axis) and the height of the acoustic peaks. Only for Arm movements we find predicted trends, such that higher coherence between movement and respiration activity is associated with higher acoustic peaks (especially for the amplitude envelope).

Brief Discussion

The current exploratory analyses show a promising indication that the physical impetus of a wrist or arm gesture of the dominant hand, occurring around the moment of the production of a CV mono-syllabic vocalization /pa/ (in-phase movements), imparts boosting effects on the amplitude envelope and the fundamental frequency (F0) of speech as compared to a passive control condition or to gestures that are 90° out-of-phase timed with vocalizations. We obtain that chest-wall kinematics are affected by gesturing, especially when the gesture's physical impetus unfolds more precisely around the vowel vocalization. That the moment of physical impetus plays a role in the current effects is further evidenced by the sensitive timing relationships with peak deceleration (proxy for peak impetus) and vocal midpoint, showing higher peaks in F0, amplitude envelope, and respiration activity, when the vocal midpoint is closer to the unfolding of the peak deceleration. Furthermore, we find that peak deceleration timing is more predictive of respiration activity for the arm vs. the wrist condition. All in all, the findings replicate earlier results in a continuous vocalization task showing an effect of physical impetus on vocalization acoustics (Pouw et al., 2019), extend it to intermittent CV vocalizations, and further by specify its underlying processes by taking into account chest wall activity and the time of a physical impetus relative to vocalizations.

In the confirmatory analysis further specified in the pre-registration below, we will generate comprehensive results about the role of upper limb movement entrainment with respiratory activity as to predict acoustic modulations, which in the current exploratory dataset were inconclusive. We will also perform more detailed analysis of acoustics, including other markers than peak amplitude and maximum F0. Particularly we could wonder whether the gesture effects on F0 can only be found at the start of the vowel, which is where the maximum F0 is observed now due to a classic “pitch skip” effect caused by the vowel being preceded by a voiceless obstruent (Hanson, 2009). Therefore, to exclude possible “pitch skip” artefacts, in our more comprehensive study we will also perform exploratory analysis on midpoint F0.

Pre-registration Confirmatory Analysis

As mentioned, all data is already collected, thus the current pre-registration only constrains the analysis procedure. The confirmatory analysis that will be performed will be identical to the current exploratory analysis except for some small changes in amplitude envelope and F0 extraction procedures (see below). Thus, the analysis code (aggregation script: <https://osf.io/96cmz/>, analysis script: <https://osf.io/mwa2z/>) will be reused for the confirmatory data analysis. The confirmatory dataset consists of 29 participants, which means there are $29 \times 20 \times 8 = 4640$ vocalizations that we will analyze.

Deviations from current protocol: Acoustic Processing

We used two new scripts to automatically extract the F0 and the amplitude envelope from all audio files so as to speed up pre-processing procedures. For the amplitude envelope we used a rewritten version in R of the He & Dellwo (2017) PRAAT script (see <https://osf.io/uvkj6/>) made available by (Pouw & Trujillo, 2019). We also wrote another automatic extraction R script which extract F0 traces (<https://osf.io/m43qy/>), using R-package `wrassp` (Winkelmann, Bombien, & Scheffers, 2018) which uses a K. Schaefer-Vincent algorithm. For F0 detection, we used custom ranges set for male (50-400Hz) and female (80-640Hz) participants.

Outliers

Should we decide to remove outliers from the data we will report this in our analysis, and will provide statistical description about what consequences this has for our main conclusions.

Alpha restriction of Confirmatory Hypothesis Testing

Since we will be performing a host of analyses the chances for obtaining false positives will increase. To reduce this chance, for the confirmatory analysis, we will only render p -values lower than **.013** ($.05/4$) as statistically significant. We divide alpha by four as we have four major confirmatory analysis (1: effects of control condition versus phasing conditions on acoustic and respiratory peaks, 2: effects of phasing conditions and movement conditions on acoustic and

respiratory peaks, 3: role of peak deceleration on acoustic and respiratory peaks, 4: cross-wavelet coherence between respiration and movement on acoustic peaks). We predict that the current results will be replicated, and that we will also obtain reliable effects of coherence on acoustic peak.

Exploratory analysis

It is likely that we will perform further exploratory analysis. For example, we might think of more precise analyses, or change our analysis based on requests from reviewers, or novel patterns in the confirmatory dataset warrant further identification with other analysis. If this is the case, we will report these analyses as exploratory in nature. A specific exploratory expansion of the current analysis is that we will also look at midpoint F0 next to max F0 to make sure that condition effects shown here also arise at moments of vowel vocalization that is less affected by articulatory constraints having to do with uttering the preceding obstruent consonant (see Hanson, 2009).

References

- Bernstein, N. (1967). *The Co-ordination and Regulations of Movements* ([1st English ed.] edition). Pergamon Press.
- Blasi, D. E., Moran, S., Moisik, S. R., Widmer, P., Dediu, D., & Bickel, B. (2019). Human sound systems are shaped by post-Neolithic changes in bite configuration. *Science*, 363(6432), eaav3218. <https://doi.org/10.1126/science.aav3218>
- Boersma, P., & Weenink, D. (2019). Praat: Doing phonetics by computer [Computer program] (Version 6.1.03). Retrieved from <http://www.praat.org/>
- Chu, M., & Hagoort, P. (2014). Synchronization of speech and gesture: Evidence for interaction in action. *Journal of Experimental Psychology: General*, 143(3). <https://doi.org/10.1037/a0036281>
- Cordo, P. J., & Nashner, L. M. (1982). Properties of postural adjustments associated with rapid arm movements. *Journal of Neurophysiology*, 47(2), 287–302. <https://doi.org/10.1152/jn.1982.47.2.287>
- Cravotta, A., Busà, M. G., & Prieto, P. (2019). Effects of Encouraging the Use of Gestures on Speech. *Journal of Speech, Language, and Hearing Research*. <https://doi.org/10.21437/SpeechProsody.2018-42>
- Cravotta, A., Grazia, B. M., & Prieto, P. (2018). *Restraining and encouraging the use of hand gestures: Effects on speech*. <http://dx.doi.org/10.21437/SpeechProsody.2018-42>
- Cwiek, A., & Fuchs, S. (2019). Iconic Prosody is rooted in sensori-motor properties: Fundamental frequency and the vertical space. *41st Annual Meeting of the Cognitive Science Society At*. Presented at the CogSci 2019, Montreal, Canada.
- Danner, S. G., Barbosa, A. V., & Goldstein, L. (2018). Quantitative analysis of multimodal speech data. *Journal of Phonetics*, 71, 268–283. <https://doi.org/10.1016/j.wocn.2018.09.007>

- Esteve-Gibert, N., & Prieto, P. (2013). Prosodic structure shapes the temporal Realization of intonation and manual gesture movements. *Journal of Speech, Language, and Hearing Research*, 56(3), 850–864. [https://doi.org/10.1044/1092-4388\(2012/12-0049\)](https://doi.org/10.1044/1092-4388(2012/12-0049))
- Fuchs, S., Koenig, L. L., & Petrone, C. (2019). Exploring the source of short-term variations in respiratory data. *The Journal of the Acoustical Society of America*, 145(1), EL66–EL71. <https://doi.org/10.1121/1.5087272>
- Ginosar, S., Bar, A., Kohavi, G., Chan, C., Owens, A., & Malik, J. (2019). Learning individual styles of conversational gesture. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 3497–3506. Retrieved from <https://arxiv.org/abs/1906.04160>
- Hanson, H. M. (2009). Effects of obstruent consonants on fundamental frequency at vowel onset in English. *The Journal of the Acoustical Society of America*, 125(1), 425–441. <https://doi.org/10.1121/1.3021306>
- Hardus, M. E., Lameira, A. R., Schaik, C. S., & Wich, S. A. (2009). Tool use in wild orang-utans modifies sound production: A functionally deceptive innovation? *Proceedings of the Royal Society B: Biological Sciences*, 276(1673), 3689–3694. <https://doi.org/10.1098/rspb.2009.1027>
- He, L., & Dellwo, V. (2017). Amplitude envelope kinematics of speech: Parameter extraction and applications. *The Journal of the Acoustical Society of America*, 141(5), 3582–3582. <https://doi.org/10.1121/1.4987638>
- Ingber, D. W. (2008). Tensegrity and mechanotransduction. *Journal of Bodywork and Movement Therapies*, 12(3), 198–200. <https://doi.org/10.1016/j.jbmt.2008.04.038>
- Iverson, J. M., & Thelen, E. (2005). Hand, mouth and brain: The dynamic emergence of speech and gesture. *Journal of Consciousness Studies*, 22.

- Kelso, J. A., & Tuller, B. (1984). Converging evidence in support of common dynamical principles for speech and movement coordination. *The American Journal of Physiology*, 246(6 Pt 2), R928-935. <https://doi.org/10.1152/ajpregu.1984.246.6.R928>
- Kelso, J. A., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology. Human Perception and Performance*, 10(6), 812-832.
- Krahmer, E., & Swerts, M. (2007). The effects of visual beats on prosodic prominence: Acoustic analyses, auditory perception and visual perception. *Journal of Memory and Language*, 57(3), 396-414. <https://doi.org/10.1016/j.jml.2007.06.005>
- Krivokapic, J., Tiede, M. K., Tyrone, M. E., & Goldenberg, D. (2016). *Speech and manual gesture coordination in a pointing task*. <https://doi.org/10.21437/SpeechProsody.2016-255>
- Kucherenko, T., Hasegawa, D., Henter, G. E., Kaneko, N., & Kjellström, H. (2019). Analyzing Input and Output Representations for Speech-Driven Gesture Generation. *Proceedings of the 19th ACM International Conference on Intelligent Virtual Agents - IVA '19*, 97-104. <https://doi.org/10.1145/3308532.3329472>
- Kugler, P. N., Scott Kelso, J. A., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Advances in Psychology* (pp. 3-47). [https://doi.org/10.1016/S0166-4115\(08\)61936-6](https://doi.org/10.1016/S0166-4115(08)61936-6)
- Ladefogod, P. (1968). Linguistic aspects of respiratory phenomena. In *Sound Production in Man* (Ed. A. bouhuys) (pp. 141-151). New York: New York Academy of Sciences.
- Loehr, D. P. (2012). Temporal, structural, and pragmatic synchrony between intonation and gesture. *Laboratory Phonology*, 3(1), 71-89. <https://doi.org/10.1515/lp-2012-0006>

McClave, E. (1998). Pitch and Manual Gestures. *Journal of Psycholinguistic Research*, 27(2), 69–89.

<https://doi.org/10.1023/A:1023274823974>

McNeill, D. (1992). *Hand and Mind: What Gestures Reveal about Thought*. Chicago: University Of Chicago Press.

McNeill, D. (2005). *Gesture and Thought*. Retrieved from

<https://www.press.uchicago.edu/ucp/books/book/chicago/G/bo3633713.html>

Ohala, J. J. (1990). Respiratory Activity in speech. In *Speech production and speech modeling* (Eds. W. J. Hardcastle and A. Marchal) (pp. 22–53). Dordrecht: Kluwer.

Parrell, B., Goldstein, L., Lee, S., & Byrd, D. (2014). Spatiotemporal coupling between speech and manual motor actions. *Journal of Phonetics*, 42, 1–11.

<https://doi.org/10.1016/j.wocn.2013.11.002>

Perrier, P., & Fuchs, S. (2015). Motor Equivalence in Speech Production. In *The Handbook of Speech Production* (pp. 223–247). <https://doi.org/10.1002/9781118584156.ch11>

Petrone, C., Fuchs, S., & Koenig, L. L. (2017). Relations among subglottal pressure, breathing, and acoustic parameters of sentence-level prominence in German. *The Journal of the Acoustical Society of America*, 141(3), 1715–1725. <https://doi.org/10.1121/1.4976073>

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., & R Team, R. C. (2019). *nlme: Linear and nonlinear mixed effects models* [R].

Pouw, W., & Dixon, J. A. (2019). Entrainment and Modulation of Gesture–Speech Synchrony Under Delayed Auditory Feedback. *Cognitive Science*, 43(3), e12721.

<https://doi.org/10.1111/cogs.12721>

Pouw, W., Harrison, S. H., & Dixon, J. (2019). Gesture-speech physics: The biomechanical basis of the emergence of gesture-speech synchrony. *Journal of Experimental Psychology: General*.

<https://doi.org/10.1037/xge0000646>

- Pouw, W., Paxton, A., Harrison, S. J., & Dixon, J. A. (In Press). Acoustic specification of upper limb movement in voicing: Exploratory data report and pre-registration. *Proceedings of the 6th Meeting of Gesture and Speech in Interaction*. Presented at the Paderborn, Germany.
<https://doi.org/10.31234/osf.io/5rcdu>
- Pouw, W., Paxton, A., Harrison, S. J., & Dixon, J. A. (Under Review). *Social Resonance: Acoustic Information about Upper Limb Movement in Voicing*. Retrieved from
<https://psyarxiv.com/ny39e>
- Pouw, W., & Trujillo, J. P. (2019). *Tutorial Gespin2019—Using video-based motion tracking to quantify speech-gesture synchrony*. Retrieved from 10.17605/OSF.IO/RXB8J
- Prieto, P., & Esteve-Gibert, N. (2018). *The Development of Prosody in First Language Acquisition (Trends in Language Acquisition Research)*. John Benjamins.
- Richardson, M. (2009). *Polhemus applications and example code*. Retrieved from
<http://xkiwilabs.com/software-toolboxes/>
- Rochet-Capellan, A., Laboissière, R., Galván, A., & Jean-Luc, S. (2008). The speech focus position effect on jaw–finger coordination in a pointing Task. *Journal of Speech, Language, and Hearing Research*, 51(6), 1507–1521. [https://doi.org/10.1044/1092-4388\(2008/07-0173\)](https://doi.org/10.1044/1092-4388(2008/07-0173))
- Rosch, A., & Schmidbauer, H. (2014). *WaveletComp 1.1: A guided tour through the R package*. 59.
- Ruiter, J. P. de. (2000, August). The production of gesture and speech.
<https://doi.org/10.1017/CBO9780511620850.018>
- Rusiewicz, L. H., Susan, S., Iverson, J., & Szuminsky, N. (2013). Effects of Prosody and Position on the Timing of Deictic Gestures. *Journal of Speech, Language, and Hearing Research*, 56(2), 458–470. [https://doi.org/10.1044/1092-4388\(2012/11-0283\)](https://doi.org/10.1044/1092-4388(2012/11-0283))
- Shattuck-Hufnagel, S., & Ren, A. (2018). The prosodic characteristics of non-referential co-speech gestures in a sample of academic-lecture-style speech. *Frontiers in Psychology*, 9(1514).
<https://doi.org/10.3389/fpsyg.2018.01514>

- Silva, P., Moreno, M., Mancini, M., Fonseca, S., & Turvey, M. T. (2007). Steady-state stress at one hand magnifies the amplitude, stiffness, and non-linearity of oscillatory behavior at the other hand. *Neuroscience Letters*, 429(1), 64–68. <https://doi.org/10.1016/j.neulet.2007.09.066>
- Stetson, R. H. (1928). *Motor Phonetics: A Study of Speech Movements in Action*. Retrieved from <https://www.springer.com/gp/book/9789401521475>
- Treffner, P., & Peter, M. (2002). Intentional and attentional dynamics of speech–hand coordination—ScienceDirect. *Human Movement Science*, 21(5–6), 641–697. [https://doi.org/10.1016/S0167-9457\(02\)00178-1](https://doi.org/10.1016/S0167-9457(02)00178-1)
- Turvey, M. T., & Fonseca, S. T. (2014). The Medium of Haptic Perception: A Tensegrity Hypothesis. *Journal of Motor Behavior*, 46(3), 143–187. <https://doi.org/10.1080/00222895.2013.798252>
- Wagner, P., Cwiek, A., & Samlowksi, B. (In Press). Exploiting the speech-gesture link to capture fine-grained prosodic prominence impressions and listening strategies. *Journal of Phonetics*, 74.
- Wagner, P., Malisz, Z., & Kopp, S. (2014). Gesture and speech in interaction: An overview. *Speech Communication*, 57, 209–232. <https://doi.org/10.1016/j.specom.2013.09.008>
- Winkelmann, R., Bombien, L., & Scheffers, M. (2018). wrassp: Interface to the “ASSP” Library (Version 0.1.8). Retrieved from <https://CRAN.R-project.org/package=wrassp>