Prosodic entrainment in dialog acts∗

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Abstract

We examined prosodic entrainment in spoken dialogs separately for several dialog acts in cooperative and competitive games. Entrainment was measured for intonation features derived from a superpositional intonation stylization as well as for rhythm features. The found differences can be related to the cooperative or competitive nature of the game, as well as to dialog act properties as its intrinsic authority, supportiveness and distributional characteristics. In cooperative games dialog acts with a high authority given by knowledge and with a high frequency showed the most entrainment. The results are discussed amongst others with respect to the degree of active entrainment control in cooperative behavior.

1 Introduction

In conversation the utterances of speakers become more and more similar to each other. This phenomenon is called entrainment or accommodation and can be observed at various levels of linguistic representation.

1.1 Related work

Entrainment affects the choice of words [9, 16, 43] and syntactic constructions [14, 28, 8]. Entrainment is also observed in phonetic measures of speaking rate [38, 37], intensity [38, 37], voice quality [37], and pitch [26, 25, 38, 11] is reported in data from dialogues and from speech shadowing experiments. In these studies evidence for entrainment is derived from acoustic measurements [37, 11], word and sentence form analyses [28], and from perceptual similarity ratings [47, 48]. Entrainment has also been measured on the basis of categorical intonation features as derived automatically [60] or by manual labeling [24].

Entrainment is shown to be influenced by the attitudes and the power relation of the interlocutors, among other factors. Entrainment is stronger in case of mutual positive attitude of the interlocutors, than in case of negative attitude [59], which is in line with the predictions of theoretical models such as the Communication Accommodation Theory (CAT) [21]. CAT also predicts that entrainment will be dependent on the dominance relation between interlocutors. When there is an imbalance in power between two interlocutors, the one with lower status (or authority/dominance) will entrain more to the one with higher status [23]. Empirical evidence for this claim has been found for talkshow data [26] and for data from the judicial domain [5, 10], where power hierarchies are well reflected in the degree of entrainment.

In addition to mutual attitude and power, several other social factors are correlated with entrainment. As reviewed in [30] and [4], entrainment is positively correlated with perceived social attractiveness [51], mutual likability [67], competence [71], and supportiveness [22]. Remarkably, not only entrainment but also disentrainment can be positively linked to such social variables [18, 19]. [40] introduced an unsigned synchrony measure not distinguishing between entrainment and disentrainment but just quantifying their amount in absolute terms. This unsigned measure was more positively associated with perceived engagement, encouragement, and the contribution to successful task completion than a signed measure distinguishing between entrainment and disentrainment.

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The degree of control the speakers have over entrainment is still under debate. In the CAT framework an active control of entrainment is assumed in order to negotiate social relations. On the other hand, \[51, 52\] and \[12\] suggest, that entrainment is rather an automatic mechanism based on a perception-production link in which the activation of linguistic patterns increases the likelihood to re-use such patterns. A hybrid approach is proposed by \[34, 39, 67\], in that accommodation is partially automatic but also actively controlled to adapt to within- and inter-speaker influences. Simulations of this hybrid mechanism have been computed \[10\] in an exemplar-theoretic framework \[11, 31\].

Regardless of the degree of active control over entrainment, its benefit is well documented: entrainment has been shown to increase the success of conversation in terms of low inter-turn latencies, a reduced number of interruptions \[37, 43\], and for objective task success measures \[63\]. Related to the success of conversation \[60\] found more entrainment in cooperative than in competitive dialogs for prosodic event sequences. These findings on social variables and conversation success are again in line with the claim from CAT that entrainment enhances social approval and communication efficiency.

In the empirical work mentioned above entrainment was measured by comparing the properties of more and less closely related units, i.e. adjacent vs. non-adjacent speech segments, or segments from the same vs. from different dialogs (local and global entrainment, respectively; see \[18\] for a systematic overview). For spoken dialogs these units are most commonly turns (e.g. \[38\]) or stretches of speech in a fixed time frame (e.g. the TAMA approach by \[33\]). But so far very little work has been done for units that are defined with respect to their function in a dialog, namely dialog acts. For this reason it is not well known yet to what extent entrainment depends on functional dialog units. One work that attempts to relate entrainment to dialog function is \[3\], which examined prosodic entrainment in Slovak for the discourse particle \[no\] with respect to usage statistics and several acoustic parameters. \(No\) serves to signal affirmation, backchannel, and mild disagreement. It was shown that for parts of the underlying data that frequency entrainment was absent for \(no\) in general but present for \(no\) with one of its discourse functions. In other work, \[42\] found a higher amount of lexical entrainment for dialog acts with little informational content as greeting, closing, backchannel, and agreement. Less entrainment was found for dialog acts expressing opinions as apologies and action directives.

### 1.2 Goals of this study

**Hypotheses**  This study aims to contribute to this yet understudied aspect of entrainment as it relates to dialog acts. Our focus is on prosodic entrainment, which we investigate in speech from an interactive game task where participants play under cooperative and competitive game conditions. We examine acoustic evidence of prosodic entrainment as a function of the dialog act of the utterance in cooperative and competitive play. Dialog acts are differentiated along the social dimensions of authority and supportiveness, by frequency, and by local predictability in order to test these influences on entrainment behavior on the dialog act level. Based on the findings from the cited prior work on the effects on entrainment of interlocutor attitudes and status relations, and work showing the benefit of entrainment for task success we formulate the following hypotheses:

**H1** There is more entrainment in intrinsically low than in high authority dialog acts.

**H2** There is more entrainment in supportive dialog acts than in dialog acts that are neutral or negative in providing support for the interlocutor.

Low and high authority dialog acts both cause local authority imbalances in that they decrease or increase the speaker’s authority relative to the interlocutor. Hypothesis 1 thus serves to examine whether this local imbalance has a similar effect on entrainment as general authority imbalances in the judicial data of \[5, 16\].

The effect of supportive dialog acts in boosting entrainment is restrictedly expected for speech produced in cooperative game play, where interlocutors must work together towards a shared goal. Supportive dialog acts are predicted to be rare in competitive game play, and accordingly we focus on cooperative play for testing Hypothesis 2.

Additional hypotheses (H3, H4) relate to the frequency and predictability of a dialog act. Entrainment is positively correlated with task success, and is expected to be optimized in conditions of cooperative interaction. In cooperative game play, optimization can be achieved when entrainment is concentrated in the most frequent dialog acts, where the expected benefit of smooth turn transitions can be maximized.
Optimization can also be achieved through the selective use of disentrainment with dialog acts that are locally unpredictable. In such cases disentrainment disrupts common prosodic patterns and in this way may serve to attract the interlocutor’s attention.

H3 Entrainment will be greater in frequent dialog acts than in less frequent ones.

H4 Disentrainment will be more frequent in locally unpredictable dialog acts.

H3 extends the above mentioned studies on the positive impact of entrainment on smooth turn transitions [37, 43]. H4 describes a possible concrete case of a cooperative disentrainment behavior which is more generally suggested by studies such as [49] referred to above.

**Implication** If entrainment differs among dialog acts and between cooperative and competitive settings, this can be taken as an indication that it cannot only be an automatic process in terms of a perception-action loop but is also at least partially actively controlled.

**Prosodic stylization** Our approach extends the prosodic feature set used in prior studies of prosodic entrainment. Prosodic analyses in prior work (cited above) are restricted to simple acoustic measures like the mean or maximum value of fundamental frequency (f0) [1, 38, 37], and its variance [26]. In the study presented here, we add features derived from a parametric superpositional intonation stylization, that allow for the comparison of complex and temporally dynamic pitch patterns in different prosodic domains.

2 Data

Our analysis is based on a subset of the speech data from the Illinois Game Corpus [46, 62] that is comprised of Tangram game dialogs by American English speakers in cooperative and competitive settings. The tangram is a puzzle consisting of seven pieces that can be combined to form shapes that resemble various common objects, such as a boat, house or person. Both dialog partners were separately presented with Tangram silhouettes that were hidden from the view of the other partner. The task was to decide whether the silhouettes were the same or different by verbally describing them to each other. In the cooperative setting the partners solved this common goal in a joint effort. In the competitive setting, the partners were required to solve this task competitively, and the one who solved the puzzle first over the most number of trials was awarded a candy prize as the winner. Undergraduate students (ages 18–29) from the University of Illinois, all native monolingual speakers of American English, were recruited as paid participants in this study. Twelve pairs of participants took part in the experiment. They were prompted to engage in free conversation for a few minutes after which they played the Tangram game together, first playing cooperatively and then competitively, with different Tangram silhouette images in each condition. Participants were seated in chairs facing one another, with no intervening table and with the printed Tangram silhouettes positioned off to the side, facing each participant. Audio and video recordings were made on separate channels for each participant. Participants provided written consent for the use of these recordings in research. For the current study a dialog-act annotated subset of 16 dialogs (10 cooperative, 6 competitive) by 11 interlocutor pairs was used, of which eight were Female-Female pairs and three were Male-Female pairs. Mean dialog duration amounts to 7 minutes 40 seconds. The used part of the corpus was manually dialog-act segmented and annotated using the tag set of [10, 11], which is described in more detail in section 3.1 Additional tags e.g. for comments and offtalk (see [62]) not belonging to the original tag set were ignored for the current study, so that the examined data consists of 4011 dialog act segments.

3 Dialog acts

3.1 Inventory

The applied tagset was developed by [10, 11] in order to describe conversational moves, i.e. initiations and responses with certain discourse purposes. The complete label set is shown in Table 1 and is briefly described following the guidelines given in [11] and illustrated by some examples from our corpus. Dialog
acts were labeled in parallel by two annotators working with the text transcriptions alone (no audio). Mismatches were subsequently resolved by discussion between these two.

- **Acknowledgment AC.** Listener feedback e.g. to signal accordance or acceptance. Examples: *Ok., Yeah., Like you’re thinking.*
- **Alignment AL.** Checks the attention, agreement, or readiness of the interlocutor. Examples: *Or do you want more?, Ok ready?*
- **Check CH.** Requests the interlocutor to confirm an information. Examples: *Like this?, Ok so so it has an open door?*
- **Clarify CL.** A reply that includes additional information which was not explicitly asked for. Example: *it’s like the house and then it’s like right next to it there’s like a horse stable (answer to “Does it have like a little like a little thing on the side on the right)., It’s more like it’s inwards towards the horse’s head (answer to “ok so if he was riding the horse does it look like his chest would be sticking out then?”).*
- **Explain EX.** Providing information not directly elicited by the partner (thus no reply) Examples: *It looks like a more geometric batman symbol., The bottom looks like a person it looks like a person in a boat.*
- **Instruct IN.** Commands the interlocutor to perform an action. Examples: *Hold on!, Look at me!*
- **Question-W QW.** Wh-question. Examples: *So what what image do you think we have?, Does yours have one or two legs?*
- **Question-YN QY.** Yes-no question. Examples: *Does it have a door?, Are the arms like this kinda arms?*
- **Ready RE.** Indicating readiness to go on (here as opposed to [11] not restricted to game initial position). Examples: *Ok!, Alright!*
- **Reply-No RN.** No-reply. Examples: *No., Head head’s not down (answer to “Head down?”).*
- **Reply-W RW.** A reply conveying more information than “yes” or “no” but not more than what was asked. Examples: *Like a diamond face (answer to “And is it like a full face? Like a like a this face?”), Two legs (answer to “Does yours have one or two legs?”).*
- **Reply-Y RY.** Yes-reply. Examples: *Yes., You can go first (answer to “Can I go first?”).*

### 3.2 Grouping

In order to test the hypotheses formulated in section 1 we subdivided the dialog acts along 4 dimensions: authority, supportiveness, frequency, and local predictability. These dimensions are summarized in Table 1 with counts for each dimension in Table 2 and detailed explanations in the following paragraphs.

- **Authority** Following [6, 17] authority is given by knowledge (epistemic authority) or by a superior position which enables a person to give orders (deontic/executive authority). We thus clustered all dialog acts fulfilling one of these two conditions to the high authority group, and all others to the low authority group. Examples for high-authority dialog acts are EX and CL fulfilling the knowledge condition, and IN to influence the interlocutor. Low authority dialog acts are those that are usually neutral with respect to dominance (AC, AL, RE), or reflect a dependency of the speaker on the cooperation of the interlocutor, which generally holds for non-executive request (AL, CH, QW, QY). Alignment AL in principle could also express a dominance relation, but this was not observed in our data, so we assigned AL to the low-authority group.

- **Supportiveness** Dialog acts further can be subdivided into two groups according to the degree of their supportiveness. We consider a dialog act to be supportive if it helps the interlocutor to get to a common ground [13], i.e. if it provides information (EX, CL, RY, RN, RW) or serves to ensure that given information was understood (AL, AC).
### Table 1: Dialog acts and their grouping.

| id | dialog act     | authority | support | frequency |
|----|----------------|-----------|---------|-----------|
| AC | Acknowledgment | low       | yes     | high      |
| AL | Alignment      | low       | yes     | low       |
| CH | Check          | low       | no      | high      |
| CL | Clarify        | high      | yes     | low       |
| EX | Explain        | high      | yes     | high      |
| IN | Instruct       | high      | no      | low       |
| QW | Question-W     | low       | no      | low       |
| QY | Question-YN    | low       | no      | high      |
| RE | Ready          | low       | no      | high      |
| RN | Reply-No       | high      | yes     | low       |
| RW | Reply-W        | high      | yes     | low       |
| RY | Reply-Y        | high      | yes     | high      |

### Table 2: Number of dialog act segments for each dimension’s levels.

| authority | support | frequency | predictability |
|-----------|---------|-----------|----------------|
| high      | low     | high      | low            |
| 1982      | 2029    | 2651      | 1360           |
| 3558      | 453     | 3813      | 198            |

**Frequency**  
The frequency distinction was simply derived by calculating the probability of each dialog act in our corpus and setting the median probability value as the boundary dividing the high- and low-frequency dialog acts. We used probabilities instead of raw frequencies to allow for later cross-corpus comparisons.

**Local predictability**  
Local predictability does not provide an overall dialog act categorization but classifies each dialog act in each context it occurs. As an approximation this local context is given by the preceding dialog act in the dialog, so that local predictability can be measured in terms of dialog act bigram probabilities $P(da_i|da_{i-1})$. This is the conditional probability of the dialog act at position $i$ given the preceding dialog act. Both for the unigram probabilities above and for the bigram probabilities maximum likelihood estimates were used. Again, the median value of the bigram probabilities was taken to divide the dialog acts in context into a high and a low predictability group.

### 4 Prosodic analyses

Our goal is to assess prosodic entrainment in pitch, loudness and tempo, considering general global measures (maximum, median, standard deviation) that hold of dialog acts, and local measures that hold of prosodic phrases and pitch accent domains within the dialog act. We also assess entrainment in the temporally dynamic patterns of f0 across prosodic phrases and accent domains. We focus the analysis of local measures on the initial and final prosodic phrases, and the initial and final pitch accents in a dialog act. These initial and final regions demarcate the prosodic structuring of the act and are the locations where critical and obligatory intonational features are specified (see [35] for an overview). To extract these acoustic measures we use automated methods only, which enables replication and comparison of findings among different speech datasets.

#### 4.1 Preprocessing

**Transcription and Alignment**  
Audio files for each dialog were manually segmented into chunks and orthographically transcribed. The text within each chunk was then automatically aligned to the signal using the multilingual WEBMAUS webservice [52] with the parameter setting for American English. For the sake of subsequent prosodic structure inference, word stress was added to the phonemic transcriptions by the help of the Balloon Grapheme-Phoneme Converter [55] also available as a webservice [52].
F0 and energy  F0 was extracted by autocorrelation (PRAAT 6.0.35 [7], sample rate 100 Hz). Voiceless utterance parts and f0 outliers were bridged by linear interpolation. The contour was then smoothed by Savitzky-Golay filtering [65] using third order polynomials in 5 sample windows and transformed to semitones relative to a base value. This base value was set to the f0 median below the 5th percentile of an utterance and served to normalize f0 with respect to its overall level. Energy in terms of root mean squared deviation was calculated with the same sample rate as f0 in Hamming windows of 50 ms length.

Prosodic structure  The following prosodically relevant time points were extracted automatically within each chunk using the open source CoPaSul toolkit [57, 59]: syllable nuclei, prosodic phrase boundaries, and pitch-accented syllables as described in detail in [58]. Syllable nucleus assignment follows the procedure introduced in [50] to a large extent. An analysis window \( w_a \) and a reference window \( w_r \) with the same time midpoint were moved along the band-pass filtered signal in 50 ms steps. For syllable nucleus assignment the energy is required to be higher in \( w_a \) than in \( w_r \) by a certain factor, and additionally had to surpass a threshold relative to the maximum energy of the recording.

Phrase boundaries were detected automatically by means of a bootstrapped nearest centroid classifier. From pitch register discontinuity features derived for each right-edge word boundary [61] and from vowel length z-scores two centroids for phrase-final and non-final word boundaries were bootstrapped based on two simplifying assumptions: (1) each pause is preceded by a boundary, and (2) since prosodic phrases have a minimum length, in the vicinity of pauses in both directions there are no further boundaries. The minimum length was set to 1 second. From this initial clustering feature weights were calculated from the mean cluster profile derived separately for each feature. The remaining word boundaries were then classified as phrase boundaries or not phrase boundaries, based on their weighted Euclidean distances to the two centroids.

Pitch accents were detected in an analogous fashion, using local pitch shape and energy features within the word-stressed syllables and by two different simplifying assumptions for cluster initialization: (1) all words longer than a threshold \( t_a \) in seconds are likely to be content words that contain a high amount of information and are thus taken as “accented” representatives, and (2) all words shorter than a threshold \( t_na \) are likely to be function words with a low amount of lexical information and are thus taken as “no accent” representatives. \( t_a \) and \( t_na \) were set to 0.5 and 0.1 sec, respectively, thus to rather extreme word length values in order to increase the precision of the initial candidate selection.

In [58] this procedure was optimized with respect to F1 scores on spontaneous speech data and yielded F1 values of 0.61 and 0.63 for boundary and accent detection, respectively. This indicates rather moderate precision and recall values, which is a trade-off to the advantages of the automated processing described above. However, the value ranges of the chosen features – pitch discontinuity for boundaries, pitch shape and energy for accents – are split by the clustering such that boundaries are placed at high discontinuities, and syllables with salient pitch and energy movements are identified for further accent analyses. In other words, the automated procedure is tuned to avoid false positives, at the cost of not detecting boundaries and accents that have lower acoustic salience.

4.2 Feature extraction

In addition to the general f0 and energy features mentioned above, we derived features related to pitch register and the local pitch event from the contour-based, parametric, and superpositional CoPaSul stylization framework [56], which represents f0 as a superposition of a global register and a local pitch accent component. This stylization is presented in Figure 1. Rhythmic features were also extracted, as described below. All features introduced here can again be extracted by means of the open source CoPaSul prosody analysis software [57, 59].

All features are listed in Table 3 along with the feature set name they belong to and a short description. A more detailed description is given in the subsequent sections.

4.3 General f0 and energy features

For the feature sets GEN and GF0 for general energy and f0 characteristics within each dialog act we calculated the median, the maximum, and the standard deviation of the f0 and the energy contour, respectively.
Figure 1: Superpositional f0 stylization within the CoPaSul framework. On the prosodic phrase level a base, mid- and topline (solid) are fitted to the f0 contour (dotted) for register stylization. Level is represented by the midline, and range by a regression line fitted to the pointwise distance between base and topline. On the local pitch event level comprising accents and boundary tones the f0 shape is represented by a third-order polynomial, one for each of the two events (left). The f0 Gestalt properties, i.e. its register deviation from the phrase-level register is quantified by generating a local register representation the same way as for the phrase level (right) and by calculating the root mean squared deviations between the midlines and the range regression lines.

| Feature set | Feature | Description |
|-------------|---------|-------------|
| GEN         | max     | energy maximum in dialog act |
| GEN         | med     | energy median in dialog act |
| GEN         | sd      | energy standard deviation in dialog act |
| GF0         | max     | f0 maximum in dialog act |
| GF0         | med     | f0 median in dialog act |
| GF0         | sd      | f0 standard deviation in dialog act |
| IP          | rng.c0.F/L | f0 range intercept of first/last phrase |
| IP          | rng.c1.F/L | f0 range slope of first/last phrase |
| IP          | lev.c0.F/L | f0 level intercept of first/last phrase |
| IP          | lev.c1.F/L | f0 level slope of first/last phrase |
| ACC         | c0-3.F/L | polynomial coef of the first/last pitch accent |
| ACC         | rng.c0.F/L | f0 range intercept of first/last pitch accent |
| ACC         | rng.c1.F/L | f0 range slope of first/last pitch accent |
| ACC         | lev.c0.F/L | f0 level intercept of first/last pitch accent |
| ACC         | lev.c1.F/L | f0 level slope of first/last pitch accent |
| ACC         | gst.lev.F/L | f0 level deviation of first/last pitch accent |
| ACC         | gst.rng.F/L | f0 range deviation of first/last pitch accent |
| RHY         | syl.rate | mean syllable rate |
| RHY         | syl.prop.en | syllable influence on energy contour |
| RHY         | syl.prop.f0 | syllable influence on f0 contour |

Table 3: Description of prosodic features grouped by feature sets.
4.4 Prosodic phrase characteristics

The IP feature set describes f0 register characteristics of the intonational phrase. According to [64], f0 register in the prosodic phrase domain can be represented in terms of the f0 range between high and low pitch targets, and the f0 mean level within this span. To capture both register aspects and their change over time, within each prosodic phrase we fitted a base-, a mid, and a topline by means of linear regressions as shown in Figure 1. This line fitting procedure works as follows: A window of length 50 ms is shifted along the f0 contour with a step size of 10 ms. Within each window the f0 median is calculated (1) of the values below the 10th percentile for the baseline, (2) of the values above the 90th percentile for the topline, and (3) of all values for the midline. This gives three sequences of medians, one each for the base-, the mid-, and the topline, respectively. These lines are subsequently derived by linear regressions, with time normalized to the range from 0 to 1. As described in further detail in [64], this stylization is less affected by local events such as pitch accents and boundary tones and does not need to rely on error-prone detection of local maxima and minima. Based on this stylization the midline is taken as a representation of pitch level. For pitch range we fitted a further regression line through the pointwise distances between the topline and the baseline. A negative slope thus indicates convergence of top- and baseline, whereas a positive slope indicates divergence.

From this register level and range representation we extracted the following features for the first and for the (occasionally identical) last prosodic phrase in (or overlapping with) a dialog act: intercept and slope of the midline, and intercept and slope of the range regression line. That gives eight features subsumed to the IP feature set.

4.5 Pitch accent characteristics

We next normalized each f0 value to the corresponding local range with the two reference points on the base- and topline (cf section 4.4) set to 0 and 1, respectively. By this normalization f0 values between base- and topline range from 0 to 1, f0 values below the baseline are smaller than 0, and values above the topline are greater than 1. We fitted third-order polynomials to this f0 contour residual around the syllable nuclei associated with the first and the last local pitch event (accent or boundary tone) in a dialog act. The stylization window of length 300 ms was placed symmetrically on the syllable nucleus, and time was normalized to the range from −1 to 1. This window length of approximately 1.5 syllables was chosen to capture the f0 contour on the accented syllable in some local context.

The coefficients of the fitted polynomials represent different aspects of local f0 shapes. Given the polynomial \( \sum_{i=0}^{3} s_i \cdot t^i \) for the normalized time variable \( t \), the coefficient \( s_0 \) is related to the local f0 level relative to the local range. \( s_1 \) and \( s_3 \) are related to the local f0 trend (rising or falling) and to peak alignment. \( s_2 \) determines the peak curvature (convex or concave) and its acuity. Next to the polynomial coefficients we measured local register values by re-applying the stylization introduced in section 4.4 within the analysis window around the pitch accent.

Finally, pitch accent Gestalt was measured in terms of local register deviation from the corresponding stretch of global register. This was simply done by calculating the root mean squared deviation (RMSD) between the pitch accent midline and the corresponding part of the phrase midline. For the accent and phrase range regression lines the same procedure was used.

From these stylizations the feature set ACC emerges for the first and for the last local pitch event in a dialog act. It contains (1) the polynomial coefficients describing the local f0 shape, (2) the intercept and slope coefficients for the mid- and the range regression line describing the local register, and (3) the local level and range deviation from the underlying phrase in terms of the RMSD between the accent- and phrase-level regression lines.

4.6 Rhythm features

The RHY feature set captures at the level of the dialog act properties traditionally termed as "rhythmic", including syllable rate (number of detected syllable nuclei per second) and the influence of the syllable level of the prosodic hierarchy on the energy and f0 contours. Influence means, to what extent the syllable oscillator determines the shape of these contours. This influence manifests itself in regular fluctuations at the syllable rate. To quantify the syllabic influence on any of these contours we performed a discrete cosine transform (DCT) on this contour as in [29]. We then calculated the syllable influence \( w \) as the...
Figure 2: Rhythm features: Quantifying the influence of syllable rate on the f0 contour (analogously for the energy contour). For this purpose a discrete cosine transform (DCT) is applied to the contour. The absolute amplitudes of the coefficients around the syllable rate are summed and divided by the summed absolute amplitudes of all coefficients below 10 Hz. This gives the proportional influence of the syllable on the contour. In the left case the syllable oscillator (syllable rate is 4.8 Hz) has a relatively low impact on the f0 contour whereas on the right the impact of the 4 Hz syllable oscillator is relatively high. Conversely, the impact of the lower-frequency pitch accent oscillator in the 2 Hz region is high in the left case and low on the right.

The relative weight of the coefficients around the syllable rate $r$ ($+/ - 1$ Hz to account for syllable rate fluctuations) within all coefficients below 10 Hz as follows:

$$w = \frac{\sum_{r-1 \leq f(c) \leq r+1 \text{Hz}} |c|}{\sum_{f(c) \leq 10 \text{Hz}} |c|}$$

The higher $w$ the higher thus the relative influence of the syllable rate on the contour. Furthermore, a high relative syllable influence implies a lower impact of other macroprosodic oscillators as pitch accents and vice versa, so that $w$ also can be regarded as an inverse measure of pitch accent influence. This procedure which is shown in Figure 2 was first used to quantify the impact of hand stroke rate on the energy contour in counting out rhymes [20]. The upper cutoff of 10 Hz goes back to the reasoning that contour modulations above 10 Hz do not occur due to macroprosodic events as accents or syllables, but amongst others due to microprosodic effects.

5 Entrainment measurement

5.1 Method

In this study we focus on global entrainment, i.e. we compare identical dialog act pairs within a dialog with pairings between speakers not engaged in any common game conversation. The within-dialog sample was generated as follows: for each dialog act of speaker A we randomly picked one dialog act of the same kind uttered by speaker B from the preceding course of the dialog, if available. For the across-dialog sample we randomly paired the dialog act of speaker A with one dialog act of the same kind uttered by an unrelated speaker C from another dialog. Being unrelated further implies that A and C did not engage in any common conversation in this corpus.

As pointed out in [28, 18] accommodation can be expressed, amongst others, in terms of convergence or synchrony. As visualized in Figure 3 convergence means that feature values become more similar. Convergence-related distance is trivially represented by the absolute distance of the feature value pair, the lower the distance, the higher the convergence. Synchrony means that feature values vary in parallel. [18] proposes to calculate correlations over a sequence of segment pairs. Here we choose a more straightforward approach operating on a single dialog act segment pair only. We simply subtract the respective speakers’ mean values from the feature values before calculating the absolute distance. Synchrony-related distance is thus low, if the speakers realize a feature either both above or below their respective means. By that we derive for each feature and each dialog act segment pair one convergence- and one synchrony-related distance value. Clearly, and as depicted in Figure 3 the terms ”convergence” and ”synchrony”
describe patterns of change over time for two signals. We have operationalized these notions in terms of static measures here, but in the remainder of this paper, for the sake of readability, we abbreviate convergence- and synchrony-related distance by convergence and synchrony, respectively.

5.2 Entrainment by dialog act

For an initial harvesting of the data separately for cooperative and competitive dialogs we statistically compared the within- and across-dialog differences by two-sided t-tests for independent samples for each of the 12 dialog act types, for each of the 5 feature sets, and for the 2 distance measures. The significance level was set to 0.05.

5.3 Entrainment by dialog act grouping

In order to test the effects of the dialog act groupings on entrainment we pooled all data across the 5 feature sets and the 2 entrainment measures in the following way: within each dialog act segment we obtained for each single feature and each of the entrainment measures (convergence and synchrony) 2 values as described in section 5.1, a within the same dialog distance, \( d_s \), and an across different dialogs distance, \( d_d \). We then simply subtracted \( d_d \) from \( d_s \) to obtain the distance delta \( d \). \( d \) values well below 0 thus reflect a greater within dialog similarity and indicate an entrainment tendency, whereas values well above 0 indicate a disentrainment tendency. We tested the effect of the dialog act grouping on entrainment by two linear mixed effects models, one with the fixed effects authority, support, and dialog condition (cooperative vs. competitive), and the other with the fixed effects frequency, local predictability, and again dialog condition. In both models the dependent variable is given by \( d \), and the speaker uttering the dialog act from which \( d \) is calculated is taken as a random effect. In both tests a random slope model was calculated for the speaker Id and the fixed effects. In case of significant interactions the models were re-applied on the respective subsets. For the linear mixed effects models we used the R function `lmer` from the package `lme4` [2] and for p-value assignment the R function `Anova` from the package `car` [19].

6 Results

6.1 Entrainment by dialog act

Profiles Figure 4 shows entrainment profiles for two dialog acts EX (explain) and IN (instruct) in cooperative and competitive dialogs for the feature set IP and the convergence distance measure. The solid vertical lines give the mean within dialog distances \( d_s \) of the features in the set IP, and the dashed lines the mean across dialog distances \( d_d \). A solid line left of its dashed counterpart indicates entrainment, and the opposite order indicates disentrainment. It can be seen that the entrainment profiles of EX and IN behave in exactly the opposite way. While EX shows entrainment in cooperative dialogs and disentrainment in competitive dialogs, for IN it is the other way round. This is also well reflected in Table 4 showing the results of the t-tests for all dialog acts, feature sets and entrainment measures in the cooperative and competitive dialogs, respectively. Significant distance differences indicating entrainment are marked by a + sign, significant differences for disentrainment by a − sign. Not significant cases are marked by a zero. Profiles and tables show clear differences in entrainment behavior in cooperative and competitive dialogs. Overall, for dialog acts a lower number of significant entrainment cases is observed in cooperative than in competitive dialogs (28 against 36% of all combinations between dialog acts and feature sets). Furthermore, in cooperative dialogs disentrainment occurs more often (14 against 9%).
Figure 4: Entrainment profiles for the dialog acts EX (top row) and IN (bottom row) and the feature set IP in cooperative (left) and competitive (right) dialogs. The solid, vertical (straight) lines give the mean distances in terms of convergence across randomly picked dialog instances in the same dialog ($s$). The dashed vertical (straight) lines represent mean distances across randomly picked unrelated speaker pairs ($d$). The means are calculated over all features in the set IP. Values for each feature on the y-axis shown in thin (jagged) solid lines ($s$), and thin dashed lines ($d$). An entrainment tendency is indicated by a solid vertical line left of its dashed counterpart. For disentrainment the solid line is right of the dashed one.

A closer look at the single dialog acts reveals that the supportive dialog acts EX, CL, and replies on average undergo more entrainment and less disentrainment in cooperative dialogs than in competitive ones, whereas for the not-supportive dialog acts IN and questions, the pattern is the opposite.

6.2 Entrainment by dialog act grouping

**Authority and support**  Tables 5 and 6 show the entrainment and disentrainment proportions separately for cooperative and competitive dialogs and for dialog act authority and supportiveness. In cooperative dialogs high-authority dialog acts show more entrainment and less disentrainment than low-authority ones. In competitive dialogs the ratio is nearly balanced. For supportiveness there is only a difference to report for the competitive dialogs: supportive dialog acts show much less entrainment than non-supportive ones.

Table 4 captures the interaction of authority and support by showing the proportions of dialog acts exp-
Table 5: Proportion of dialog acts exhibiting entrainment (+) and disentrainment (−) for authority, support, frequency and local predictability levels in cooperative dialogs. Proportions are calculated within each level, which implies that the remainder proportion (of neither entrainment nor disentrainment) is 1 minus the proportion for + and −, e.g. $1 - 0.5 - 0.1 = 0.4$ for high authority.

| authority | support | frequency | predictability |
|-----------|---------|-----------|---------------|
| high/yes  | 0.5 0.1 | 0.3 0.1   | 0.4 0.1       |
| low/no    | 0.2 0.3 | 0.3 0.1   | 0.1 0.1       |

Table 6: Proportion of dialog acts exhibiting entrainment (+) and disentrainment (−) for authority, support, frequency and local predictability levels in competitive dialogs. Proportions are calculated within each level, which implies that the remainder proportion (of neither entrainment nor disentrainment) is 1 minus the proportion for + and −, e.g. $1 - 0.5 - 0.1 = 0.4$ for high authority.

| authority | support | frequency | predictability |
|-----------|---------|-----------|---------------|
| high/yes  | 0.5 0.1 | 0.2 0.2   | 0.6 0.0       |
| low/no    | 0.6 0.0 | 0.7 0.0   | 0.5 0.0       |

The impact of the factors authority and support was further tested by a linear mixed effects model with random slopes with distance delta $d$ as the dependent variable (values below 0 indicate entrainment), dialog condition (cooperative vs. competitive), authority (high vs. low), support (yes vs. no) as fixed effects, and speaker as a random effect. The test reveals a significant impact of dialog condition ($\chi^2 = 22.8944$, $p < 0.0001$): $d$ is smaller in competitive than in cooperative dialogs. Further significant interactions are observed for all effect combinations ($\chi^2 \geq 27.1360$, $p < 0.0001$), i.e. authority and supportiveness interact, and both as well as their interaction behave differently in cooperative and competitive dialogs. We further tested this behavior by re-applying linear mixed effects random slope models for authority and support as fixed effects separately for the cooperative and for the competitive subset.

For the cooperative dialogs no further significant difference was found – neither for authority ($\chi^2 = 0.3951$, $p = 0.5296$) nor for support ($\chi^2 = 0.0022$, $p = 0.9122$) nor for their interaction ($\chi^2 = 2.6425$, $p = 0.1040$). For cooperative dialogs data alone, there were no significant effects for authority ($\chi^2 = 0.5296$) or support ($\chi^2 = 0$, $p = 0.9974$), but their interaction was significant ($\chi^2 = 25.1918$, $p < 0.0001$). Further splitting the cooperative dialog data by authority and re-applying a linear mixed effects model with support as fixed effect shows no significant difference for the low-authority dialog acts ($\chi^2 = 0.0245$, $p = 0.8757$), but a significant difference for the high authority ones ($\chi^2 = 5.3074$)

| authority | cooperative | competitive |
|-----------|-------------|-------------|
|           | high  low   | high  low   |
| support   | +  − +  −   | +  − +  −   |
| yes       | 0.34 0.04 0.2 | 0.25 0.28 0.18 0.1 |
| no        | 0.0 0.5 0.33 | 0.12 0.6 0.0 0.47 0.03 |

Table 7: Entrainment (+) and disentrainment (−) probabilities for all authority (columns: high, low) and support (rows: no, yes) level combinations in cooperative and competitive dialogs. Probabilities are calculated within each level combination, which implies that the probability of neither entrainment nor disentrainment is 1 minus the probabilities for + and −.
p = 0.02124): high authority dialog acts show more entrainment if they are also supportive.

This interplay of authority and support in cooperative and competitive dialogs is shown in Figure 5. Though only significant for cooperative dialogs an opposite trend for high-authority dialog acts is visible in these interaction plots. In cooperative dialogs high-authority dialog acts show more entrainment if they are also supportive, whereas in competitive dialogs there is an opposite tendency: for these dialogs not supportive high-authority dialog acts show most entrainment.

Frequency and local predictability

In Tables 5 and 6 the general trend is visible that high predictability and high frequency are related to a higher amount of entrainment. Disentrainment is raised for unpredictable dialog acts in the competitive setting only.

The impact of the factors frequency and local predictability was again tested by a linear mixed effects random slope model with distance delta \(d\) as the dependent variable, dialog condition (cooperative vs. competitive), frequency (high vs. low), local predictability (high vs. low) as the fixed effects, and speaker as a random effect. Next to the significant impact of dialog condition the test revealed significant interactions for all effect combinations \(\chi^2 \geq 41.0847, p < 0.0001\), i.e. frequency and local predictability interact, and both as well as their interaction behave differently in cooperative and competitive dialogs.

We further tested this behavior by re-applying linear mixed effects random slope models for frequency and predictability as fixed effects separately for the cooperative and for the competitive subset. For the cooperative subset we found a weakly significant impact of frequency on \(d\) in the expected direction, i.e. more entrainment for high frequency \(\chi^2 = 2.7097, p = 0.0997\). Predictability did not have a significant impact \(\chi^2 = 0.2609, p = 0.6095\). For the competitive subset we found a further significant interaction \(\chi^2 = 11.0077, p = 0.0009\) which was due to a close to weakly significant impact of predictability \(\chi^2 = 2.6437, p = 0.104\) for the high-frequency condition only. Again this impact goes into the expected direction, i.e. less entrainment for low predictability. These tendencies, though weak, are further illustrated by the interaction plots in Figure 6 in cooperative dialogs more entrainment is found at high frequency (w.s.), for competitive dialogs less entrainment for low local predictability (n.s.).
7 Discussion and conclusion

7.1 Dialog acts as entrainment units

To the best of our knowledge this is the first study examining the prosodic entrainment related to dialog acts in detail.

We offer two arguments why dialog acts might be a more appropriate unit for entrainment measurement than e.g. adjacent turns: First, dialog acts determine the value range of several acoustic parameters. As an example from the frequency code paradigm [45], questions tend to be uttered with higher pitch than answers. That’s also why prosodic features can be successfully used for automatic dialog act classification [65, 61]. Therefore, if one simply measures the similarity of an acoustic feature between adjacent turns and not between dialog acts, thus neglecting dialog act intrinsic value ranges, the entrainment results run the risk of being obscured.

Second, cooperative speakers often simply cannot entrain in adjacent turns on several variables for e.g. syntactic or pitch contour patterns. To give an illustrative example: if a speaker asks a question, a cooperative dialog partner will neither exactly repeat this question, thus imitate it as a whole, nor will she imitate the intonation pattern of the question, unless she wants to mock the inquirer. A cooperative partner will instead stick to the conventions for coherent DA sequencing [66] and thus will give an answer or ask back for clarification choosing appropriate intonation patterns. In other words, if she imitates at all, she cannot imitate the preceding turn but a reaction to this turn, which is an answer dialog act which occurred earlier in the dialog.

7.2 Dialog condition related entrainment differences

Remarkably, in the current study we found overall more entrainment in competitive than in cooperative dialogs which on first sight is in contrast to our previous findings on the same data for sequence comparisons of prosodic events [60]. There we found a greater event sequence similarity in cooperative dialogs. However, this finding was already put into perspective by another study on this corpus [15] comparing entrainment in cooperative and competitive dialogs separately for several prosodic variables. These variables showed highly varied patterns of entrainment and disentrainment behavior in cooperative and competitive dialogs. In the current study instead of focusing on few (sequence similarity) variables we were operating with much larger feature sets which in total we expect to give a more robust estimate about the overall amount of entrainment. This robustness claim is further supported in that we obtained the same tendencies for several random dialog act segment pairings. In any case, as will become clear in the subsequent parts of the discussion, in our data cooperative and competitive behavior cannot simply be described by an overall entrainment comparison, but needs a more fine-grained analysis based on intrinsic characteristics of dialog acts.

7.3 Dialog act related entrainment differences

**Game structuring** Overall, game structuring, which is mainly carried out by the dialog act RE undergoes entrainment to a large extent (cf. Table 4). Thus interlocutors highly entrain on the level of organizing the sequence of actions in the game.

**Expected dialog act effects** Based on the relations between entrainment and authority reported in section [4] we expected more entrainment in low authority dialog acts than in high-authority ones (H1). Furthermore, based on the potentially supportive nature of both entrainment and disentrainment, we expected more entrainment in supportive (H2) and in frequent dialog acts (H3), and disentrainment in unpredictable dialog acts (H4). H3 is motivated by the enhancement of turn transition smoothness by entrainment, and H4 by the support of marking unexpected events. Finally, H2, H3, and H4 are expected to be more strongly confirmed in the cooperative dialogs than in the competitive ones.

**Authority and supportiveness** From our data hypothesis H1 needs to be rejected. We did not find more entrainment in low-authority dialog acts. Neither can H2 be confirmed as is, since the pattern we found is more complex. From the interaction of authority and supportiveness shown in Figure 5 and Table 7 one can conclude the following: in cooperative dialogs those dialog acts are entraining that are
both of high authority and high supportiveness, as EX and CL, whereas the not supportive IN strongly
disentrains (cf. Table 4). In competitive dialogs there is more entrainment also for IN, the high-authority
dialog act that is not supportive but imposes an obligation to the interlocutor (cf. Table 4).

From this one can conclude that at least in cooperative dialogs there is a clearly distinctive entrainment
behavior for different types of authority. While – in line with the literature – executive authority provokes
disentrainment, supporting authority by knowledge shows entrainment. The latter type of authority
enables the speaker to provide the information needed by the interlocutor to successfully solve the game,
which is thus further supported by accommodation.

**Frequency and local predictability** We found a weak frequency effect on entrainment in cooperative
dialogs only, so that H3 was partly confirmed. There frequent dialog acts entrain more. In the context
of conversation facilitation [37, 43] this frequency effect can be interpreted to contribute to the joint
cooperative effort to quickly reach the common goal by smoothing the transitions from and to often
occurring building blocks in the dialog.

Local dialog act predictability did not have a significant effect on entrainment, thus H4 is to be
rejected. In our data we did not find a sufficiently strong indication that a lack of predictability would
be the reason for cooperative disentrainment [49].

**Active control in cooperative behavior** Since we found entrainment differences among dialog acts
and between cooperative and competitive settings, it can be concluded that entrainment is not only an
automatic process in terms of a perception-action loop. Rather it is also actively controlled in order to
provide support in joint cooperative actions. In [62] we found, for the same corpus, text-based differences
between cooperative and competitive dialog acts related to word n-gram entropies and proportions of pro-
nouns, affirmations, as well as to selectional preferences for dialog acts. Both could be well interpreted
in terms of the Gricean cooperative principle [27] which consists of the four conversation maxims of ap-
propriate quantity, quality, relevance, and manner, and in terms of Relevance Theory [59, 69]. Relevance
Theory states that the relevance of an utterance for the hearer is defined as a function of positive cog-
nitive effect and processing effort. The positive cognitive effect reflects the importance of the conveyed
information for the hearer. The processing effort is the needed labor for the hearer to extract and make
use of a conveyed information. Related to communication behavior, a cooperative speaker is expected
to maximize the relevance in terms of providing important information in an easy-to-process way. How
does this relate to our findings? In addition to selectional preferences of dialog acts found in [62], e.g.
a preference of information-conveying dialog acts like EX and CL in cooperative dialog acts, in the current
study we also found different entrainment behavior for these dialog acts. Notably, for EX and CL with
the highest information content only a single feature set undergoes disentrainment in cooperative dialog
(GF0 for EX), while there are six instances of disentrainment in competitive dialog acts. Especially, the
feature set ACC related to pitch accents and thus to the encoding of information status [53] disentrains
for both dialog acts, which might be used by the speakers to impede the processing of important new
information in the competitive setting.

Taken together the positive impact of authority by knowledge, frequency, and information transmission
on entrainment provide evidence that entrainment is partly under active control to fulfill the fourth
Gricean maxim of manner, i.e. to appropriately convey information, and – in a relevance-theoretic sense
– to minimize the processing effort for the interlocutor.

7.4 Conclusion

We measured entrainment in cooperative and competitive dialogs separately for several dialog acts and
for a large amount of intonation, energy, and rhythmic variables derived from a computational prosodic
stylization. Overall, the speakers highly entrain in dialog events serving to structure the game. For
cooperative dialogs we found more entrainment in frequent dialog acts which can contribute to a smooth
processing of frequently occurring dialog units. Furthermore, it turned out that the concept of authority
as a source of entrainment needs to be subdivided into authority by knowledge and executive authority,
the former leading to entrainment the latter to disentrainment in cooperative dialogs. Finally, the finding
that entrainment patterns differ as a function of dialog act and dialog condition provides evidence that
entrainment is not an entirely automatic process but is at least in part actively controlled as a component
of voluntary cooperative or competitive behavior.
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References

[1] Babel, M. and D. Bulatov: The role of fundamental frequency in phonetic accommodation. Language and Speech, 55:231–248, 2012.
[2] Bates, D., M. Mächler, B. Bolker and S. Walker: Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1):1–48, 2015.
[3] Beňuš, Š.: Conversational Entrainment in the Use of Discourse Markers. In Bassis, S., A. Esposito and F. Morabito (eds.): Recent Advances of Neural Networks Models and Applications, Smart innovations, systems, and technologies, vol. 26, pp. 345–352. Springer, 2014.
[4] Beňuš, Š.: Social aspects of entrainment in spoken interaction. Cognitive Computation, 6(4), 2014.
[5] Beňuš, Š., R. Levitan and J. Hirschberg: Entrainment in spontaneous speech: The case of filled pauses in Supreme Court hearings. In Proc. 3rd IEEE conference on cognitive infocommunications, pp. 793–797, Košice, Slovakia, 2012.
[6] Bocheňski, J.: Was ist Autorität? Einführung in die Logik der Autorität. Herder, Freibug, Germany, 1974.
[7] Boersma, P. and D. Weenink: PRAAT, a system for doing phonetics by computer. Techn. Rep., Institute of Phonetic Sciences of the University of Amsterdam, 1999. 132–182.
[8] Branigan, H., M. Pickering, J. McLean and A. Cleland: Participant role and syntactic alignment in dialogue. Cognition, 104:163–197, 2007.
[9] Brennan, S. and H. Clark: Conceptual pacts and lexical choice in conversation. J Exp Psychol Learn Mem Cogn, 22(6):1482–93, 1996.
[10] Carletta, J., A. Isard, S. Isard, J. Kowtko, G. Doherty-Sneddon and A. Anderson: HCRC Dialogue Structure Coding Manual (HCRC/TR-82). Human Communication Research Centre, University of Edinburgh, Edinburgh, Scotland, 1996.
[11] Carletta, J., A. Isard, S. Isard, J. Kowtko, G. Doherty-Sneddon and A. Anderson: The reliability of a dialogue structure coding scheme. Computational Linguistics, 23(1):13–31, 1997.
[12] Chartrand, T. and J. Bargh: The chameleon effect: The perception-behavior link and social interaction. Journal of Personality and Social Psychology, 76(6):893–910, 1999.
[13] Clark, H. and E. Schaefer: Contributing to Discourse. Cognitive Science, pp. 259–294, 1989.
[14] Cleland, A. and M. Pickering: The Use of Lexical and Syntactic Information in Language Production: Evidence from the Priming of Noun-phrase Structure. Journal of Memory and Language, 49:214–230, 2003.
[15] Cole, J. and U. Reichel: Prosodic entrainment – the cognitive encoding of prosody and its relation to discourse function. Keynote at Framing speech satellite workshop of the Speech Prosody conference, Boston, 2016.
[16] Danescu-Niculescu-Mizil, D., L. Lee, B. Pang and J. Kleinberg: Echoes of power: Language effects and power differences in social interaction. In Proc. 21st international conference on World Wide Web, pp. 699–708, Lyon, France, 2012.
[17] De George, R.: The Nature and Limits of Authority. University Press of Kansas, Lawrence, 1985.
[18] De Looze, C., S. Scherer, B. Vaughan and N. Campbell: Investigating automatic measurements of prosodic accommodation and its dynamics in social interaction. Speech Communication, 58:11–34, 2014.

[19] Fox, J. and S. Weisberg: An R Companion to Applied Regression. Sage, Thousand Oaks CA, 2 ed., 2011.

[20] Fuchs, S. and U. Reichel: On the relation between pointing gestures and speech production in German counting out rhymes: Evidence from motion capture data and speech acoustics. In Proc. P&P, pp. 51–54, Munich, Germany, 2016.

[21] Giles, H. and N. Coupland: Language: Contexts and Consequences. Brooks/Cole, Pacific Grove, CA, 1991.

[22] Giles, H., A. Mulac, J. Bradac and P. Johnson: Speech accommodation theory: The first decade and beyond. In McLaughlin, M. (ed.): Communication Yearbook, vol. 10, pp. 13–48. Sage, Newbury Park, CA, 1987.

[23] Giles, H. and T. Ogay: Communication Accommodation Theory. In Whaley, B. and W. Samter (eds.): Explaining Communication: Contemporary Theories and Exemplars, pp. 293–310. Lawrence Erlbaum, Mahwah, NJ, 2007.

[24] Gravano, A., v. Beňuš, R. Levitan and J. Hirschberg: Three ToBI-based measures of prosodic entrainment and their correlations with speaker engagement. In Proc. IEEE Spoken Language Technology Workshop, pp. 578–582, South Lake Tahoe, NV, 2014.

[25] Gregory, S., K. Dagan and S. Webster: Evaluating the relation of vocal accommodation in conversation partners’ fundamental frequencies to perceptions of communication quality. J. Nonverbal Behavior, 21:23–43, 1997.

[26] Gregory, S. and S. Webster: A nonverbal signal in voices of interview partners effectively predicts communication accommodation and social status perceptions. J. Pers. Soc. Psychol., 70:1231–1240, 1996.

[27] Grice, H.: Logic and Conversation. In Cole, P. and J. Morgan (eds.): Speech acts, vol. 3 of Syntax and semantics, pp. 41–58. Academic Press, New York, 1975.

[28] Gries, S.: Syntactic Priming: A Corpus-based Approach. Journal of Psycholinguistic Research, 2005.

[29] Heinrich, C. and F. Schiel: The influence of alcoholic intoxication on the short-time energy function of speech. J. Acoust. Soc. Am., 135(5):2942–2951, 2014.

[30] Hirschberg, J.: Speaking more like you: Entrainment in conversational speech. In Proc. Interspeech, pp. 27–31, Florence, Italy, 2011.

[31] Johnson, K.: Speech perception without speaker normalization: An exemplar model. In Johnson, K. and J. Mullenix (eds.): Talker Variability in Speech Processing, pp. 145–166. Academic Pres, San Diego, 1997.

[32] Kisler, T., U. Reichel and F. Schiel: Multilingual processing of speech via web services. Computer, Speech, and Language, 45(C), 2017.

[33] Kousidis, S., D. Dorran, C. McDonnell and E. Coyle: Times series analysis of acoustic feature convergence in human dialogues. In Proc. Interspeech, pp. 1692–1695, 2008.

[34] Kraljic, T., S. Brennan and A. Samuel: Accommodating variation: Dialects, idiolects, and speech processing. Cognition, 107(1):54–81, 2008.

[35] Ladd, R.: Intonational Phonology. Cambridge University Press, 2 ed., 2008.
[36] Lee, C., M. Black, A. Katsamanis, A. Lammert, B. Baucom, A. Christensen, P. Georgiou and S. Narayanan: Quantification of Prosodic Entrainment in Affective Spontaneous Spoken Interactions of Married Couples. In Proc. Interspeech, pp. 793–796, Makuhari, Chiba, Japan, 2010.

[37] Levitan, R., A. Gravano, L. Willson, Š. Benuš, J. Hirschberg and A. Nenkova: Acoustic-prosodic entrainment and social behavior. In NAACL HLT ’12 Proc. of the 2012 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, pp. 11–19, Montréal, Canada, 2012.

[38] Levitan, R. and J. Hirschberg: Measuring acoustic-prosodic entrainment with respect to multiple levels and dimensions. In Proc. Interspeech, pp. 3081–3084, Florence, Italy, 2011.

[39] Lewandowski, N.: Talent in nonnative phonetic convergence. PhD thesis, Institute for Natural Language Processing (IMS), University of Stuttgart, 2012.

[40] Lewandowski, N. and D. Duran: Exemplar-theoretic modeling of phonetic convergence in dialogs. In Abstractbook Abstraction, Diversity, and Speech Dynamics, p. 35, Herrsching am Ammersee, 2017.

[41] Mittelhammer, K. and U. Reichel: Characterization and prediction of dialogue acts using prosodic features. In Jokisch, O. (ed.): Elektronische Sprachverarbeitung 2016, vol. 81 of Studentexte zur Sprachkommunikation, pp. 160–167. TUDpress, Dresden, Germany, 2016.

[42] Mizukami, M., K. Yoshino, G. Neubig, D. Traum and S. Nakamura: Analyzing the Effect of Entrainment on Dialogue Acts. In Proc. of the SIGDIAL 2016, pp. 310–318, Los Angeles, USA, 2016.

[43] Nenkova, A., A. Gravano and J. Hirschberg: High Frequency Word Entrainment in Spoken Dialogue. In Proc. of the 46th Annual Meeting of the Association for Computational Linguistics on Human Language Technologies, pp. 169–172, 2008.

[44] Nosofsky, R.: Attention, similarity, and the identification-categorization relationship. Journal of Experimental Psychology: General, 115:39–57, 1986.

[45] Ohala, J.: The frequency code underlies the sound symbolic use of voice pitch. In Sound symbolism, pp. 325–347. Cambridge University Press, Cambridge, 1994.

[46] PAGE: Prosodic and Gestural Entrainment in Conversational Interaction across Diverse Languages. http://page.home.amu.edu.pl/.

[47] Pardo, J.: On phonetic convergence during conversational interaction. J. Acoust. Soc. Am., 119:2382–2393, 2006.

[48] Pardo, J.: Measuring phonetic convergence in speech production. Frontiers in Psychology, 4:Article 559, 2013.

[49] Perez, J., R. Galvez and A. Gravano: Disentrainment may be a positive thing: A novel measure of unsigned acoustic-prosodic synchrony, and its relation to speaker engagement. In Proc. of Interspeech, pp. 1270–1274, San Francisco, 2016.

[50] Pettiginger, H., S. Burger and S. Heid: Syllable Detection in Read and Spontaneous Speech. In Proc. ICSLP, vol. 2, pp. 1261–1264, Philadelphia, 1996.

[51] Pickering, M. and S. Garrod: Toward a Mechanistic Psychology of Dialogue. Behavioral and Brain Sciences, 27:169–225, 2004.

[52] Pickering, M. J. and S. Garrod: An integrated theory of language production and comprehension. Behavioral and Brain Sciences, 36(4):329–347, 2013.

[53] Pierrehumbert, J. and J. Hirschberg: The Meaning of Intonational Contours in the Interpretation of Discourse. In Cohen, P., J. Morgan and M. Pollack (eds.): Intentions in Communication, pp. 271–311. MIT Press, Cambridge, 1990.
[54] Putnam, W. and R. Street: The conception and perception of noncontent speech performance: Implications for speech accommodation theory. Language, 46:97–114, 1984.

[55] Reichel, U.: PerMa and Balloon: Tools for string alignment and text processing. In Proc. Interspeech 2012, p. paper no. 346, Portland, Oregon, 2012.

[56] Reichel, U.: Linking bottom-up intonation stylization to discourse structure. Computer, Speech, and Language, 28:1340–1365, 2014.

[57] Reichel, U.: CoPaSul Manual – Contour-based parametric and superpositional intonation stylization. RIL, MTA, Budapest, Hungary, 2016. https://arxiv.org/abs/1612.04765.

[58] Reichel, U.: Unsupervised extraction of prosodic structure. In Trouvain, J., I. Steiner and B. Möbius (eds.): Elektronische Sprachverarbeitung 2017, vol. 86 of Studientexte zur Sprachkommunikation, pp. 262–269. TUDpress, Dresden, Germany, 2017.

[59] Reichel, U.: CoPaSul software. GitHub Repository, 2018. https://github.com/reichelu/copasul.

[60] Reichel, U. and J. Cole: Entrainment analysis of categorical intonation representations. In Proc. P&P, pp. 165–168, Munich, Germany, 2016.

[61] Reichel, U. and K. Mády: Comparing parameterizations of pitch register and its discontinuities at prosodic boundaries for Hungarian. In Proc. Interspeech 2014, pp. 111–115, Singapore, 2014.

[62] Reichel, U., N. Pörner, D. Nowack and J. Cole: Analysis and classification of cooperative and competitive dialogs. In Proc. Interspeech, p. paper 3056, Dresden, Germany, 2015.

[63] Reitter, D. and J. Moore: Alignment and task success in spoken dialogue. Journal of Memory and Language, 76:29–46, 2014.

[64] Rietveld, T. and P. Vermillion: Cues for Perceived Pitch Register. Phonetica, 60:261–272, 2003.

[65] Savitzky, A. and M. Golay: Smoothing and Differentiation of Data by Simplified Least Squares Procedures. Analytical Chemistry, 36(8):1627–1639, 1964.

[66] Schegloff, E.: Sequence Organization in Interaction. Cambridge University Press, Cambridge, 2006.

[67] Schweitzer, A. and N. Lewandowski: Social Factors in Convergence of F1 and F2 in Spontaneous Speech. In Proc. 10th International Seminar on Speech Production, pp. 391–394, Cologne, 2014.

[68] Shriberg, E., R. Bates, A. Stolcke, P. Taylor, D. Jurafsky, K. Ries, N. Coccaro, R. Martin, M. Meteer and C. V. Ess-Dykema: Can Prosody Aid the Automatic Classification of Dialog Acts in Conversational Speech?. Language and Speech 41(3-4), pp. 439–487, 1998.

[69] Sperber, D. and D. Wilson: Relevance: Communication and Cognition. Blackwell, Oxford, 1986.

[70] Sperber, D. and D. Wilson: Relevance Theory. In Ward, G. and L. Horn (eds.): Handbook of Pragmatics, pp. 607–632. Blackwell, Oxford, 2004.

[71] Street, R.: Speech convergence and social evaluation in fact-finding interviews. Human Communication Research, pp. 139–169, 1984.