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Using Measures of Vocal Entrainment to Inform Outcome-Related Behaviors in Marital Conflicts

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***Abstract*—Behavioral entrainment is an important, naturally-occurring dynamic phenomenon in human interactions. In this paper, we carry out two quantitative analyses of the vocal entrainment phenomenon in the context of studying conflictual marital interactions. We investigate the role of vocal entrainment in reflecting different dimensions of couple-specific behaviors, such as *withdrawal*, that are commonly-used in assessing the effectiveness on the outcome of couple therapy. The results indicate a statistically-significant relation between these behaviors and vocal entrainment, as quantified using our proposed unsupervised signal-derived computational framework. We further demonstrate the potential of the signal-based vocal entrainment framework in characterizing influential factors in distressed couples relationship satisfaction outcomes.**

I. INTRODUCTION

Behavioral entrainment, which occurs naturally in interpersonal interactions, is a complex and subtly coordinated behavioral dynamic between the interacting dyad. The phenomenon has received much attention across research disciplines in human behavioral science. Numerous psychological literatures have stated the importance of understanding the patterns and variations of behavioral entrainment to bring insights into, and even form theories about, higher-level human interaction dynamics and abstract human internal states. For example, Berneiri et al. demonstrated the existence of behavioral entrainment when an interlocutor is signaling his/her explicit communicative intent for continuing engagement in the interactions [1]; likewise, Marinetti et al. described a theoretical framework of emotion processes in social interactions incorporating the phenomenon of behavioral entrainment as a crucial component [2]. The behavioral entrainment phenomenon has, in general, been mentioned as a mechanism of achieving efficiency, increasing mutual understanding, and regulating emotions between the interacting dyads [1], [3].

Behavioral entrainment - due to its *subtle* nature - is a difficult *behavioral dynamic* to measure objectively using human observational coding approaches despite its crucial role for better analyzing the underlying affective and cognitive processes. Hence, a computational tool that is capable of calculating quantitative descriptors of behavioral entrainment directly using signals is a promising avenue for enriching the study of this complex phenomenon. Recently, we introduced a computational framework for quantifying entrainment reflected in one communicative channel, *vocal entrainment*, using acoustic signals [4]. This approach circumvents several shortcomings of existing quantification methods, such as the issues of handling the asynchronous structure of turn taking, incorporating the multivariate properties of acoustic cues, and introducing the notion of directionality in the entrainment process; it is also applicable to quantifying vocal entrainment in spontaneous natural language dialogs.

With the availability of our proposed computational tool for quantifying vocal entrainment, we carry out three analyses to bring quantitative insights into this complex and multi-faceted phenomenon in the context of studying conflictual interactions of distressed couple. Our findings indicate that,

1) The computational measures of vocal entrainment we proposed are indicative of couples' extreme *positive* and *negative* affective states
2) Vocal entrainment encompasses a range of behaviors, and its quantitative descriptors correlate with multiple couple-specific behavioral dimensions that are related to relationship satisfaction outcomes
3) Vocal entrainment descriptors can provide a detailed picture of couple's vocal coordination as reflected in their *withdrawal* behavior patterns

We demonstrated through the use of our computational method in analyzing affective states (finding 1 above) that in general, a higher degree of vocal entrainment is associated with a more positive affect [4]. The result signified that vocal entrainment is indicative of a positive behavioral process during the couples' interactions.

In this work, we perform two further analyses to understand the role of vocal entrainment in characterizing couple-specific behaviors with an aim at potentially shade lights into the role of vocal entrainment in assessing the overall effectiveness of couple therapy. First, we examine whether this complex behavioral dynamic bears a statistically-significant relationship with the four major high-level behavioral dimensions/categories, *withdrawal, problem solving, positivity, negativity* (commonly-used in psychology as means for monitoring changes in couples' behavior in order to study the effectiveness of a couple therapy [5], [6]). Each of these high-level behavioral dimensions is derived from a combination of multiple human-rated behavioral codes derived from codified manuals. The result indicates that with simple session-level statistics of our proposed computational measures, the phenomenon of vocal entrainment, are significantly-correlated with these four major behavioral dimensions to varying degrees and in differing directions.

Second, we carry out a canonical correlation analysis of vocal entrainment measures with the *withdrawal* behavior - the behavioral dimension that carries the most information regarding vocal entrainment as shown in our correlation analysis with the four major behavioral dimensions. Our results indicate that the most indicative behavioral code out of this behavioral dimension is the code, *discussion*, which can be intuitively thought of as measuring of the engagement level. We also quantitatively characterize influences between the spouses in their vocal coordination as reflected in the dynamics of their *withdrawal* behavior.

The rest of the paper is organized as follows, Section 2 describes the research methodology including details of the database, the vocal entrainment computational framework, and the canonical correlation analysis. Section 3 presents a discussion and results on Analyses 2 and 3 as described above and summarized in Table II. Section 4 concludes with some further discussion of future work directions.

II. RESEARCH METHODOLOGY

A. The Couple Therapy Corpus

We use the Couple Therapy Corpus for the present work [7]. The corpus was collected as a part of the largest longitudinal, randomized control trial of psychotherapy for severely and stably distressed couples as they engaged in problem-solving interactions. Sevier et al. [6] assessed the effectiveness of this psychotherapy through analyzing couples' interactions. They showed that there were four major behavioral dimensions, *negativity, withdrawal, positivity, and problem solving*, related to the outcome variable of couples' relationship satisfaction. These dimensions were derived through a combination of principal component analysis and parallel analysis, from the 32 manually-coded behavioral measures (derived from the Social Support Interaction Rating System (SSIRS) [8] and the Couples Interaction Rating System (CIRS) [9]). We use the following categorization of the behavioral codes in each dimension of couples behaviors based on work done by Sevier et al. [6]:

- *negativity*: belligerence, contempt, anger, blame, defensiveness, pressure for change
- *withdrawal*: discussion (reversed), withdraws, defines problem (reversed), avoidance
- *positivity*: affection, emotion support offered, humor
- *problem solving*: negotiate, make agreement, offers solution, instrumental support

Literature [5], [6] has shown that an increase in *positivity* and *problem solving* correspond to an increase in relationship satisfaction and a decrease for the other two dimensions.

We use a subset of the original 569 sessions of problem-solving interactions due to the varying noise conditions and variable audio quality for the recorded sessions. This resulted in a subset of 371 sessions (103 unique couples) with a total of 741 ratings available for the present work. Description of the data selection criterion, extraction of various low-level acoustic features (e.g., pitch, energy, MFCCs) and the automatic speaking turn segmentation algorithm, which were performed as preprocessing prior to the computation of vocal entrainment measures, are detailed in our previous work [10].

B. PCA-based Vocal Entrainment Measures

In order to quantify the degree of vocal entrainment, the notion of computing similarity between two interlocutors' speaking characteristics, using principal component analysis (PCA) in an unsupervised way was introduced in our previous work [4]. We have since extended the method by introducing the use of symmetric similarity measures and improving the similarity metric computation. The detailed computational formulation and psychology-inspired verification of these signal-derived vocal entrainment measures can be found in our previous work [11].

Given two sets of multivariate time series observations, $\mathbf{X_1}$ and $\mathbf{X_2}$, we can compute two sets of principal components, $\mathbf{W_1}$ and $\mathbf{W_2}$, and two associated diagonal variance matrices, $\mathbf{\Sigma_1}$ and $\mathbf{\Sigma_2}$. Two types of similarity measures, symmetric and directional, are computed based on these representations.

1) Symmetric Entrainment Measures: The idea behind symmetric entrainment measures is centered on computing cosine angles between the principal components. We compute two different symmetric measures using equations based on whether the computation involves weighting each component by its associated variance as follows:

$$\begin{aligned} ssim_u(\mathbf{X_1}, \mathbf{X_2}) &= trace(\mathbf{W_{1L}^T W_{2L} W_{2L}^T W_{1L}}) \\ &= \sum_{i=1}^{k} \sum_{j=1}^{k} \cos^2(\theta_{ij}) \end{aligned} \tag{1}$$

where θ_{ij} is the angle between the i^{th} component from $\mathbf{X_1}$ and j^{th} component from $\mathbf{X_2}$, and $\mathbf{W_{1L}}$ and $\mathbf{W_{2L}}$ contain the reduced number of principal components.

$$ssim_w(\mathbf{X_1}, \mathbf{X_2}) = \frac{\sum_{i=1}^{k} \sum_{j=1}^{k} (\lambda_{X_{1,i}} \lambda_{X_{2,j}} \cos^2(\theta_{ij}))}{\sum_{i=1}^{k} \lambda_{X_{1,i}} \lambda_{X_{2,i}}} \tag{2}$$

where $\lambda_{X_{1,i}}, \lambda_{X_{2,i}}$ are the diagonal elements from $\mathbf{\Sigma_1}, \mathbf{\Sigma_2}$.

2) Directional Entrainment Measures: The entrainment process is inherently directional: how a person entrains toward the other need not be symmetric. We can quantify this notion of inherent directionality by computing similarity as representing one time series in the PCA space of another time series. We compute the degree that it is entraining *toward* the other time series, $\mathbf{X_2}$, denoted as $dsim_{to}$, as the similarity between $\mathbf{X_1}$ and $\mathbf{X_2}$ when representing $\mathbf{X_1}$ in the PCA space of $\mathbf{X_2}$. The degree that it is getting entrained *from* another

TABLE I

*Summary of correlation analyses between vocal entrainment quantitative descriptors and the four behavioral dimensions. An 'p' refers to a statistically significant positive correlation, and 'n', negative correlation (** indicates p-value < 0.01 and * indicates p-value < 0.05) .*

	$dsim_{to}$			$dsim_{fr}$			$ssim_u$			$ssim_w$			effect size
	μ	max	min	μ	max	min	μ	max	min	μ	max	min	average
negativity	-	-	n**	p**	p**	p**	n**	-	n**	n**	-	n**	0.18
withdrawal	p**	p**	p**	n**	n**	n**	-	-	-	-	-	-	**0.20**
positivity	-	n*	-	-	n*	-	-	-	-	-	-	-	0.08
problem solving	p**	p**	p**	-	-	-	n**	n**	n**	n**	-	n**	0.16

process, $dsim_{fr}$, is computed as the similarity between $\mathbf{X_1}$ and $\mathbf{X_2}$ when representing $\mathbf{X_2}$ in the PCA space of $\mathbf{X_1}$.

The procedure of computing $dsim$ involves retaining all of the principal components after projecting one time series onto the PCA space of another one. The variance associated with all the components after normalization sums to one and can be treated as a probability distribution. We then obtain two vectors of discrete probability distribution on which we compute Kullback-Leibler Divergence (KLD) as measures of dissimilarity (hence, it can be easily interpreted reversely as similarity).

3) Acoustic Features: The multivariate feature time series used for computing vocal entrainment comprise word-level vocal parameters calculated at each speaking turn. Low level acoustic descriptors are extracted at a frame rate of 10ms, and contour parametrization and statistical functionals are used to generate vocal parameters for every word. A total of 35 vocal parameters are computed at each word as summarized in the following list:

- Pitch Parameters (5): $\left[\alpha_1, \alpha_2, \alpha_3, \mu f_{0w}, \sigma^2 f_{0w}\right]$
- Intensity Parameters (3): $\left[\beta_1, \mu\text{int}_w, \sigma^2\text{int}_w\right]$
- Syllabic Speech rate (1) : $\left[\text{sylb}_\mu\right]$
- MFCCs (26): $\left[\mu\text{MFCC}_w\left[i\right], \sigma^2\text{MFCC}_w\left[i\right]\right]$, $(i = 0 \ldots 12)$

In this work, we compute a total of four measures of vocal entrainment based on locally-computed PCA, denote here as $dsim_{fr}, dsim_{to}, ssim_u, ssim_w$, for every speaking turn change.

C. Canonical Correlation Analysis

Canonical correlation analysis (CCA) is a multivariate statistical analysis technique that subsumes most of the parametric univariate and multivariate statistical analyses introduced by Hotelling [12]. It is a framework for assessing linear relationship between two multidimensional variables, $\mathbf{X}$ and $\mathbf{Y}$, that can be of different lengths. The idea behind CCA is to find two basis vectors, $\mathbf{w_x}$ and $\mathbf{w_y}$, such that the correlation between the corresponding projections of these two sets of variables are maximized. The mathematical formulation involves solving the following eigenvalue equation ($\mathbf{C}$'s denote covariance matrices, ρ corresponds to canonical correlation, and μ is a vector of mean values):

$$\mathbf{B^{-1}A\hat{w}} = \rho\mathbf{\hat{w}} \tag{3}$$

where,

$$\mathbf{A} = \begin{bmatrix} 0 & \mathbf{C_{xy}} \\ \mathbf{C_{yx}} & 0 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{C_{xx}} & 0 \\ 0 & \mathbf{C_{yy}} \end{bmatrix}, \text{ and } \mathbf{\hat{w}} = \begin{bmatrix} \mu_x \mathbf{\hat{w}_x} \\ \mu_y \mathbf{\hat{w}_y} \end{bmatrix}$$

Canonical correlation analysis, in essence, involves performing standard parametric statistical analysis after finding the canonical variables/functions through linear projections of each set of variables into spaces with maximal joint correlation. In this work, we can treat vocal entrainment measures as $\mathbf{X}$ and behavioral codes of interest as $\mathbf{Y}$ to carry out the canonical correlation analysis.

III. ANALYSES RESULTS AND DISCUSSIONS

In this section, we present two analyses as described above and in Table II: first we analyze whether there is a significant correlation between individual vocal entrainment measures and the four behavioral dimensions; second, we perform a canonical correlation analysis between the vocal entrainment measures and the specific behavioral dimension, *withdrawal*. Behavioral codes ratings are represented by the mean ratings of human annotators. In this study, we examine the session-level statistics of vocal entrainment measures, computed by taking the mean, maximum, and minimum (resulting in 4 measures × 3 functionals = 12 features) at the session level.

A. Correlation Analysis: the Four Behavioral Dimensions

We represent the score of each behavioral dimensions as the average of different code ratings within that dimension (see Section 2.1) to be consistent with the study in [6]. Spearman correlation is computed between all 12 individual measures of vocal entrainment with the score of the four behavioral dimensions.

TABLE II

SUMMARY OF THE THREE ANALYSES AND THE ANALYZED BEHAVIORS

Past work [4]:	Positive and Negative affective states.
Sec. III-A:	**High-level** behavioral dimensions, *withdrawal, problem solving, positivity, negativity*.
Sec. III-B:	**Behavioral codes that comprise** the dimension of *withdrawal*: *discussion, withdraws, defines problem,* and *avoidance*.

TABLE III

Summary of canonical correlation analysis results of 'withdrawal' behavioral dimension with vocal entrainment

Test of Dimensionality						
Dimension	Wilk's Lambda (λ)	F - Value	Degree of Freedom	Significance	Canonical Correlation	Sq. Canonical Correlation
1 to 4	**0.652**	13.841	24	< 0.001	**0.569** (1^{st} dim.)	**0.323** (1^{st} dim.)
2 to 4	0.964	1.794	15	0.03	0.142 (2^{nd} dim.)	0.021 (2^{nd} dim.)

1^{st} Dimension Canonical Variate/Function			
Variable	Standard Canonical Coefficients	Structure Coefficients (r_s)	Sq. Structure Coefficients (r_s^2)
$dsim_{to_{\mu}}$	-0.701	**-0.554**	0.307
$dsim_{fr_{\mu}}$	0.389	**0.778**	0.605
$dsim_{to_{\max}}$	0.428	-0.198	0.04
$dsim_{fr_{\max}}$	0.128	**0.595**	0.354
$dsim_{to_{\min}}$	-0.243	**-0.695**	0.483
$dsim_{fr_{\min}}$	0.219	**0.672**	0.452
discussion	-1.115	**-0.950**	0.902
defines problem	0.079	**-0.436**	0.190
avoidance	0.301	-0.031	< 0.001
withdraws	0.032	**-0.482**	0.232

Table I shows a summary of results. We indicate with an 'n' if that vocal entrainment measure has a statistically-significant negative correlation with the specific behavioral dimension and a 'p' if it has a positive correlation; effect size, in this work, is computed by averaging the absolute correlation of the features that are statistically significant. The first thing to note is that with just these session-level statistics of vocal entrainment, even while the correlation strength is relatively 'weak', many of these purely signal-derived measures are statistically-significantly correlated with the high-level behavioral dimensions. This supports the view that vocal entrainment can been seen as a subtle process underlying many of these categorically, and manually-coded, behavioral constructs.

A second interesting observation is that measures of directional entrainment can complement the conventional interpretation of behavioral entrainment - often 'symmetric', where two processes are becoming similar without considering which one is *driving* this phenomenon. For example, an increase in the symmetric entrainment measures seems to be negatively associated with both behavioral dimensions, *negativity* and *problem solving*, but these two dimensions are related to the couple therapy outcome in an opposite direction. However, by examining the directional entrainment measures, we can see a clear distinction between these two dimensions. This finding indicates a crucial need for quantifying the directionality of the entrainment process as it can carry significant information regarding the interaction. We believe such a quantitative understanding of behavioral entrainment can potentially strengthen our knowledge in supporting various theoretical frameworks of human social interactions. Lastly, the effect size is different across the four different dimensions, which shows that vocal entrainment possesses varying degrees of explanatory power in characterizing these abstract human-annotated behaviors for study of marital conflict.

B. *Canonical Correlation Analysis:* Withdrawal

As seen in Table I, vocal entrainment measures best explain the *withdrawal* dimension if represented using the session-level statistics. We carry out further detailed analysis using canonical correlation analysis between the vocal entrainment and the *withdrawal* dimension, which consists of *discussion, withdraws, defines problem,* and *avoidance* behavioral codes. Canonical correlation analysis is conducted on two set of variables: the set of behavioral codes defining *withdrawal*, and the set of *six* significant vocal entrainment measures (mean, maximum, and minimum of $dsim_{to}$ and $dsim_{fr}$).

Table III summarizes various statistics from the analysis. At an overall level, there exists a strong statistical significant (*p*-value < 0.001) relationship between vocal entrainment measures and the *withdrawal* behavior; the Wilks' lambda (λ) is 0.652 indicating that the model explains a significant portion of the variance, 34.8% (1-λ), across the two sets of variables. We only present analysis results of the first dimension in Table III because it captures most of the relevant information between the two sets of variables (32.3% of the variances). We only interpret the variables that have a $|r_s| > 0.40$ as the threshold in determining the importance of each variable in forming the canonical variate.

The first interesting point to note here is that, Sevier et al. demonstrated through the use of principal component analysis on the manually-rated behavioral codes that the *discussion* code, out of the four behaviors in defining *withdrawal* pattern, has the largest loading factor. In our analysis, we can interpret the first canonical dimension as the most informative 'common' component between the phenomenon of vocal entrainment (as derived from observed 'signals') and the behavioral marking of *withdrawal*. From Table III, we see that the most significant determining factor in the first canonical variate from the behavioral codes side is also *discussion*. This behavioral code of *discussion* can be intuitively thought as a measure of *engagement* in the interaction, making the result intuitively consistent and in accordance with the knowledge in the psychology literature.

Our second observation is that the proposed computational framework provides further insights into the directional influences between the spouses. From the results shown in Table III, we can interpret that, in general, an increase in the degree of vocal entrainment (vocal characteristic matching) *toward* the other person is associated with a decrease in the *withdrawal* dimensions (especially significant for *discussion*, *defines problem* and *withdraws*) - potentially related to better relationship satisfaction. The phenomenon holds for measures of entraining *from* the other spouse except it associates with an increase of the *withdrawal* (note that the interpretation on directional measures, *discussion* and *defines problem* ratings are all reversed). The analysis provides empirical evidence that these spouses' vocal entrainment (computed at the entire session-level) is not only statistically related to this expert-coded *withdrawal* construct (often used in associating with the outcome of the couple therapy) but provides a quantitative picture of the coupling behaviors in the interacting spouses' vocal channels.

In summary, our canonical correlation analysis results show that there exists a statistically-significant relationship between vocal entrainment and an important behavioral dimension of distressed couples, *withdrawal*. This relationship can be explained in part as the variation on the overall vocal engagement level (captured by these signal-derived measures and explained by the manually-coded behavior, *discussion*) of the spouses in their problem-solving interactions. The results further demonstrate the potential of this 'signal-based' computational framework in bringing an objective view of behavioral entrainment phenomenon in the domain of couples interactions; it offers an objective grounding for further exploration of its influencing dynamics in studies of interactions of marital conflicts.

IV. CONCLUSIONS AND FUTURE WORKS

With the availability of a computational framework for quantifying a subtle yet important aspect of interpersonal interaction dynamics, vocal entrainment, we examine two hypotheses in quantitatively relating vocal entrainment to expert-coded behaviors, closely related to the couple therapy outcome, in couples interactions. Our analyses results not only provide further insights and understanding about vocal entrainment with these expert-derived behavioral codes to the field of psychology, but also offer an objective view of analyzing this abstract process, which has repeatedly to be been implicated as an essential mechanism underlying behavioral dependency in human interactions, through the use of signal processing methodologies.

There are many potential future directions. One of the main limitations of this work is that we examined vocal entrainment at the session-level. Some of the most pressing challenges of analyzing behavioral entrainment, despite the recurring emphasis of its importance, not only involves its subtlety (this can be addressed in a signal-based approach) but also its dynamical function (it is often viewed as a 'process' instead of a 'fixed behavior'). We need to further develop a proper understanding of behavioral entrainment in a dynamic fashion, and even more importantly, we need to devise an appropriate way of grounding these novel dynamic signal-based methods in theory of psychological significance. We also plan to develop computational tools in quantifying other aspects of entrainment. An integrative understanding of multiple communicative channels of entrainment can further enhance and bring insights into the quantitative studies of human communication.

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