Behavioral dynamics of conversation and (mis)communication in noisy environments

Kelly Miles (kelly.miles@mq.edu.au)
ECHO Laboratory, Department of Linguistics,
Macquarie University, 2109, Australia

Adam Weisser (adam.weisser@mq.edu.au)
ECHO Laboratory, Department of Linguistics,
Macquarie University, 2109, Australia

Manuel Varlet (m.varlet@westernsydney.edu.au)
The MARCS Institute for Brain, Behaviour and Development,
Western Sydney University, Australia

Rachel W. Kallen (rachel.kallen@mq.edu.au)
School of Psychological Sciences,
Macquarie University, 2109, Australia

Michael J. Richardson (michael.j.richardson@mq.edu.au)
School of Psychological Sciences,
Macquarie University, 2109, Australia

Jörg M. Buchholz (jorg.buchholz@mq.edu.au)
ECHO Laboratory, Department of Linguistics,
Macquarie University, 2109, Australia

Abstract

While communication is an essential part of life, it is not always easy and effortless. This is especially true when talking with someone in a noisy environment. Although communicating in noise is often the rule rather than the exception, very little research has investigated the behavioral processes individuals might use to minimize miscommunication when listening becomes challenged. Here we explored synergistic speech and movement processes that 22 pairs of adults used to hear and be heard when (mis)communicating in noise. The results revealed intricate dynamics both with respect to acoustic optimization of the speech produced and heard, as well as how individuals modulate interpersonal distance and behavioral coordination patterns.

Keywords: communication breakdown; interactive communication; other-initiated repair requests; interpersonal motor coordination; background noise; speech intelligibility

Introduction

Having a conversation is not always easy, especially in noisy environments such as busy restaurants, train stations or nightclubs. To hear and be heard in such situations, people must juggle both verbal and non-verbal channels of communication, while simultaneously negotiating the constraints imposed by physical boundaries, physiology and perceptual limits, and social and cultural norms. This requires that individuals expertly coordinate numerous behavioral processes across multiple modalities and time scales, reciprocally and functionally modulating behavior to maximize comprehension in relation to environmental constraints.

Not surprisingly, previous research has demonstrated how the mere act of conversing with another individual is characterized by a cascade of coordinated interpersonal behaviors. For example, the vocabularies (Kulesza, Dolinski, Huisman, & Majewski, 2014), accents (Giles, 1973), and speaking rates and patterns (Natale, 1975; Street, 1984) of interlocuters become aligned over the course of a conversational exchange. The movements, gestures, body postures (Condon & Ogston, 1967; Shockley, Santana, & Fowler, 2003) and gaze patterns (Richardson, Dale, & Tomlinson, 2009) of conversing individuals become synchronized during a conversation, with nonconscious mimicry also amplified (Gueguen, Jacob, & Martin, 2009). In a similar vein, the strength of neural coupling between speakers and listeners has been shown to covary during successful communication (Stephens, Silbert, & Hasson, 2010). Research has also demonstrated how the interpersonal coordination processes synonymous with effective conversation can increase feelings of social connectedness (Marsh, Richardson, & Schmidt, 2009), affiliation (Chartrand & Bargh, 1999; Lakin, Jefferis, Cheng, & Chartrand, 2003), likeability and rapport (Hove & Risen, 2009; Miles, Nind, & Macrae, 2009), as well as facilitate prosocial behavior (Cirelli, Einarson, & Trainor, 2014; Fusaroli, Rączaszek-

In M. Goldwater, F. K. Anggoro, B. K. Hayes, & D. C. Ong (Eds.), *Proceedings of the 45th Annual Conference of the Cognitive Science Society*.

Leonardi, & Tylén, 2014; Marsh, Johnston, Richardson, & Schmidt, 2009; Miles, Lumsden, Richardson, & Neil Macrae, 2011; Schmidt & Fitzpatrick, 2016; Schmidt, Morr, Fitzpatrick, & Richardson, 2012; R. C. Schmidt, Nie, Franco, & Richardson, 2014) and promote cooperative interaction (Reddish, Fischer, & Bulbulia, 2013). Thus, these coordinated processes also appear to provide the behavioral foundation for positive social interaction in general (Marsh, Richardson, Baron, & Schmidt, 2006).

Despite how robust the above findings are, the various verbal and nonverbal alignments and behavioral coordination processes that have been empirically observed between people have only been investigated under stationary (i.e., movement restricted) and normal (typically comfortable) conversational conditions. An important yet open question is therefore how individuals dynamically and reciprocally structure their ongoing behavior to effectively maintain communication within every-day, noisy environments.

When dealing with daily signal-to-noise ratio (SNR) challenges, there are several ways that conversing individuals might mitigate the effects of environmental noise to boost speech intelligibility (Aubanel, Cooke, Villegas, & Lecumberri, 2011) and minimize communication breakdowns. For example, conversing individuals can adjust their speech by increasing their speech level relative to the noise (e.g., the Lombard effect; Lombard, 1911), slowing their speech rate (Payton, Uchanski, & Braida, 1994; Picheny, Durlach, & Braida, 1989) or simply move closer to one another (Hadley, Whitmer, Brimijoin, & Naylor, 2021; Weisser, Miles, Richardson, & Buchholz, 2021) to indirectly increase the speech level at the listener's ears. Indeed, given the large body of research demonstrating how interpersonal and social behavioral coordination is typically synergistic, (i.e., different behavioral degrees-of-freedom self-organize via reciprocal compensation to ensure task success), it seems likely that individuals employ all these processes concurrently (both consciously and unconsciously) over the course of a conversation to maximize comprehension and flow (Shockley, Richardson, & Dale, 2009).

Of course, when the SNR challenge becomes too overwhelming for people in the real world and mutual understanding is jeopardized, communication breakdowns inevitably occur. Such breakdowns often result in an other-initiated repair (OIR) request (Albert & de Ruiter, 2018; Dingemanse et al., 2015). An example minimum sequence of an other-initiated repair is the signaling of a trouble source (e.g., 'what did you say?') and the subsequent repair of the trouble source (e.g., 'I said, I love manta rays'). Here we not only use OIRs during conversations to index communication difficulty, but we quantify the coordinated behavioral adjustments that individuals spontaneously employ to re-establish communication following breakdowns.

We theorize that processes to maintain successful communication in challenging background noise are derived through reciprocal compensation, such that pairs react to changes in the other given the demands of the environment (Riley, Richardson, Shockley, & Ramenzoni, 2011). As such, we anticipate that interpersonal synergies will manifest across modalities, where increasing background noise will drive pairs closer to each other and increase speech levels, and the stability of interpersonal motor coordination will strengthen. In addition, we expect that the physical barrier imposed by the table when pairs are seated (as opposed to when they are standing while talking – see Figure 1) will greatly impact interpersonal synergy. Given the pairs cannot physically move closer to each other when seated across the table - along with the physiological and psychological limitations of talking loudly (or too loud) - we expect the magnitude and stability of interpersonal motor coordination to increase more in the seated condition compared to standing as the level of background noise increases.

Materials and methods

Participants

Data of 44 participants in 22 pairs were analyzed in a within-subjects design. Pairs were related to one another either as friends (14 pairs), couples (6), or siblings (2).

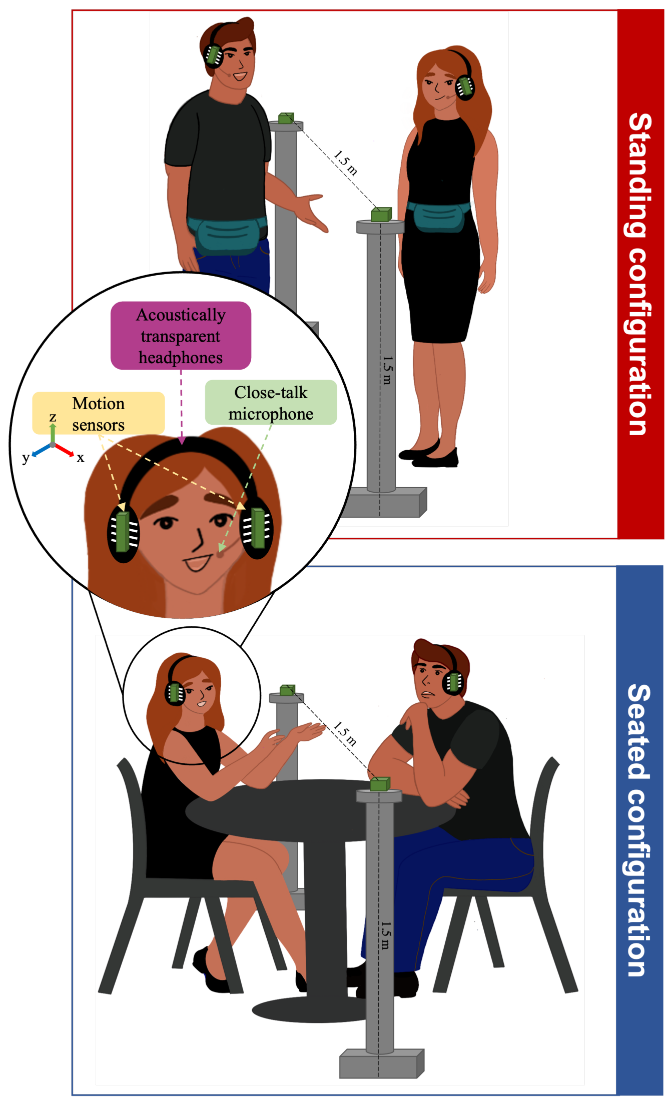

Figure 1. Illustration of the experimental setup

All participants were hearing, with pure tone thresholds better than 20 dB HL in both ears. The average age was 22.2 years for female participants (32) and 24.4 for the male participants (12).

Procedure

The experiment took place in a room of dimensions 4.11 × 2.59 × 2.54 m^3 and reverberation time of T_{30} = 0.7 s. The pairs were fitted with headphones and microphones, as well as their respective wireless receiver and transmitter along with two wireless motion trackers mounted to their headphones. The participants were instructed to have free conversations for two minutes after a cue was given, just before the playback of the noise stimulus began. Conversations were held either in a standing or a seated configuration. In the standing configuration, pairs began by standing in front of each other at 2.5 m and they were instructed to move freely, as needed, for comfortable conversation. In the seated configuration, the participants sat across a round table that was 0.76 cm in diameter and were instructed that they could position themselves where comfortable but they had to remain seated. Figure 1 illustrates the experimental setup.

Materials

Background noise stimuli were five real-world scenes from the Ambisonic Recordings of Typical Environments (ARTE) database (Weisser et al., 2019): Library (mean free-field level of 53 dB SPL), Living Room (63.3 dB SPL), Cafe (2) (71.7 dB SPL), and Train Station (77.1 dB SPL), Food Court (2) (79.6 dB SPL). Two additional noise stimuli were presented of a Party without background music (No Music Party; 85.0 dB SPL) and a Party with background music (Music Party; 92.0 dB SPL). The scenes were presented to participants using non-individualized binaural reproduction over open headphones (Sennheiser HD-800), which allowed for nearly-transparent acoustic communication between participants. The signals were generated in Matlab through a UFX RME sound card and a Sennheiser SR 300 IEM transmitter and were received by portable stereo wireless headphone receivers (Sennheiser EK 300 IEM) worn by the participants, which provided calibrated output level for the headphones.

Speech levels

Near-field speech signals were recorded using individual DPA d:fine™ FIO66 omnidirectional headset (boom) microphones that were placed near the participants' mouths. Speech was recorded throughout the duration of each background noise (2 minutes) at a sampling rate of 44.1 kHz with 24 bits depth using the UFX RME sound card. The absolute output levels of the individual boom microphones were calibrated with reference to an omnidirectional microphone at a distance of 1 m (Beechey, Buchholz, & Keidser, 2018; Weisser et al., 2021).

Motion capture

The head position of each participant was tracked using two motion trackers that were mounted on the outer left and right earpieces of participant headphones without obstructing their grills. Tracked data of each marker were of six degrees of freedom—including both position (*x, y, z*) and rotation (*pitch, yaw, roll*)—which were obtained using a Polhemus Latus motion tracking system. Motion data from the markers were wirelessly detected by receptors that were mounted on 1.25 m stands with distance of 1.5 m between them that together provided full coverage of the participants' positions at precision of ±0.5 mm. The data from the markers were sampled at 120 Hz which was synchronized to the audio playback and recording setup. The raw motion data were smoothed using a 10 Hz low-pass filter (fourth-order Butterworth) prior to the analysis.

Interpersonal Distance The interpersonal distance between participants was calculated for each trial with respect to the central, 3D-position of each participant's head. At each time-step, we calculated the averaged (x, y, z) position of the motion tracking sensors attached to the left and right earpieces of the participants' headphones. From the resulting "center-of-head" (x, y, z) positional time series, a single interpersonal distance time series for each trial was calculated as the relative distance between the center-of-head position of participants in a pair.

Coordination analyses Due to the variable and stochastic nature of the participants' body movements when conversing, Cross-Recurrence Quantification Analysis (CRQA) was employed to measure the magnitude and stability of the movement coordination that emerged between the pairs. As noted above, CRQA determines the dynamic similarity or covariance of two time-series trajectories independent of the distribution, stochasticity, or stationarity of the underlying data. In short, CRQA involves determining whether the states of two systems or behavioral trajectories are recurrent (close together, overlap) in reconstructed phase space and is known to be highly sensitive to the subtle space–time correlations that can occur between two motion trajectories (see Marwan, 2003; Shockley, 2005; Zbilut, Giuliani, & Webber, 1998).

To determine the stability of the movement coordination (MAXLINE) that occurred between participants we performed CRQA analysis on the participants' center-of-head movement vector time series. We computed a single 3D movement displacement vector time series for each participant from their center-of-head time series and performed CRQA on the displacement vector time series for each trial. CRQA requires the selection of several key parameters for (i) defining the dimension of reconstructed phase space that movement trajectories are embedded in and (ii) determining what trajectory states in phase space are close enough together to be considered recurrent (see Marwan, Carmenromano, Thiel, & Kurths, 2007; Shockley et al., 2003, for details). For the data presented here, we employed an embedding dimension of six (determined using *false-nearest* *neighbors analyses*), a time-lag (T-lag) of 23 samples (determined using *average mutual information analysis*), and a recurrent point radius of 20% of the mean distance between points. All data were also z-score normalized prior to analysis. Note that following recommended practice (Marwan, 2003; Shockley, Butwill, Zbilut, & Webber, 2002; Webber Jr & Zbilut, 2005), we validated that the results were not parameter dependent by conducting CRQA using embedding dimensions of 5 and 7, and T-Lags of 12, 18, 34, and 47, and radii of 15% and 25% of the mean distance between points, with the same pattern of results observed across all parameter settings.

Communication breakdown analyses

All conversations were professionally transcribed and made available in a single text file. The first author read the transcription and selected all interactions in which communication breakdowns occurred, coded as all instances of overt signaling of an other-initiated repair. The time codes of the communication breakdowns were documented to time align with the motion and speech acoustics.

Results

Our analysis revealed three interrelated phases of behavioral modification and coordination. First, *transient behavior,* which manifested at the onset of background noise and involved initial, rapid adjustments to enable a 'baseline' level of successful communication. Second, *sustaining behavior,* which perpetuated after the initial transient adjustments had abated and comprised subtle, yet continuous, movement coordination processes and speech level adjustments that occur throughout conversation. Finally, reactive or intermittent *resetting* behaviors, which corresponded to a marked reduction of interpersonal distance and/or a marked increase in speech level following a communication breakdown and OIR. In what follows, we present the results of our analysis with regards to each phase in turn.

Transient behavior

Transient behavior refers to the initial behavioral processes that operate to set conversing individuals up for initial communication success.

Interpersonal distance adjustments The interpersonal distance variation of pairs over the first 20 seconds following the onset of each background noise level is displayed in Figure 2 (top). As can be seen, pairs rapidly adjusted their interpersonal distance by moving closer to each other within the first 5 to 10 seconds of their conversation. As expected, this adjustment was dependent on background noise level and was less pronounced in the seated compared to the standing configuration due to the physical constraint imposed by the table. There was a significant interaction between background noise and talker configuration on the change in interpersonal distance (F (1, 283) 21.08, p <0.001, η_p^2= 0.07) with the significantly larger effect of background noise on interpersonal distance evident when pairs were standing compared to when seated. Specifically, there was a linear increase in change in interpersonal distance as environmental loudness increased: for every 1 dB increase in background noise, change in interpersonal distance increased by 0.70 cm [SE: 0.20 cm; CL: 0.30 cm, 1.09 cm) when seated, and 2.0 cm (SE: 0.20 cm; CL: 1.61 cm, 2.40 cm) when standing.

Speech level adjustments Similar to the findings for interpersonal distance, Figure 2 (bottom) illustrates how the pairs also rapidly adjusted their speech levels in response to the background noise. There was a significant main effect of background noise on change in speech levels (the difference between final and starting states), only (F (1, 277) 123.18, p <0.001, η_p^2= 0.31). Interestingly, there was no effect of talker configuration, (F (1, 277) 0.418, p = 0.59, η_p^2= 0.001), with speech levels increasing by a mean of 0.32 dB (SE: 0.03; CL: 0.26, 0.38) for every 1 dB increase in background noise for both the standing and sitting configuration conditions.

Sustaining behavior

An inspection of Figure 2 revealed that after the initial, transient adjustments in interpersonal distance and speech level, both interpersonal distance and speech level remained relatively stable over the remaining course of conversational trials. This is not to say that the speech levels and movements of individuals were static. On the contrary, both the movements and speech levels of individuals continued to fluctuate over the course of the conversational trials, with these subtle fluctuations assumed to reflect the behavioral coordination process that pairs employ to effectively sustain and facilitate ongoing communication. Of interest here was whether the effects of environmental noise on the occurrence and stability of interpersonal coordination were modulated by the differential physical movement constraints that characterized the sitting and standing configurations.

Interpersonal movement coordination To determine whether and how interpersonal motor coordination processes covaried with background noise and talker configuration we quantified the magnitude and stability of the postural (body) movement coordination that emerged between the pairs using CRQA. The CRQA analysis revealed main effects of background noise (F (1, 283) 18.66, p = 0.011, η_p^2= 0.06) and talker configuration (F (1, 283) 15.32, p <0.001, η_p^2= 0.05) on the stability of coordination, and also a significant interaction between background noise and talker configuration (F (1, 283) 11.93, p <0.001, η_p^2= 0.04). As can be seen from an inspection of Figure 3, pairs maintained relatively unvarying coordination stability over the entire range of background noise levels while standing but exhibited high stability of coordination in the loudest background noises when seated. More specifically, for every 1 dB increase of background noise level, coordination stability increased by 0.99% [CL: 0.64%, 1.34%] when pairs were conversing, but only while seated.

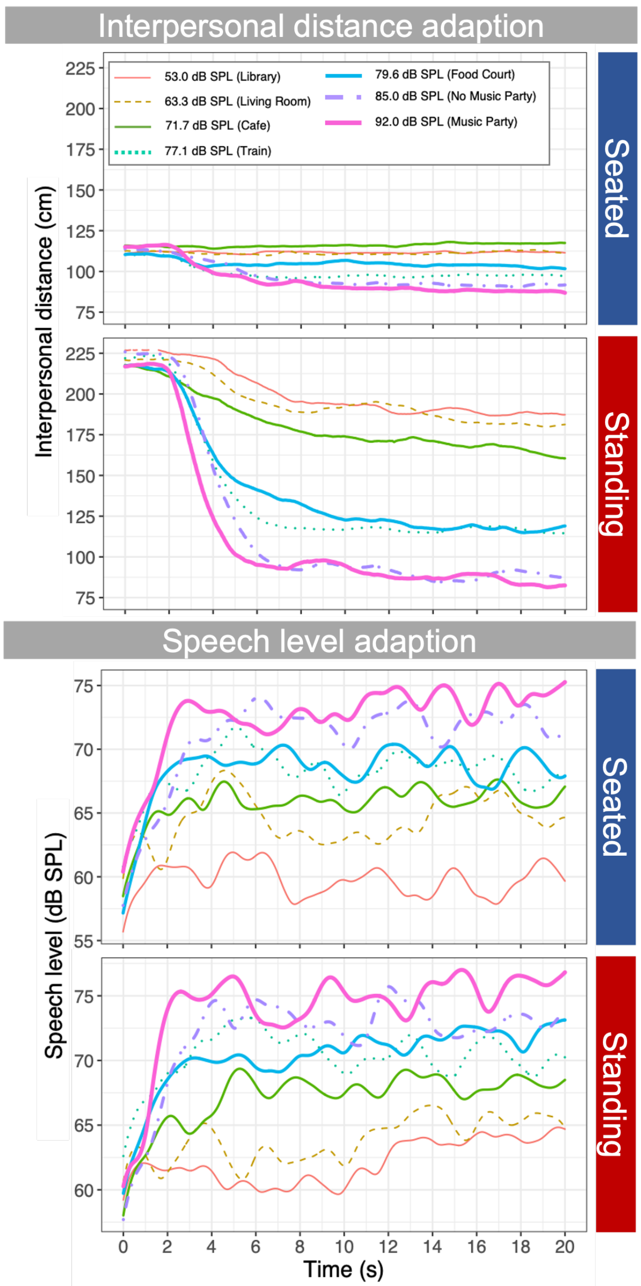

Figure 2. The adaptive behavior of interpersonal distance (**top**) and speech level (**bottom**) as a function of time with background noise and talker configuration as parameters.

Resetting behavior

Here we examined how background noise and talker configuration impacted the number of communication breakdowns that occurred during conversations and quantified the resetting behaviors pairs used to resolve these breakdowns.

The total number of communication breakdowns across all participants is plotted in Figure 4 and as expected, reveals that there was an increase in the number of breakdowns as background noise level increased. Interestingly, below 78 dB SPL (i.e., at the four quietest environments) the number of breakdowns remained relatively low and minimally changed across the levels of noise. Above 78 dB SPL, however, communication breakdowns steeply increased with noise level. Analyzing only the three background noise levels above 78 dB SPL, we found a significant main effect of background noise (F (1, 151) = 40.65, p <0.001, η_p^2= 0.21), no main effect of talker configuration (F (1, 151) = 0.042, p = 0.838, η_p^2<0.001), with no interaction (F (1, 151) = 0.008, p = 0.926, η_p^2< 0.001). That is, for every 1 dB increase in background noise, the number of communication breakdowns increased, on average, by 0.15 [SE: 0.024; CL: 0.107, 0.203]. This corresponds to an increase of one communication breakdown for every noise level increase of approximately 7 dB.

An analysis of the pairs' behavior at the locus of communication breakdowns revealed significant changes in interpersonal distance and speech level in response to a communication breakdown. There was a significant reduction in interpersonal distance (F (1, 791) = 8.095, p = 0.005, η_p^2=0.01) and significantly increased speech levels (F (1, 787) = 71.29, p <0.001, η_p^2 0.08) between pre-communication breakdown and post-communication interpersonal distance and speech level measures, respectively. Averaged across the levels of talker configuration and background noise, pairs moved 5 cm closer, and the talkers' speech levels were 3.2 dB SPL louder, in direct response to a listener signaling a communication breakdown (i.e., before and after the breakdown).

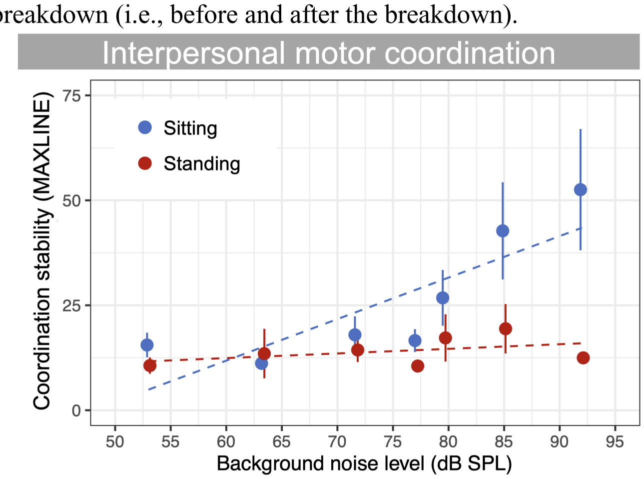

Figure 3. Mean and standard error of the coordination stability between pairs as a function of background noise level and talker configuration, with dashed regression lines to show statistical modeling.

Discussion

We identified multimodal processes of reciprocal compensation that the pairs used to hear and be heard when establishing and maintaining communication, and when re-establishing communication after breakdown. In summary, the findings revealed three dynamic phases of adaptive behavior, which we defined here as *transient*, *sustaining*, and *resetting* behavioral processes, and that these processes entail

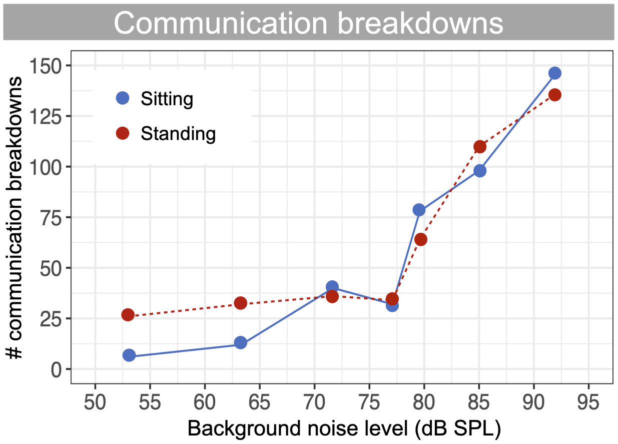

Figure 4. Total number of communication breakdowns while participants were in the seated or standing configuration across different levels of background noise.

reciprocal modifications in interpersonal distance, postural movement coordination and speech level that synergistically compensate for changes in background noise level and environmental constraint (i.e., standing versus seated at a table). The findings also demonstrated that even though pairs were free to employ these behavioral processes to hear and be heard, 80 dB SPL represents a critical threshold where communication breakdowns significantly increased (Figure 4), suggesting that there is a noise level above which reciprocal compensation cannot fully compensate for the poor SNR conditions.

Regarding the transient behavioral processes observed in the current study, these occurred immediately following the onset of background noise and manifested as rapid and proportional adjustments in both interpersonal distance and speech levels (Figure 2). Unsurprisingly, the greatest initial or transient change in initial interpersonal distance occurred when the pairs were free to move around in the standing configuration and background noise levels were at their loudest. Given the physical barrier of the table restricting the pairs' motion, interpersonal distance adjustments were also found to be minimal when pairs were in the seated configuration and talking in the quietest background noise. Although initial speech levels also increased as the magnitude of background noise increased, speech levels were surprisingly robust to the imposed physical restraint of the table, with similar speech level adjustments observed when pairs were seated and standing. In combination with finding that pairs' sustaining behavior entailed more movement coordination in the seated compared to the standing condition (see below for further discussion), this could indicate that in response to increasing background noise, individuals preferentially employ movement-based compensatory behaviors over changes in speech level. Indeed, while increasing speech levels were observed here and are often necessary for effective communication, minimizing changes in speech level by simply moving closer together or coordinating one's movements with an interlocutor would be preferable to 'shouting' in most social situations.

With respect to the subtle, behavioral processes that operated to sustain communication following the transient adaptations, we observed that movement coordination only became more stable (greater MAXLINE) as background noise increased in the seated configuration (Figure 3). That is, only when the pairs were restricted in their physical movement did coordination stability increase as a function of background noise. While this indicates that the stability of movement coordination is modulated by interpersonal distance, it also implies that sustained coordination might be operating as a joint action to signal that one is committed to enduring through the challenge of conversing in background noise (i.e., a pro-social signal to continue conversing through adversity) and, moreover, functions to facilitate communication by assisting with tracking the signal in the noise (Paxton & Dale, 2017). A subsequent possibility that could be explored in future work, therefore, is that interpersonal motor coordination may serve as a metric of listening difficulty (Hadley & Ward, 2021) and/or communication and listening effort.

Finally, when communication breakdowns inevitably occurred, particularly at higher levels of background noise, pairs exhibited resetting behaviors. Our analysis demonstrated that following the signaling of a breakdown or OIR, pairs moved on average 5 cm closer to each other, which quantifies the 'leaning forward' effect that reportedly takes place following the signaling of a breakdown (Rasmussen, 2014; Trujillo & Holler, 2021). It is also possible that this movement was coupled with additional compensatory mechanisms such as head turning and ear cupping (Mortensen, 2016) which may be serving as a gain mechanism to boost the speech signal at the ear (e.g., Brimijoin, McShefferty, & Akeroyd, 2012). We also observed an increase of 3.2 dB in the talker's average speech level in response to the listener signaling a communication breakdown, which is a common, although rarely quantified, behavioral adjustment (Berger & Battista, 1993; Ringle & Bruce, 1982).

The current study provides the first comprehensive investigation of the behavioral processes individuals spontaneously employ to facilitate and sustain effective communication in the presence of realistic background noise. The results obtained here provide clear evidence that individuals expertly coordinate and reciprocally adapt numerous behavioral processes across multiple modalities to maximize comprehension as a function of environmental constraint. Accordingly, the findings of the current study also further emphasize the importance of investigating interpersonal conversation and interaction, as well as human social interaction in general, as a complex, embedded dynamical system of synergistic, multiscaled behavioral processes (Eiler, Kallen, & Richardson, 2017; Riley, Richardson, Shockley, & Ramenzoni, 2011; Shockley et al., 2009).

Acknowledgments

We wish to acknowledge the participants who took part in this study and thank them for their time. Thank you to David McAlpine for insightful comments on the manuscript. The authors acknowledge the following funding agencies: Miles, Buchholz: Martin Lee Centre for Innovations in Hearing Health; Richardson: FT180100447; Varlet: DP220103047.

References

Albert, S., & de Ruiter, J. P. (2018). Repair: The Interface Between Interaction and Cognition. *Topics in Cognitive Science, 10*(2), 279-313.

Aubanel, V., Cooke, M., Villegas, J., & Lecumberri, M. L. G. (2011). *Conversing in the presence of a competing conversation: effects on speech production*. Paper presented at the Interspeech 2011.

Beechey, T., Buchholz, J. M., & Keidser, G. (2018). Measuring communication difficulty through effortful speech production during conversation. *Speech Communication, 100*, 18-29.

Berger, C. R., & Battista, P. d. (1993). Communication failure and plan adaptation: If at first you don't succeed, say it louder and slower. *Communication Monographs, 60*(3), 220-238.

Brimijoin, W. O., McShefferty, D., & Akeroyd, M. A. (2012). Undirected head movements of listeners with asymmetrical hearing impairment during a speech-in-noise task. *Hearing Research, 283*(1-2), 162-168.

Chartrand, T. L., & Bargh, J. A. (1999). The chameleon effect: The perception–behavior link and social interaction. *Journal of Personality and Social Psychology, 76*(6), 893-910.

Cirelli, L. K., Einarson, K. M., & Trainor, L. J. (2014). Interpersonal synchrony increases prosocial behavior in infants. *Developmental Science, 17*(6), 1003-1011.

Condon, W. S., & Ogston, W. D. (1967). A segmentation of behavior. *Journal of Psychiatric Research, 5*(3), 221-235.

Dingemanse, M., Roberts, S. G., Baranova, J., Blythe, J., Drew, P., Floyd, S., . . . Enfield, N. J. (2015). Universal Principles in the Repair of Communication Problems. *PLOS ONE, 10*(9), e0136100.

Eiler, B. A., Kallen, R. W., & Richardson, M. J. (2017). Interaction-dominant dynamics, timescale enslavement, and the emergence of social behavior. In *Computational social psychology*: Routledge.

Fusaroli, R., Rączaszek-Leonardi, J., & Tylén, K. (2014). Dialog as interpersonal synergy. *New Ideas in Psychology, 32*, 147-157.

Giles, H. (1973). Accent mobility: A model and some data. *Anthropological Linguistics*, 87-105.

Gueguen, N., Jacob, C., & Martin, A. (2009). Mimicry in social interaction: Its effect on human judgment and behavior. *European Journal of Social Sciences, 8*(2), 253-259.

Hadley, L. V., & Ward, J. A. (2021). Synchrony as a measure of conversation difficulty: Movement coherence increases with background noise level and complexity in dyads and triads. *PLOS ONE, 16*(10), e0258247.

Hadley, L. V., Whitmer, W. M., Brimijoin, W. O., & Naylor, G. (2021). Conversation in small groups: Speaking and listening strategies depend on the complexities of the environment and group. *Psychonomic Bulletin & Review, 28*(2), 632-640.

Hove, M. J., & Risen, J. L. (2009). It's All in the Timing: Interpersonal Synchrony Increases Affiliation. *Social Cognition, 27*(6), 949-960.

Kulesza, W., Dolinski, D., Huisman, A., & Majewski, R. (2014). The Echo Effect: The Power of Verbal Mimicry to Influence Prosocial Behavior. *Journal of Language and Social Psychology, 33*(2), 183-201.

Lakin, J. L., Jefferis, V. E., Cheng, C. M., & Chartrand, T. L. (2003). The chameleon effect as social glue: Evidence for the evolutionary significance of nonconscious mimicry. *Journal of Nonverbal Behavior, 27*(3), 145-162.

Lombard, E. (1911). Le signe de l'élévation de la voix. *Ann. Mal. Oretl. Larynx, 37*, 101-119.

Marsh, K. L., Johnston, L., Richardson, M. J., & Schmidt, R. C. (2009). Toward a radically embodied, embedded social psychology. *European Journal of Social Psychology, 39*(7), 1217-1225.

Marsh, K. L., Richardson, M. J., Baron, R. M., & Schmidt, R. C. (2006). Contrasting Approaches to Perceiving and Acting With Others. *Ecological Psychology, 18*(1), 1-38.

Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social Connection Through Joint Action and Interpersonal Coordination. *Topics in Cognitive Science, 1*(2), 320-339.

Marwan, N. (2003). *Encounters with neighbours: current developments of concepts based on recurrence plots and their applications*: PhD thesis, University of Potsdam.

Marwan, N., Carmenromano, M., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics Reports, 438*(5-6), 237-329.

Miles, L. K., Lumsden, J., Richardson, M. J., & Neil Macrae, C. (2011). Do birds of a feather move together? Group membership and behavioral synchrony. *Experimental Brain Research, 211*(3-4), 495-503.

Miles, L. K., Nind, L. K., & Macrae, C. N. (2009). The rhythm of rapport: Interpersonal synchrony and social perception. *Journal of Experimental Social Psychology, 45*(3), 585-589.

Mortensen, K. (2016). The Body as a Resource for Other-Initiation of Repair: Cupping the Hand Behind the Ear. *Research on Language and Social Interaction, 49*(1), 34-57.

Natale, M. (1975). Social Desirability as Related to Convergence of Temporal Speech Patterns. *Perceptual and Motor Skills, 40*(3), 827-830.

Paxton, A., & Dale, R. (2017). Interpersonal Movement Synchrony Responds to High- and Low-Level Conversational Constraints. *Frontiers in Psychology, 8*, 1135.

Payton, K. L., Uchanski, R. M., & Braida, L. D. (1994). Intelligibility of conversational and clear speech in noise

and reverberation for listeners with normal and impaired hearing. *The Journal of the Acoustical Society of America, 95*(3), 1581-1592.
Picheny, M. A., Durlach, N. I., & Braida, L. D. (1989). Speaking clearly for the hard of hearing III: An attempt to determine the contribution of speaking rate to differences in intelligibility between clear and conversational speech. *Journal of Speech, Language, and Hearing Research, 32*(3), 600-603.
Rasmussen, G. (2014). Inclined to better understanding—The coordination of talk and 'leaning forward' in doing repair. *Journal of Pragmatics, 65*, 30-45.
Reddish, P., Fischer, R., & Bulbulia, J. (2013). Let's Dance Together: Synchrony, Shared Intentionality and Cooperation. *PLOS ONE, 8*(8), e71182.
Richardson, D. C., Dale, R., & Tomlinson, J. M. (2009). Conversation, Gaze Coordination, and Beliefs About Visual Context. *Cognitive Science, 33*(8), 1468-1482.
Riley, M. A., Richardson, M. J., Shockley, K., & Ramenzoni, V. C. (2011). Interpersonal synergies. *Frontiers in Psychology, 2*, 38.
Ringle, M. H., & Bruce, B. C. (1982). Conversation failure. *Strategies for Natural Language Processing*, 203-221.
Schegloff, E. A., Jefferson, G., & Sacks, H. (1977). The preference for self-correction in the organization of repair in conversation. *Language, 53*(2), 361-382.
Schmidt, R. C., & Fitzpatrick, P. (2016). The origin of the ideas of interpersonal synchrony and synergies. In *Interpersonal coordination and performance in social systems*: Routledge.
Schmidt, R. C., Morr, S., Fitzpatrick, P., & Richardson, M. J. (2012). Measuring the Dynamics of Interactional Synchrony. *Journal of Nonverbal Behavior, 36*(4), 263-279.
Schmidt, R. C., Nie, L., Franco, A., & Richardson, M. J. (2014). Bodily synchronization underlying joke telling. *Frontiers in Human Neuroscience, 8*.
Shockley, K. (2005). Cross recurrence quantification of interpersonal postural activity. *Tutorials in Contemporary Nonlinear Methods for the Behavioral Sciences*, 142-177.
Shockley, K., Butwill, M., Zbilut, J. P., & Webber, C. L. (2002). Cross recurrence quantification of coupled oscillators. *Physics Letters A, 305*(1-2), 59-69.
Shockley, K., Richardson, D. C., & Dale, R. (2009). Conversation and coordinative structures. *Topics in Cognitive Science, 1*(2), 305-319.
Shockley, K., Santana, M.-V., & Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in cooperative conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 326-332.
Stephens, G. J., Silbert, L. J., & Hasson, U. (2010). Speaker–listener neural coupling underlies successful communication. *Proceedings of the National Academy of Sciences, 107*(32), 14425-14430.
Street, R. L. (1984). Speech convergence and speech evaluation in fact-finding interviews. *Human Communication Research, 11*(2), 139-169.
Trujillo, J. P., & Holler, J. (2021). The kinematics of social action: visual signals provide cues for what interlocutors do in conversation. *Brain Sciences, 11*(8), 996.
Webber Jr, C. L., & Zbilut, J. P. (2005). Recurrence quantification analysis of nonlinear dynamical systems. *Tutorials in Contemporary Nonlinear Methods for the Behavioral Science, 94*(2005), 26-94.
Weisser, A., Buchholz, J. M., Oreinos, C., Badajoz-Davila, J., Galloway, J., Beechey, T., & Keidser, G. (2019). The Ambisonic Recordings of Typical Environments (ARTE) Database. *Acta Acustica united with Acustica, 105*(4), 695-713.
Weisser, A., Miles, K., Richardson, M. J., & Buchholz, J. M. (2021). Conversational distance adaptation in noise and its effect on signal-to-noise ratio in realistic listening environments. *The Journal of the Acoustical Society of America, 149*(4), 2896-2907.
Zbilut, J. P., Giuliani, A., & Webber, C. L. (1998). Detecting deterministic signals in exceptionally noisy environments using cross-recurrence quantification. *Physics Letters A, 246*(1-2), 122-128.