QUANTIFYING REGULATION MECHANISMS IN DATING COUPLES THROUGH A DYNAMICAL SYSTEMS MODEL OF ACOUSTIC AND PHYSIOLOGICAL AROUSAL

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ABSTRACT

Negative emotional arousal during conflict has been related to negative outcomes in romantic relationships and degraded quality of family life. Despite its extensive study in psychology, it is still challenging to quantify emotional arousal in a meaningful way with objective indices beyond traditionally-used self-reported scores. We examine the association of acoustic and physiological arousal between dating couples through speech prosodic patterns and Electrodermal Activity (EDA) features. We use a dynamical systems model (DSM) approach to capture the interplay of arousal indices within and between people. The DSM parameters reflect the amount of self-regulation with respect to the acoustic and physiological cues within a person, the degree of cross-regulation between the two modalities, as well as the within-couple co-regulation. Our results through statistical analysis and classification experiments indicate a significant association between the estimated system parameters and the participants' self-reported relationship satisfaction measures. This is consistent with previous findings and can help towards better understanding regulation mechanisms and escalation effects of emotional arousal during couples' discussions.

***Index Terms*—** audio, physiology, prosody, electrodermal activity, dynamical systems model

1. INTRODUCTION

Emotion regulation refers to the process by which people influence their emotional arousal and the way they experience or express it [1]. It has been linked to one's ability for state regulation, cognitive processing, and social competence [2]. Beyond the individual level, emotion regulation has also been studied at the interpersonal context in terms of child-adult interactions [3] and adult romantic dyads [4]. In the latter, emotion self- and co-regulation has been related to attachment, temperament, physio-logical reactivity, and marital outcomes [4, 5, 6].

Previous research on emotion regulation has emphasized, among other things, the control of expression through the awareness and reduction of emotional arousal [7]. Emotional arousal is manifested in acoustic, linguistic, visual, and/or phy-siological channels. In the context of family studies, increased emotional arousal has been linked to family conflict, negative child outcomes, and failure of therapeutic interventions [8]. An important aspect is the escalation of arousal during conflict which can result in negative relationship implications [9]. In this work, we examine the interplay of emotional arousal -as expressed through vocal and physiological indices- in young couples during a conflict discussion and its association to relationship satisfaction levels. We propose an interpretable model for capturing the evolution of objective signal-derived indices of acoustic and physiological cues from an individual, that complements traditionally used self-reported measures of arousal.

The interplay between acoustic and physiological arousal within an individual and in the dyad level is quantified through a dynamical systems model (DSM). DSMs have been used in several domains to represent the behavior of a system or a process over time and have been successfully applied in dyadic interactions to capture coupling effects [10]. This is enabled by their ability to describe the underlying generative mechanisms of human-derived signals with high variability. For example, Ferrer *et al.* have used a coupled linear oscillator to capture the amount of self-reported affect regulation [11] and the physiological interrelation between partners [12]. A similar model has been proposed to distinguish couples' co-regulation from co-dysregulation in the light of health-related outcomes [13]. Ram *et al.* have modeled families as a nonlinear system in relation to adaptive stabilization and organization [14]. Finally, the nature of couples' interactions quantified through system complexity and chaotic analysis has been associated with their outcomes and dyadic characteristics [15]. A small number of preliminary studies [16, 17] has focused on quantifying the interconnection of multimodal indices within an individual and the effect of the interactor's stimuli to those, with emphasis on directly observable (acoustics) and non-observable (physiology) cues.

We model the acoustic and physiological arousal of young dating couples engaging in a conflict discussion. Acoustic arousal is measured through the combination of speech energy, prosody and frequency-based indices, since these have been related to affect in several emotional corpora and in various human-centered studies [18, 19]. Physiological arousal is captured through the Skin Conductance Response (SCR) frequency of the Electrodermal Activity (EDA), which is a psychophysiological signal linked to emotion, stress, and cognitive processing [20]. We use a coupled linear oscillator to model the co-evolution of acoustic and physiological arousal within an individual, where the system's input is the acoustic arousal of the interacting partner. The knowledge-driven design of the DSM allows us to intuitively relate the estimated system parameters to a person's self-regulation within and across modalities, as well as to the cross-partner regulation. Through statistical analysis and clas-

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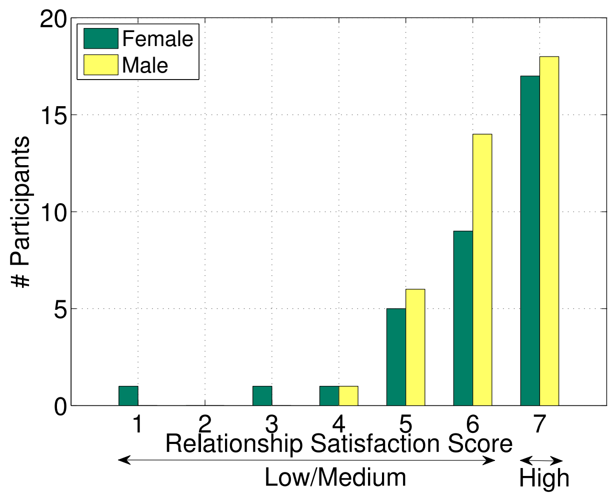


Fig. 1. Histogram of self-reported relationship satisfaction scores for female and male partners.

sification experiments, our results indicate a significant association of the DSM parameters with self-reported relationship satisfaction scores. Weaker associations exist between relationship satisfaction and the raw arousal measures, demonstrating the benefit of DSM models, that focus on the (co-)evolution and interplay of arousal indices rather than the actual raw levels, towards better understanding dyadic couples' characteristics. Our findings are consistent with previous work in the literature of family studies [4, 6] and are discussed in relation to helping individuals towards better understanding escalation mechanisms of emotional arousal and facilitating real-time feedback in couples' therapy.

2. DATA DESCRIPTION

Our data comes from the USC Family Studies Project (FSP) which investigates the role of close relationships in adults and young adults. It includes 74 young adults (37 couples) aged between 18-25 years performing an in-lab visit with tasks of various emotional intensity. Couples engage in a 10min "change discussion", during which they talk about things they would like to change in their relationship. This can give us insights about the way the participants think about and handle conflict. Data from a reading task, in which participants speak out a pre-defined set of utterances in neutral voice, will serve as a baseline for the acoustic arousal measures (Section 3.1).

Each person completed the Relationship Satisfaction Questionnaire, adapted from the Quality of Marriage Index [21], which contains five items related to the degree of satisfaction in various areas of the relationship. These items were averaged yielding a unified index, the values of which are shown in Fig. 1.

Audio recording was performed at 48kHz with high quality microphones placed in front of the participants. EDA was captured at 62.5Hz with gel electrodes from the palm through the BIOPAC® system. Manual synchronization between the two streams was performed through a door knock (for the audio) and a flag in the BIOPAC AcqKnowledge software (for physiology), simultaneously occurring at the beginning and ending of the discussion.

3. METHODS

3.1. Acoustic Arousal Features

The original audio was manually segmented into turns, to which speaker labels were assigned. Acoustic arousal was computed as a single measure incorporating speech intensity, pitch, and HF500 (computed as the ratio of energy above 500Hz divided by the energy between 80Hz and 500Hz). In order to take into account relative speaker changes, each of these measures was scored cumulatively against a reference probabilistic distribution, that was created based on the corresponding features during a neutral reading sample task. The final acoustic arousal score was created from the weighted average of the three features' scores as described in [18, 22]. This measure achieved state-of-the-art performance for cross-corpus automatic arousal recognition. Other appealing characteristics of the measure are its low-dimensionality and interpretability.

3.2. Physiological Arousal Features

EDA is a commonly used psychophysiological signal related to the sympathetic nervous system, that prepares the human body for action in times of danger and stress [20]. It is measured through the changes of sweat in the ducts and is decomposed into a tonic and phasic part. The first depicts the signal levels, while the second captures the fluctuations superimposed onto the tonic part, called SCRs. The latter have been related to several psychophysiological factors [20].

EDA was pre-processed through a low-pass filter of 62 samples to remove high-frequency noise. Movement artifacts were automatically detected by fitting a predetermined knowledge-driven structure to the original EDA signal [23]. SCR detection was automatically performed through the LedaLab toolbox [24]. Physiological arousal has been measured through the SCR frequency, computed as the number of SCRs between the beginning of successive speaker turns divided by the corresponding time.

3.3. Dynamical Systems Model (DSM)

We use a coupled linear oscillator framework that incorporates the acoustic and physiological arousal within a person and the effect of the interacting partner's acoustic stream on these measures. Let X_1, Y_1 be the acoustic and physiological arousal measures from partner 1, X_2 the acoustic arousal measure from partner 2, and X_1^*, Y_1^*, X_2^* the corresponding average measures computed over the whole session, denoting equilibrium points. The system can be written as

$$\frac{d}{dt}\begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} X_1^* - X_1 \\ Y_1^* - Y_1 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} (X_2^* - X_2) \quad (1)$$

Variable a_{11} in (1) captures the within modality change over the acoustic arousal for partner 1, while a_{22} represents the corresponding change within the physiological stream. The interrelation of the two arousal streams within partner 1 is expressed through a_{12} and a_{21}. Finally, the effect of the acoustic stream of partner 2 on the acoustic and physiological arousal of partner 1 is incorporated in variables b_1 and b_2, respectively. The same equation (1) can be applied to partner 2 by interchanging the acoustic and physiological arousal measures.

The DSM parameters can be further interpreted in the light of self- and co-regulation mechanisms. Variables a_{11} and a_{22} can be related to the amount of self-regulation with respect to acoustic and physiological arousal within each individual. Negative values of these variables indicate fluctuations away from the equilibrium and therefore low self-regulation and potentially increased escalation effects. On the other hand, positive values of a_{11} and a_{22} denote high self-regulation. Similarly, a_{12} and a_{21} represent cross-modality regulation, i.e. the degree to which an increase in acoustic arousal causes an increase in physiological arousal and vice-versa, with positive values associated with higher regulation. Finally, b_1 and b_2 are related to cross-partner regulation. Negative values of these variables indicate a strong impact of one's acoustic arousal to his/her partner's acoustic and physiological cues, suggesting a lower ability of the partner to regulate his/her arousal under external stimuli.

Parameter estimation is performed through the System Identification Toolbox in MATLAB®, which uses an iterative gradient descent optimization algorithm.

3.4. Evaluation

We evaluate our approach through the use of empirical hypotheses from the literature of the relevant domain. Previous findings in family studies suggest the relation of emotional regulation processes to individual and dyadic characteristics [4, 5]. Hence, we examine the association of the estimated self- and co-regulation indices - obtained from the DSM parameters (Section 3.3) - with the self-reported relationship satisfaction scores (Section 2). We compare the proposed DSM parameters against a baseline, that consists of the original acoustic and physiological arousal values averaged over each participant.

3.4.1. Linear Mixed Effects (LME) Model

LME examines the association of variables in multilevel data with multiple sources of correlation [25]. Its use is particularly compelling in our application, since it overcomes the dependence arising from the nested structure of the two partners within a couple. Rather than computing correlation values for each DSM parameter separately, LME allows us to jointly examine the effect of the various regulation mechanisms to the relationship satisfaction scores. Let $R^{(ij)}$ be the relationship satisfaction score of the j^{th} partner ($j = 1, 2$) within the i^{th} couple ($i = 1, \ldots, 37$) and $a_{11}^{(ij)}$, $a_{12}^{(ij)}$, $a_{21}^{(ij)}$, $a_{22}^{(ij)}$, $b_1^{(ij)}$, $b_2^{(ij)}$ be the corresponding estimated DSM parameters. The LME equation can be written as

$$\begin{aligned} R^{(ij)} =& \gamma_{00} + u_{0i} + \gamma_{10} a_{11}^{(ij)} + \gamma_{20} a_{12}^{(ij)} + \gamma_{30} a_{21}^{(ij)} + \\ &+ \gamma_{40} a_{22}^{(ij)} + \gamma_{50} b_1^{(ij)} + \gamma_{60} b_2^{(ij)} + r_{ij} \end{aligned} \quad (2)$$

where γ_{00} is the global relationship satisfaction mean, u_{0i} is the couple-specific mean, and r_{ij} is the residual. The LME parameters γ_{10} and γ_{40} reflect the association between a participant's relationship satisfaction rating and his/her self-regulation, as manifested in the acoustic and physiological modality, respectively. Similarly, γ_{20}, and γ_{30} denote the link between relationship satisfaction and cross-modal regulation within a person. Finally, γ_{50} and γ_{60} indicate the association between relationship satisfaction and a couple's co-regulation, i.e. the degree to which one's acoustic arousal affects his/her partner's audio and physiology.

Similarly for the baseline model, if $X^{(ij)}$ and $Y^{(ij)}$ are the mean acoustic and physiological arousal from the j^{th} partner of the i^{th} couple, the LME equation can be expressed as

$$R^{(ij)} = \delta_{00} + v_{0i} + \delta_{10} X^{(ij)} + \delta_{20} Y^{(ij)} + e_{ij} \quad (3)$$

where δ_{00} and v_{0i} are the global and couple-specific means and e_{ij} is the residual. The parameters δ_{10} and δ_{20} reflect the association between relationship satisfaction and acoustic/physiological arousal.

3.4.2. Classification

We perform classification tasks to further validate the hypothesized associations and also examine the ability of our proposed DSM model to generalize on unseen data. Because of the highly skewed distribution of relationship satisfaction scores towards the right (Fig. 1), we binarize the corresponding data into two groups. The first group contains the participants with "high relationship satisfaction" ($\geq$6.5), while the second contains the remaining individuals and is referred as "low/medium relationship satisfaction" class (Fig. 1). This results in two balanced classes with respect to the number of samples. The goal of this experiment is to classify individuals in the low/medium or high relationship satisfaction group according to different combinations of the estimated DSM parameters (i.e. a_{11}, a_{12}, a_{21}, a_{22}, b_1, b_2), as well as the raw acoustic and physiological arousal features (i.e. X, Y).

We use a K-Nearest Neighbor (K-NN) classifier within a leave-one-subject-out nested cross-validation framework. During the inner fold of the nested cross-validation, we perform a leave-one-couple out cross-validation to determine the optimal number of neighbors K ($K \in \{15, 19, 23\}$) that is used in the testing phase. We evaluate our approach through the unweighted accuracy (UA) of classification, with chance-level UA being equal to 50%.

4. RESULTS

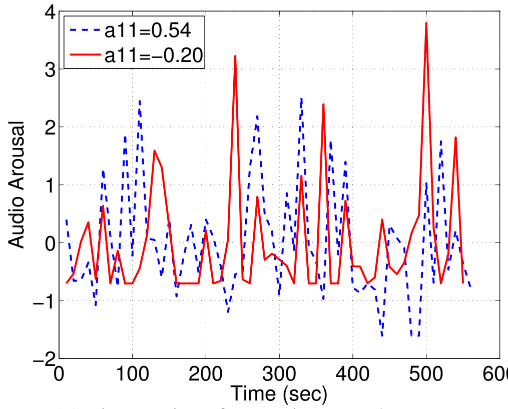
Inspection of the data suggests the existence of two main patterns. The first relates to acoustic and physiological time-series oscillating around an equilibrium point (Fig. 2, blue dotted lines), while the second includes signals moving away from the equilibrium (Fig. 2, red solid lines). Empirically, the first can be associated with positive values of the estimated DSM parameters yielding high self-regulation, while the opposite trend holds for the second.

Statistical analysis through LME suggests a significant positive association between relationship satisfaction and self-regulation, as manifested through the acoustic and physiological indices within an individual (Table 1b, γ_{10} and γ_{40}). This association appears weaker for the raw acoustic and physiological arousal measures (Table 1α, δ_{10} and δ_{20}), since the latter do not incorporate the time dependent evolution of the DSM. Our results further depict a trend towards a positive association between relationship satisfaction and co-regulation at the acoustic level (Table 1b, γ_{50}). These findings are consistent with previous literature describing the positive effects of emotion regulation to marital quality [6] and the negative impact of high physiological reactivity to self-reported dyadic characteristics [4].

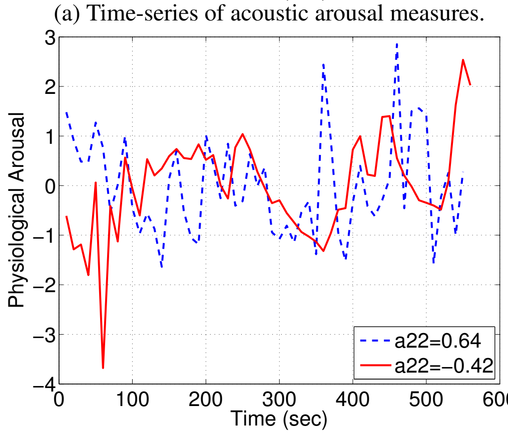
Similar observations can be made from the classification experiments (Table 2). While the mean acoustic and physiological arousal features ($[X\ Y]$) do not seem to generalize well on unseen data, the DSM parameters estimated from the corresponding streams ($[a_{11}\ a_{22}]$) result in moderate UA (63.5%). Combining self- and co-regulation features (($[a_{11}\ a_{22}\ b_1\ b_2]$)) yields further improvement (71.1%). The cross-modal association of audio and physiology ($[a_{21}\ a_{21}]$) within a person does not seem directly associated with relationship satisfaction based on the DSM model.

5. DISCUSSION

This paper describes a DSM approach to model self- and co-regulation mechanisms during a conflict discussion of young couples. Our results indicate that the estimates of acoustic and physiological regulation - as captured by the DSM parameters - are associated with self-reported characteristics of the dyad. This association is weaker for the raw arousal measures, i.e. the acoustic and physiological arousal features without the use of the DSM, suggesting



(a) Time-series of acoustic arousal measures.



(b) Time-series of physiological arousal measures.

Fig. 2. Time-series plots of acoustic and physiological arousal measures and the corresponding estimated parameters of the dynamical systems model (a_{11}, a_{22}) depicting an individual's self-regulation at the acoustic and physiological level.

the usefulness of quantifying regulation mechanisms in dyadic interactions. Such findings might enrich our understanding about the escalation of arousal during couples' conflict.

A major benefit of the proposed model is its high interpretability, since the corresponding parameters can be associated to empirical constructs studied in the psychology literature [4, 5]. Our approach further involves acoustic and physiological measures, which might be more objective compared to traditionally used self-reported emotional arousal ratings [11, 13]. Signal-derived moment-to-moment indices of self-regulation within a person and co-regulation of the interacting couple could be useful during therapy sessions [8, 26], since they might complement a psychologist's clinical opinion and guide treatment efficacy. In the context of mobile and web-based applications, such models can be also embedded in every day life allowing couples to identify and better understand potential problems through tailored feedback focusing on behavioral change [27].

Despite the rich information of the considered modalities, additional sources of data could be useful in this approach. Linguistic analysis of the utterances can yield estimates of affect complementing the existing modalities [28]. Our future work will explore additional physiological signals captured as a part of the discussed data collection. The Electrocardiogram (ECG) is an ideal complement of the EDA because of its relation to the regulatory processes of the parasympathetic nervous system. Finally, we plan to explore cross-modality regulation mechanisms in relation to individual's characteristics and use non-linear DSMs to better capture the interconnection of the underlying data streams.

Table 1. Linear mixed effects (LME) model estimates for predicting the relationship satisfaction scores (a) based on features of acoustic/physiogical arousal and (b) based on the dynamical systems model (DSM) parameters from those.

(a) Acoustic/physiological arousal

Feature	Estimate	Standard Error	P-value
Intercept	δ_{00} = 6.71	.31	<.001
X	δ_{10} = -.35	.31	.26
Y	δ_{20} = -.05	.02	.05

(b) DSM parameters

Feature	Estimate	Standard Error	P-value
Intercept	γ_{00} = 6.05	.15	<.001
a_{11}	γ_{10} = .37	.15	.01
a_{12}	γ_{20} = -.06	.05	.18
a_{21}	γ_{30} = -.05	.07	.44
a_{22}	γ_{40} = .37	.14	.01
b_1	γ_{50} = .81	.49	.09
b_2	γ_{60} = -.73	.57	.20

Table 2. Unweighted accuracy (UA) for classifying low/medium and high relationship satisfaction based on (a) the original acoustic and physiological arousal measures and (b) the dynamical systems model (DSM) parameters estimated from those measures.

(a) Acoustic/physiological arousal

Feature	UA (%)
$[X \;\; Y]$	46.3

(b) DSM parameters

Feature		UA (%)
Self-regulation	$[a_{11} \;\; a_{22}]$	63.5
	$[a_{12} \;\; a_{21}]$	42.9
	$[a_{11} \;\; a_{12} \;\; a_{21} \;\; a_{22}]$	55.4
Co-regulation	$[b_1 \;\; b_2]$	35.5
Combined	$[a_{12} \;\; a_{21} \;\; b_1 \;\; b_2]$	43.2
	$[a_{11} \;\; a_{22} \;\; b_1 \;\; b_2]$	71.1

6. CONCLUSIONS

We propose a coupled linear oscillator to capture the interplay of acoustic and physiological arousal within a person and across partners during conflict discussions of young dating couples. The system parameters are interpreted in terms of self-and co-regulation mechanisms during the interaction. Our results indicate the association of the estimated DSM parameters to the self-reported relationship satisfaction scores. Such associations appear weaker between the raw arousal measures (i.e. without the use of the DSM) and the dyadic characteristics, further indicating the importance of quantifying regulation in couples' interactions. These results are consistent with previous findings in the literature and are discussed in terms of efficient interventions and personalized feedback.

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