Version 1: This is a preprint version of an exploratory data report and pre-registration that has been time stamped on the Open Science Framework on the 18th of February 2019 (see <https://osf.io/9843h/>).

Acoustic Specification of Upper Limb Movement in Voicing: Exploratory Data Report and Pre-Registration

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Note that parts of the current manuscript may overlap verbatim with the pre-registration.

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Abstract

Hand gestures communicate complex information to listeners through the visual information created by movement. In a recent study, however, we found that there are also direct biomechanical effects of high-impetus upper limb movement on voice acoustics. Here we explored whether listeners could detect information about movement in voice acoustics of another person. In this exploratory study, participants listened to a recording of a vocalizer who was simultaneously producing low- (wrist movement) or high- (arm movement) impetus movements at three different tempos. Listeners were asked to synchronize their own movement (wrist or arm movement) with that of the vocalizer. Listeners coupled with the frequency of the vocalizer arm (but not wrist) movements, and showed phase-coupling with vocalizer arm (but not wrist) movements. However, we found that this synchronization occurred regardless of whether the listener was moving their wrist or arm. This study shows that, in principle, there is acoustic specification of arm movements in voicing, but not wrist movements. These results, if replicated, provide novel insight into the possible interpersonal functions of gesture acoustics, which may lie in communicating bodily states. The second part of the paper is a pre-registration for the confirmatory study that will assess the research question in a larger sample with more diverse and naturalistic stimuli.

Keywords: Hand Gesture, Acoustics, Phonation, Prosody, Synchronization

Introduction

Hand gestures are ubiquitously recruited for interpersonal communication. The universal assumption is that gestures solely communicate through visual presentation. Generally, there are four accepted categories of gestures. Gestures can present visual information through movements which have symbolic or iconic reference, and signal an otherwise absent states of affairs (so-called ‘symbolic’ and ‘iconic gestures,’ respectively). Gestures can also communicate through intensity changes in their movement that beat with the rhythm of speech (so-called ‘beat gestures’). Finally, gestures may be used for deictic reference through pointing to objects in the environment.

A conundrum in gesture studies is that gestures are often recruited by a gesturer who knows full well that gestures will never visually reach the listener. For example, during phone conversations, we do not stop gesturing (Bavelas, Gerwing, Sutton, & Prevost, 2008). Even speakers with congenital blindness gesture to listeners who also are blind since birth (Iverson & Goldin-Meadow, 2001). From these cases, it seems we can conclude that gestural skills are neither fully derived from having seen others’ gesturing, nor are gestures recruited for the sole sake of visual communication - at least not explicitly.

In the current paper, we will explore the possibility that visual information from gesture is but one of its (communicatively meaningful) products. Recently, we have found that upper-limb movements with relatively high physical impetus produce prominent but non-intentional changes in voice quality (Pouw, Harrison, & Dixon, 2018b). Specifically, we found peaks in the fundamental frequency (F0) and the amplitude envelope (energy in the signal) of continuous phonation of the vowel /a:/ when participants made high-impact movements that recruited the entire arm (see Figure 1) but not when producing low-

impact wrist movements or when standing still. Such peaks in phonation were observed at the moment at which posturally destabilizing forces of the arm movements were highest and at which the body counteracted such forces by tensioning of the muscles in anticipatory fashion.

Indeed, we found that anticipatory postural adjustments played a role in movement-phonation resonance, as peaks in phonation were more pronounced when participants were standing versus sitting (Pouw, Harrison, et al., 2018b). Previous research has found that, when standing, the forces produced during upper-limb movements are more destabilizing; as a result, thus the body must be more forcefully tensioned via the myofascial-skeletal network so as to keep postural integrity (Cordo & Nashner, 1982). Indeed, we argued that movement reaches the phonation system via the myofascial-skeletal network that allows forces to propagate through the body (Turvey & Fonseca, 2014). In the current case, upper-limb movements are proposed to increase alveolar (lung) pressures, which will, in turn, affect laryngeal pressures. The acoustic result is an increase in speech intensity and pitch.

Figure 1. Example movement time series and concurrent effects on phonation

Note. Example time series of the exploratory study reported in (Pouw, Harrison, & Dixon, 2018a; Pouw, Harrison, et al., 2018b) wherein a female vocalizer phonates the vowel /a:/ while moving her hand up and down with a wrist or arm motion or while standing passively. The black line shows the movement time series on the vertical dimension, the red line shows the concurrent Fundamental Frequency of the phonation, and the purple line shows the amplitude envelope, which is a measure of the energy of the voicing signal. High-impact arm movements produce prominent peaks at the maximum extension phase, while phonation in the passive and wrist-movement condition do not show such acoustic peaks.

Our previous results suggest that acoustic gesture-speech synchrony can accommodate findings as observed in naturalistic contexts. Namely, sudden increases in speech intensity and fundamental frequency are key properties that define the prosody of speech (Shattuck-Hufnagel & Ren, 2018; Wagner, Malisz, & Kopp, 2014), and spontaneous co-speech gestures are known to synchronize with such prosodic aspects of speech

(McClave, 1998; Rusiewicz & Esteve-Gibert, 2018). Scaling up to natural speech, other work has found that infants' babbling becomes more adult-like in voice quality when infants simultaneously and rhythmically move their arms (Ejiri & Masataka, 2001) and that encouraging gesture production during adults' speech production boosted maximum observed F0 and intensity of speech (Cravotta, Busà, & Prieto, 2018). Taken together, these findings are congruent with the idea that limb movement in itself is tied to changes in acoustic production, which provides a physical rudimentary basis for why gesture and speech tends to synchronize on the acoustic level.

It is important to note that there have been some findings that seem to run counter to this claim. Specifically, Hoetjes et al. (2004) found no statistically significant changes in acoustics when participants are restrained from gesturing as opposed to freely able to gesture, nor were listeners able to detect whether someone was gesturing based on listening to their speech. However, we have argued that mixed results might be obtained by averaging acoustic metrics over time (cf. Hoetjes et al.) and that inferences about acoustics and gesture might be obscured when not taking into account physical impetus of gestures.

Since gestures - especially of the more forcefully beat-like kind (see e.g., <https://osf.io/29h8z/>) - likely affect voice acoustics we can start to wonder whether listeners can pick up information about a gesturers movement through audition alone. The idea that there is acoustic information that specifies an object or event in the environment is actually non-controversial in ecological psychology of language (Fowler, 1986, 2010) and object perception (Carello, Wagman, & Turvey, 2005). Namely, Carol Fowler famously asserted that we do not hear speech sounds that we need to translate into meaningful objects of language perception but that we directly hear the *cause* of the sound - the

articulatory gestures. Evidence for this includes studies on the McGurk effect, in which otherwise ambiguous speech sounds are disambiguated by visually or even manually perceiving the articulatory gesture (Fowler & Dekle, 1991). Carello and colleagues (2005) similarly go against the orthodox conception of the informational status of sound in object perception wherein the assumption seems to be that “vision is about awareness of environmental properties, [whereas] audition seems to be largely about the awareness of sound as such” (Carello et al., 2005, pp. 2). Alternatively, a line of research in ecological acoustics has shown instead that properties of objects (e.g., object length, object thickness; volume of contained water; relative position) can actually be directly perceived by attuning to acoustic properties of the objects (Carello, Anderson, & Kunkler-Peck, 1998; Shaw, McGowan, & Turvey, 1991) - for example object acoustic properties when shaken or when hitting a surface (Carello et al., 1998).

The current idea that we can hear bodily gestures is then complementary to these Gibsonian perspectives (Gibson, 2014). In this case, we are after a direct specification of bodily action in speech acoustics. If such specification exists to some degree, this would open up the investigation into whether bodily gestures’ communicative function lies in part in its direct linkage with speech acoustics.

We have a long experimental road ahead before we could conclude that gesture acoustics serve such a communicative role in a manner similar to the visual information created by gesture. Indeed, to date there is simply no evidence that humans can hear gesture (Hoetjes, Krahmer, & Swerts, 2014). Therefore, the first research question we will target is whether there is acoustic specification of bodily movement in speech. In the current exploratory study and pre-registration plan, we investigate this by asking

participants to try to synchronize their own upper limb movements with the movements of a vocalizer merely by listening to a recording of the vocalizer voicing the vowel /a:/. If humans are able to synchronize their movements with another person only by listening to the other's voice, we can conclude that information in acoustics can specify bodily movement. This will then lead the way for the study of communicative significance of the acoustic specification of bodily movements.

Exploratory Study

To lay the groundwork for our preregistration plan of a confirmatory study, we first report the results from an exploratory study in which two participants were asked to make a wrist or arm motion while listening to a recording from a vocalizer, an original participant from Pouw, Harrison, et al. (2018a). The vocalizer was continuously voicing the vowel /a:/ while making a high-impetus arm motion or a low-impetus wrist motion at slow, medium, or fast movement tempos. Arm motions have a higher physical impetus on the body as larger body parts are involved in the movement, as compared to wrist movements. The current participants' task was to synchronize their own movement with the movement of the vocalizer performing, as they perceive it via the acoustics. Because our previous work showed that arm, but not wrist, movements reliably affected the resulting acoustics, we predict that participants will be able to adjust their tempo and synchronize the phasing of their own movements with that of the vocalizer, in the arm-movement condition, but not in the wrist-movement condition (Pouw, Harrison, et al., 2018a, 2018b).

The current exploratory study serves two purposes. First, it provides a preliminary investigation of whether there is motor information in voicing to which a listener can

attune. At this point in our inquiry, it is valuable to know if at least one person can move in synchrony with someone by listening to voicing co-produced with upper limb movements. Second, the exploratory study sets up a thorough pre-registration plan for the confirmatory study. The confirmatory study will see whether phonation is a more widespread and pervasive information source for motor resonance to which people can attune.

Method

Participants & Design

Two female graduate students (ages: 22 and 28) participated in the current exploratory study. The current study entailed a full $2 \times 2 \times 3$ within-subject design: a two-level factor 'listener movement' condition (listening while moving wrist vs. listening while moving arm), a two-level factor 'vocalizer movement' condition (wrist movement vocalization vs. arm movement vocalization), and a three-level factor 'tempo' (slowed down vs. self-paced vs. sped up). Note that slowed-down and sped-up versions were derived from the original self-paced movement vocalizer (see procedure below). Participants performed 12 trials, one for each cell of the design ($2 \times 3 \times 2$). Each trial consisted of 5 phonation cycles where the vocalizer took a full breadth and phonated until breadth was almost emptied and phonation could not be steadily maintained (Pouw, Harrison, et al., 2018a, 2018b).

Stimuli

We extracted two trials collected with a participant in a previous study wherein (henceforth referred to as the 'vocalizer'. For both trials, the vocalizer continuously voiced the vowel /a:/ (as in 'cinema') while making repetitive up-and-down upper-limb

movements at a *self-paced* tempo (around 1.8Hz). The movements were made on the sagittal plane with fingers fully extended, with a higher velocity in the down-phase so as to have a beat-like movement profile. The vocalizer was instructed to try not to let voicing be affected by the movement.

In the extracted wrist-movement vocalization trial, repetitive wrist movements of the dominant right hand were made with no movement around the elbow joint. For this wrist movement, the elbow joint was kept at a 90-degree angle. The wrist movement vocalization trial (listen to the sound-clip here: <https://osf.io/rvx3c/>) reflected a low-impetus movement relative to second arm-movement vocalization trial (sound-clip available here: <https://osf.io/ymqnu/>). The arm-movement vocalization trial was produced by the participant moving her lower arm around the elbow joint, while keeping the wrist joint locked at 0 degrees.

To construct the stimuli of different tempos, we first looped the original audio track from the vocalizer (i.e., movement with self-directed speed) 5 times, such that there were 5 voicing episodes with intermittent pauses where the vocalizer took a full breath. This self-paced vocalization track serves as our “normal” tempo stimuli. We then created two additional versions of this vocalization track, one that was artificially slowed down by 20% and one that was artificially sped up by 20%. These transformations were done with AVS Audio Editor (Online Media Technologies Ltd.), which allows for tempo transformation while maintaining the original pitch. We made a set of three vocalization tempos for both the wrist-movement vocalization conditions and arm-movement vocalization conditions. Effectively this resulted in 3 tempo conditions (slow down vs. self-paced vs. sped up). The tempo conditions provide additional information whether participants are sensitive to

movement-induced rhythm in voicing, which would be evident in in lower or higher frequency of listener movement for slowed down or sped up condition (respectively) as compared to self-paced tempo condition.

Motion-Tracking Equipment

A Polhemus Liberty sampling at 240Hz was used to record movement of the listener (L). Given that upper-limb motions were primarily defined by vertical motion (in the z-dimension), we will only perform synchrony analyses for this dimension. We smoothed z-position traces with a first-order low-pass Butterworth filter of 33 Hz.

Audio Presentation

Participants wore a Samsung Level On EO-PN900BBEGUS headphone (with noise-cancelling deactivated) with a wired connection to the PC. Volume was set at a comfortable level for the participant. The audio was pre-buffered and then played using a custom C++ script that started the audio at the exact moment that the motion tracker started recording. This ensured that the original vocalizer motion-tracking data is completely synchronized with listener motion-tracking data.

Procedure

Each participant (i.e., listener) was asked to stand upright with their elbow in a 90-degree angle. The experimenters then demonstrated the two movement types that the listener needed to make: one wrist movement and one arm movement. Subsequently the participant was informed that they would repeatedly listen to someone voicing, while the vocalizer had been concurrently moving her upper limbs at different speeds (although no additional information was given about speed manipulations). The listener was then told that they would need to synchronize with the movements of the vocalizer, based solely on

hearing her voice. Participants briefly practiced the synchronization task with an arm movement vocalization trial of self-paced tempo, while the listener was asked to move their wrist or arm in synchrony. After practicing, participants performed 12 trials (in randomized order) containing all 2 (listener movement) x 2 (vocalizer movement) x 3 (tempo) conditions wherein they heard 5 voicing episodes before going to the next trial.

Analyses¹

Spectral Analyses (FFT). We performed spectral analyses (fast Fourier transform or FFT) using R's native `stats` package (function `spectrum`) to assess changes in listeners' movement frequency as a function of vocalizer tempo condition.

Relative Phase Analyses (Φ). We performed relative-phase analyses using a simple continuous point-wise estimation method (e.g., Zelic, Kim, & Davis, 2015; see also Kelso, Del Colle, & Schoner, 1990). To calculate Φ we used the equation

$$\varphi = \frac{2\pi\Delta t}{T_v}$$

where T_v is the current time interval for the original vocalizer's maximum vertical extension (i.e., the time between each beat of the vocalizer movement). Δt reflects the asynchrony of the moment of maximum vertical extension of the listener versus the vocalizer. 2π transforms temporal dispersion into the angular dispersion. We converted the equation's output from radians to degrees such that 0 degrees indicated in-phase

¹ Data and analyses code are publicly available on this project's OSF page:

<https://osf.io/9843h/>.

coordination, -180 degree indicated anti-phase coordination with listener in the lead, and 180 degrees indicated anti-phase coordination with vocalizer in the lead.

Results

Descriptive Overview

There are two hierarchically organized research questions that need to be answered before concluding that there is (some) acoustic specification of upper-limb movements in phonation. Firstly, can participants attune to the rhythmic tempo of the movement? Secondly, if indeed participants are sensitive to rhythm in phonation, are participants able to attune to the exact phasing of the vocalizers' movement in a 1:1 in-phase fashion?

Before commencing the formal analyses of these research questions, it is helpful to inspect time series data visually, with added frequency and phasing results based on a single portion of a trial. Figure 2 shows example time series of the listener (participant 1) against the vocalizer for the different movement tempos. This example shows clear tempo differences in listener's movement for the vocalizer arm condition (but not the wrist condition) and an indication of phase-coupled synchronization in the arm conditions.

Figure 2. Example time series, spectral data, and relative phase distributions for participant 1

Note. Example of time series (ts) with concomitant spectral (FFT) and relative phase (Φ) results. Each example consists of the final voicing phase of a single trial (a trial consists of 5 voicing phases). Only trials are shown for matched movements—i.e., those in which the listener (in black) performs same movement as vocalizer (in red). The data show clearly here that the participant only adjusted movement frequency when listening to vocalizer producing an arm movement, as indicated by power distribution shifts following the frequency (Hz) of movement performed by the vocalizer. In the wrist-movement condition, there are no shifts in frequency by the listener's movement. Finally, there is a much clearer indication for phase-coupling for the listener-vocalizer arm-movement condition as compared to the listener-vocalizer wrist movement condition. This is indicated by the Φ density distributions, which show clear peaks with a consistent negative mean asynchrony for the listener-vocalizer arm condition and a much flatter distribution for the listener-vocalizer wrist condition (although there might be some wrist phase-coupling for the original tempo condition).

Acoustic Specification of Movement Tempo in Phonation (FFT Analyses). Next, we formally assessed for all the data the degree to which participants were attuning to tempo information in the vocalization. Figure 3 shows the mean spectral results for the arm- vs. wrist-movement vocalization conditions for all three tempos (and regardless of which movement listeners were making). Namely, there were no clear effects for when listeners were trying to synchronize while making wrist- versus arm-movements (see additional plot with listener movement conditions here: <https://osf.io/6adm4/>). As shown in Figure 3, we found clear evidence for listener-vocalizer tempo-specific movement coupling when the listener heard the clips in which the vocalizer was making arm movements (i.e., arm-movement vocalizations), but not those trials in which the vocalizer was making wrist movements (wrist-movement vocalizations). Thus, for wrist-movement vocalizations, participants seemed to fail to pick up movement tempo information; while listening to arm-movement vocalizations, participants could both adjust tempo of their own arm movements and wrist movements.

Figure 3. Spectral results movement frequencies for vocalizer and listener

Note. FFT results for all movement frequencies (horizontal axis in hertz [Hz]; vertical axis z-standardized power for that frequency) for both the vocalizer and the listener movement frequencies. The vocalizer wrist and arm movement frequencies show slower or faster frequencies per tempo condition by design (as we artificially manipulated the tempo for these conditions). The natural frequency of the vocalizer (original tempo condition) was about 1.75 Hz, with a slight faster frequency for when the vocalizer was making a wrist movement. Interestingly, in the arm vocalization conditions, there was clear frequency coupling between listeners' movement with that of the vocalizer. This is indicated by the large overlap of spectral peaks in arm vocalization condition.

For statistical confirmation of the results obtained in Figure 3, we assessed whether listener's dominant movement frequencies were affected by tempo condition (as well as vocalizer movement condition and listener movement condition). That is, we quantified whether tempo conditions predicted dominant frequency—with higher frequencies for fast tempo conditions and lower frequencies for slow tempo conditions, both as compared to the original tempo. To test this, we extracted the frequency with the highest observed power (i.e., dominant frequency) for each trial. Subsequently we performed `nlme` mixed regressions using participant as a random intercept (adding adding random slopes caused the model not to converge), identifying the best model by comparing model fits at increasing levels of complexity.

Compared to a model predicting the overall mean for dominant frequency, entering tempo condition as a predictor for dominant frequency improved the fit of the model (change in $\chi^2 [1] = 10.32, p = .006$). Adding to the previous model, vocalizer movement condition improved the fit of the model further, change in $\chi^2 [1] = 6.95, p = .008$. Adding the interaction between tempo (3 levels) and vocalizer-movement conditions to the previous model further improved the model, change in $\chi^2 [2] = 7.67, p = .021$. Finally, adding listener movement condition to this previous model did not significantly improve predictions of dominant frequency further (change in $\chi^2 [1] = 2.41, p = .12$).

The best-fit model with vocalizer movement and tempo (and their interaction) was assessed with post-hoc comparisons with the R package `lsmeans` (using Tukey correction for multiple comparisons). Only the arm movement vocalization condition showed tempo scaling of listener movement with that of the vocalizer, and this was only statistically

reliable for the contrast between sped-up vs. slowed down tempo condition. All model results are reported in Table 1.

Table 1. Post-hoc comparisons for frequency scaling per tempo and vocalizer movement condition

Arm Movement Vocalization	Difference estimate	t ($df=17$)	p -value (corrected)
Sped up - slowed down tempo	0.71Hz	4.89	<.001
Sped up - self-paced tempo	0.36Hz	2.52	.054
Self-paced - slowed down tempo	0.34 Hz	-2.37	.073
Wrist Movement Vocalization			
Sped up - slowed down tempo	0.181	1.25	0.443
Sped up - self-paced tempo	0.192	1.33	0.402
Self-paced - slowed down tempo	-0.011	-0.077	0.996

Acoustic Specification of Movement Phasing in Phonation (Relative Phase

Analyses: $SD \Phi$). Now that we have established that there is frequency-coupling between listener and vocalizer movement (but only for vocalizer arm movement), we assess whether there is also phase-synchronization. Note that it is possible that participants picked up the rhythmic structure in the voicing while being oblivious about the exact phases of the vocalizer's movement.

Figure 4, however, clearly shows that there was indeed listener-vocalizer phase-coupling but only for the vocalizer arm movement. Furthermore, there is not perfect in-phase locking but rather a negative mean asynchrony whereby the listener anticipates the

vocalizer with about $\Phi = 50$ degrees. Note that negative mean asynchrony is a very common phenomenon in sensorimotor synchronization tasks (Repp, 2005).

Figure 4. Distributions relative phase listener-vocalizer

Note. The left panel shows the relative phase distributions for all data combined for the vocalizer wrist movement and the vocalizer arm movement condition. On the right-hand side, data are parsed for each tempo and listener movement conditions. The clear peaked relative phase distributions for the vocalizer arm motions indicating phase-coupling for this condition, but we also saw that listeners tended to anticipate vocalizer movement.

We statistically confirmed the phase-coupling results by computing the standard deviation of Φ per trial performed. If phase-coupling is more pronounced, lower SD Φ will be observed (i.e., less variable/more stable phase relations around the average relative

phase). We assessed this using `nlme` mixed regressions (again using participant as the sole random intercept without random slopes, as adding random slopes caused the model to fail to converge).

As compared to a model predicting the overall mean, entering vocalizer movement condition as a predictor for $SD\ \Phi$ led to increased fit of the model (change in $\chi^2 [1] = 30.62$, $p < .001$). Adding tempo condition as an additional predictor did not further improve prediction of relative-phase (change in $\chi^2 [1] = 1.34$, $p = 0.51$). Adding listener movement condition as a predictor for relative phase (next to vocalizer movement) also did not improve the previous model (change in $\chi^2 [1] = 0.74$, $p = 0.378$). Therefore, the resulting best-fit model—which included vocalizer movement condition as the sole fixed effect—revealed that vocalizer arm movement condition had a lower $SD\ \Phi$ of 51 degrees as compared to the vocalizer wrist movement condition, $b = -51.09$, $t[21] = -7.81$, $p < .001$. These findings support our hypothesis that listeners synchronized their movement phasing with phase information in the vocalizer acoustics.

Brief Discussion

While these preliminary (results require replication), the current exploratory study demonstrates that it is—in principle—possible to glean information about bodily movement from voice acoustics alone. We found that listeners demonstrated both frequency-coupling and phase-coupling of their own movements with that of a vocalizer who was moving at different tempos while producing a single vowel sound. As predicted based on the absence of acoustic effects (Pouw, Harrison, et al., 2018a, 2018b), the vocalizer wrist movements (as opposed to vocalizer arm movements) were not reliably detected by the listeners; no evidence was obtained for frequency- or phase-locking in the wrist movement vocalizations. Although it appears that there must be some information about bodily gestures in phonation acoustics, the current exploratory study is unable to determine how pervasive the couplings might be. A planned confirmatory study pre-registered in the second part of this paper will provide more information about the degree to which voice acoustics can specify bodily gestures.

The current results suggest that we do not necessarily hear voicing as only voicing: Intriguingly, we can also detect within voicing the bodily states of the voicer on the basis of acoustic-body invariants. The current research therefore directly aligns with the ecological psychology of language (Fowler, 2010) and the acoustic perception of object geometry (Carello et al., 2005). Our findings may extend this research program with the idea that prosodic contrasts in speech are direct informational sources of bodily tensioned states (including hand gestures). The findings further align with research on other animals, who often modulate their vocal activity so as to appear larger (and more intimidating or appealing) in size (Hardus, Lameira, Van Schaik, & Wich, 2009).

The current line of research yields tangible implications for the continuing study of gesture-speech prosody. If the current exploratory findings can be replicated, *gesture acoustics* (Cravotta et al., 2018; Pouw, Harrison, et al., 2018b) will be shown to have affordances for real interpersonal embodied couplings. Understanding the social communicative significance these couplings would be our next research question.

Pre-Registration of a Confirmatory Study

Goal

The goal of the confirmatory study is to assess the pervasiveness of listener-vocalizer coupling in a larger sample. The confirmatory study further allows us to explore more detailed questions regarding listener-vocalizer coupling. For example, what acoustic properties are important for listener-vocalizer coupling? Do listener and vocalizer need to be similar in vocal range before listener-vocalizer coupling to emerge? Is listener-vocalizer coupling more easily established when vocalizer tempo is closer to the listener's natural frequency of movement?

Pre-Study

We will first perform a pre-study to collect natural stimuli that will be used for the confirmatory study. The pre-study essentially entails a replication of Pouw, Harrison, et al. (under review) with some small modifications to the design.

Pre-Study Design. Six undergraduates (sex: 3 male and 3 female) will be recruited for the pre-study. A within-subjects design will include two factors: movement (2 levels; wrist vs. arm movement) and tempo (3 levels; slow vs. medium vs. fast). For each condition, we will record 3 trials consisting of phonation at a consistent volume for a single breath. Thus, per participant, we will have 18 trials for a total of 108 trials, of which 36 trials will be extracted for the confirmatory study.

Pre-Study Equipment and Apparatus. All equipment and recording procedures (e.g., Polhemus Liberty Motion tracking system) reported in Pouw, Harrison, et al. will be used in the current experiment with the exception of improved audio recording setup.

Specifically, we will record audio with a condenser cardioid microphone headset MicroMic C520 (AKG, Inc.).

Pre-Study Procedure. Similar to the procedure in Pouw, Harrison et al. (under review), participants will produce movements (arm and wrist movements), but for the present study, we will include several different tempos (slow = 1.06Hz; medium = 1.33Hz; fast = 1.6Hz). Slower and faster movements are 20% tempo change from medium.

Participants will be recruited and run individually. Participants will wear a motion-tracker sensor on the index finger of their dominant hand and a microphone headset. Participants will then be introduced to the two types of movement (wrist and arm movement) that they will be asked to make. They will for each movement a baseline trial, wherein they will be asked to practice these movements at their own preferred steady-state frequency for a period of 1 minute. This will provide us some insight into the natural frequencies of these types of movement, but these data will not be used as stimuli in the proposed confirmatory study.

For further practice, participants will perform the same movements again, but this time, they will be asked to practice with an interface that shows participants whether they are moving too slow or too fast relative to the experiment-mandated tempo. This interface—programmed in C++—will show a dynamically changing bar that reflects the movement frequency as detected by the motion tracker, along with two borders of 10% lower and upper boundary, and participants will be asked to try to maintain their frequency with various speed manipulations (see Pouw, Harrison et al., under review). As a final practice, participants will be asked to perform these movements and simultaneously phonate. Participants are instructed to start moving, take a deep breath, and start

phonating the vowel /a:/ (as in cinemaa) until they feel that cannot maintain a steady phonation level.

For the main pre-study phase, each participant will perform all conditions (2 vocalizer x 3 movement tempo) for 3 breath trials. The order of conditions will be randomized for each participant.

Pre-Study Analyses and Selection of Stimuli. We will perform similar acoustic analyses as reported in (Pouw, Harrison, et al., 2018b) so as to see whether upper limb movement affected phonation. These analyses will also allow us to select trials as stimuli that are optimal for presentation in the confirmatory study. Further, we will use the results of the acoustic analyses (e.g., degree of acoustic entrainment on F0 or amplitude envelope dimension) for exploratory analyses as a way to predict listener-vocalizer coupling in confirmatory study. This will allow us to provide insight in likely specifying variables in acoustics.

We will select optimal trials from each participant (2 movement condition x 3 tempo condition). Trials will be selected on the basis of whether participants could maintain the required movement frequency and audibility of the acoustic correlates of movement.

Confirmatory Study

The stimuli created by participants in the pre-study will then be used in the confirmatory study. The confirmatory study is essentially a replication of the current exploratory study but with more natural and diverse stimuli.

Design. We will recruit 30 participants (sex: 15 female, 15 male) for the confirmatory study. Given that our exploratory study shows that listener-vocalizer coupling seems to be a strong phenomenon that can be detected on individual-level scale,

we are confident we can replicate the current phenomenon in a group of 30 participants, which will further provide us with the needed information about individual variability in listener-vocalizer coupling. Note that for replicating our main results obtained here, a generic power analyses (G*Power version 3.1.9.2) for a within-subjects analyses with 2 (vocalizer movement) x 3 (tempo) groups (= 6 groups), 80% power, $\alpha = 0.05$, 6 measurements, and a medium effect size of Cohen's $f = 0.25$, yields a recommended number of 24 participants.

The confirmatory study consists of a fully within-subjects design with a 2-level factor, vocalizer movement (wrist movement vocalization vs. arm movement vocalization); a 2-level factor, listener movement (listener wrist movement vs. listener arm movement); and a 3-level factor, tempo (slow vs. medium vs. fast). Each participant will perform each condition for 6 trials (i.e., 6 trials x 2 V movement x 2 L movement x 3 tempo = 72 trials).

Stimuli. We will have extracted 36 trials from 6 different vocalizers. Each trial will consist of 2 loops of 1 breathing-phonation cycle.

Equipment. The equipment setup used in the current exploratory study will also be used in the confirmatory study.

Procedure. Participants will undergo the same procedure as reported in the exploratory study, with some slight modifications. Firstly, participants will initially perform wrist and arm movements at their own preferred steady-state frequency for a 1-minute period, so that we know what participants' individual preferred movement frequency is.

Secondly, trial structures will be modified such that participants will hear 2 phonation cycles (i.e., 2 breathing-phonation cycles). In the first phonation cycle, participants will be instructed only to listen, and in the second cycle, participants will be

asked to synchronize with the movement of the vocalizer. This will allow participants to first attune to the structure in the acoustics before they start moving. The trials as such are shorter than in the exploratory study (which consisted of 5 phonation cycles), but this will allow us to present all 6 vocalizers to the participant. Thus, participants will perform 36 trials of about 50 seconds each. Participants will get a break of 5 minutes in between the experiment. The total experiment will take about 45 minutes.

Confirmatory Hypotheses. We will perform the same analyses as in the exploratory study, whereby we will assess evidence for frequency-coupling (reusing the FFT analyses) as well as phase-coupling (reusing the relative phase analyses) between listeners and vocalizers. We predict that frequency-coupling and phase-coupling will be evident for listener wrist and arm movements but only for vocalizer arm movement (relative to vocalizer wrist movement).

Exploratory Hypotheses. We will perform a myriad of other analyses that address following questions, including:

- Which acoustic correlates predict listener-vocalizer coupling?
- Do listeners couple more easily with vocalizers who have a vocal range similar to their own?

Does listener-vocalizer coupling increase when vocalizer movement tempo is at frequency closer to the listener's preferred (or natural) frequency?

References

- Bavelas, J., Gerwing, J., Sutton, C., & Prevost, D. (2008). Gesturing on the telephone: Independent effects of dialogue and visibility. *Journal of Memory and Language*, 58(2), 495–520. <https://doi.org/10.1016/j.jml.2007.02.004>
- Carello, C., Anderson, K. L., & Kunkler-Peck, A. J. (1998). Perception of object length by sound. *Psychological Science*, 9(3), 211–214. <https://doi.org/10.1111/1467-9280.00040>
- Carello, C., Wagman, J. B., & Turvey, M. T. (2005). Acoustic specification of object property. In J. D. Anderson & B. Fisher Anderson (Eds.), *Moving*, 79–104.
- 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. (2018). Restraining and encouraging the use of hand gestures: Effects on speech. In *9th International Conference on Speech Prosody 2018* (pp. 206–210). ISCA. <https://doi.org/10.21437/SpeechProsody.2018-42>
- Ejiri, K., & Masataka, N. (2001). Co-occurrences of preverbal vocal behavior and motor action in early infancy. *Developmental Science*, 4(1), 40–48. <https://doi.org/10.1111/1467-7687.00147>
- Fowler, C. A. (1986). An event approach to the study of speech perception from a direct-realist perspective. *Journal of Phonetics*, 14(1), 3–28.
- Fowler, C. A. (2010). Embodied, embedded language use. *Ecological Psychology*, 22(4), 286–303. <https://doi.org/10.1080/10407413.2010.517115>

- Fowler, C. A., & Dekle, D. J. (1991). Listening with eye and hand: Cross-modal contributions to speech perception. *Journal of Experimental Psychology: Human Perception and Performance*, 17(3), 816–828. <https://doi.org/10.1037/0096-1523.17.3.816>
- Gibson, J. J. (2014). *The Ecological Approach to Visual Perception : Classic Edition*. Psychology Press. <https://doi.org/10.4324/9781315740218>
- Hardus, M. E., Lameira, A. R., Van Schaik, C. P., & Wich, S. A. (2009). Tool use in wild orangutans modifies sound production: A functionally deceptive innovation? *Proceedings. Biological Sciences*, 276(1673), 3689–3694. <https://doi.org/10.1098/rspb.2009.1027>
- Hoetjes, M., Krahmer, E., & Swerts, M. (2014). Does our speech change when we cannot gesture? *Speech Communication*, 57, 257–267. <https://doi.org/10.1016/j.specom.2013.06.007>
- Iverson, J. M., & Goldin-Meadow, S. (2001). The resilience of gesture in talk: gesture in blind speakers and listeners. *Developmental Science*, 4(4), 416–422. <https://doi.org/10.1111/1467-7687.00183>
- McClave, E. (1998). Pitch and manual gestures. *Journal of Psycholinguistic Research*, 27(1), 69–89. <https://doi.org/10.1023/A:1023274823974>
- Pouw, W., Harrison, S. A., & Dixon, J. A. (2018a). The physical basis of gesture-speech synchrony: Exploratory study and pre-registration. <https://doi.org/10.31234/osf.io/9fzsv>
- Pouw, W., Harrison, S. J., & Dixon, J. A. (2018b). Gesture-speech physics: The biomechanical basis of gesture-speech synchrony. <https://doi.org/10.31234/osf.io/tgua4>

- Rusiewicz, H. L., & Esteve-Gibert, N. (2018). Set in time. In *The Development of Prosody in First Language Acquisition* (pp. 103–124). Amsterdam: Benjamins Publishing Company. Retrieved from <https://benjamins.com/catalog/tilar.23.06rus>
- Repp, B. H. (2005). Sensorimotor synchronization: a review of the tapping literature. *Psychonomic bulletin & review*, 12(6), 969-992. doi: <https://doi.org/10.3758/BF03206433>
- 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. <https://doi.org/10.3389/fpsyg.2018.01514>
- Shaw, B. K., McGowan, R. S., & Turvey, M. T. (1991). An acoustic variable specifying time-to-contact. *Ecological Psychology*, 3(3), 253–261. https://doi.org/10.1207/s15326969eco0303_4
- 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., 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>