Examining Medical Residents' Physiological Synchrony During Crisis Resource Management Training

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Abstract

Medical training places significant cognitive and emotional demands on trainees, yet curriculums often neglect addressing trainees' emotions. Crisis Resource Management (CRM) simulation training has been incorporated into medical curriculums to develop the skills necessary for the trainees' effective functioning within medical teams. Moreover, effective emotion self- and other-regulation strategies are crucial for working within teams and delivering proper care in the face of increasing mental and emotional demands.

Physiological synchrony (PS), the spontaneous similarities in individuals' physiological responses over time, has gained attention in social-psychological research due to its association with collaboration, learning quality, and performance. However, there is a lack of research in medical education investigating PS as a predictor of cohesion and performance, even though medical practice predominantly occurs within interprofessional teams. This study aims to examine the presence of PS among medical residents undergoing CRM simulation training and its impact on performance.

Thirty-two medical residents divided into ten groups ranging from three to four participants each were observed during CRM simulation scenarios. Electrodermal activity (EDA) was captured using Empatica E4 wristbands, and simulation sessions were videotaped.

Multidimensional Recurrence Quantification Analysis was conducted to determine the presence of PS. The results confirmed the statistically significant presence of PS among residents undergoing CRM training during both the pre-training and training periods. Moreover, positive correlations were found between PS levels and performance at the group level during the training period, while PS levels during the training window predicted performance of dyads within teams.

This study offers novel insights into the presence of physiological synchrony (PS) among medical residents during Crisis Resource Management (CRM) training, shedding light on its influence on performance. Importantly, this research marks the first examination of PS among medical residents within CRM training, providing unique findings that have not been previously reported. These findings underscore the importance of integrating emotion regulation education into medical curriculums, as emotions can significantly influence performance and therefore affect patients' outcomes. By implementing emotion regulation training in medical education, the well-being of medical practitioners can be potentially enhanced, reducing burnout, affect disorders, and suicide rates among the medical practitioners.

Résumé

La formation médicale impose des exigences cognitives et émotionnelles importantes aux stagiaires, mais les programmes d'études négligent souvent de prendre en compte les émotions des stagiaires. La formation à la gestion des ressources de crise (CRM) a été intégrée aux programmes d'études médicales pour développer les compétences nécessaires au fonctionnement au sein des équipes médicales. De plus, des stratégies efficaces d'autorégulation émotionnelle sont essentielles pour travailler en équipe et fournir des soins appropriés face à des exigences mentales et émotionnelles croissantes.

La synchronie physiologique (PS), les similitudes spontanées dans les réponses physiologiques des individus au fil du temps, a attiré l'attention dans la recherche psychologique en raison de son association avec la collaboration, la qualité de l'apprentissage et la performance. Cependant, il y a un manque de recherche en éducation médicale en examinant la PS comme prédicteur de la cohésion et de la performance, même si la pratique médicale se produit principalement au sein d'équipes interprofessionnelles. Cette étude vise à examiner la présence de PS chez les médecins résidents suivant une formation en simulation CRM et son impact sur la performance.

Trente-deux médecins résidents, répartis en dix groupes de trois à quatre participants chacun, ont été observés lors de scénarios de simulation CRM. L'activité électrodermique (EDA) a été capturée à l'aide de bracelets Empatica E4 et les séances de simulation ont été enregistrées sur vidéo. Une analyse de quantification de la récurrence multidimensionnelle a été effectuée pour déterminer la présence de PS. Les résultats ont confirmé la présence statistiquement significative de PS parmi les résidents en formation CRM pendant les périodes de présimulation et de simulation. De plus, des corrélations positives ont été trouvées entre les niveaux de PS et

les performances au niveau du groupe pendant la période d’entraînement, tandis que les niveaux de PS pendant la fenêtre d’entraînement prédisaient les performances des dyades au sein des équipes.

Cette étude offre des informations sans précédent sur la présence de la synchronie physiologique (PS) chez les médecins résidents pendant la formation en gestion des ressources de crise (CRM), mettant en lumière son influence sur la performance. Il est important de noter que cette recherche marque le premier examen de cette population spécifique dans le cadre de la formation CRM, fournissant des résultats uniques qui n’ont pas été rapportés auparavant. Ces résultats soulignent l’importance d’intégrer l’éducation à la régulation des émotions dans les programmes médicaux, car les émotions peuvent influencer de manière significative les performances et, en fin de compte, affecter les résultats des patients. En mettant en œuvre une formation sur la régulation des émotions dans l’enseignement médical, le bien-être des médecins peut être potentiellement amélioré, réduisant l’épuisement professionnel, les troubles affectifs et les taux de suicide chez les médecins.

Preface

I would like to express my infinite gratitude for the invaluable opportunity to conduct this research and successfully complete my work. The completion of my thesis research marks the achievement of a lifelong dream of mine.

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Contributions of Authors

Prof. Jason M. Harley (*J.M.H.*) supervised the entire project and was involved throughout the entire process (e.g. from research question formulation to interpretation and discussion of results). Dr. Sebastian Wallot (*S.W.*) shared insight, feedback, and guidance on data analysis and interpretation using Multidimensional Recurrence Quantification Analysis. Keerat Grewal (*K.G.*), Sayed Azher (*S.A.*), Matthew Moreno (*M.M.*), and Osamu Nomura (*O.N.*) provided wonderful contributions as outlined below.

Chapter 1 to Chapter 5 were written by L.P.M and J.M.H reviewed and edited each section. Chapter 4 is the manuscript that was accepted for presentation at the European Association for Research on Learning and Instruction EARLI 2023 conference.

Conceptualization: L.P.M and J.M.H conceived the presented idea.

Data Curation: K.G., S.A., M.M., and J.M.H conducted the recruitment of the participants. K.G., S.A., M.M., and L.P.M., conducted the data collection. K.G. and J.M.H led the development of the survey used to collect the demographic data of the participants. L.P.M. and M.M. participated in the adaptation of the CRM Ottawa scale, used to score the performance of the participants undergoing the CRM training. L.P.M and O.N. performed the CRM scoring of the participants.

Formal Analysis: L.P.M carried out the data extraction, data cleaning, and data organization. L.P.M. carried the MdRQA analysis of the data with the aid of S.W. L.P.M. carried out the statistical analysis with the aid of J.M.H and S.W.

Writing: L.P.M. wrote the original draft, and J.M.H. provided critical reviews and revisions. All authors supported the revision of the final draft.

List of Abbreviations

CRM: Crisis Resource Management

CVT: Control-Value Theory

EDA: Electrodermal Activity

PS: Physiological Synchrony

MdRQA: Multidimensional Recurrence Quantification Analysis

%REC: Percentage of Recurrence

Chapter 1: Medical Education: A Unique Niche

Medical training is cognitively, physically, and emotionally demanding. It requires years of training with a progressively increasing workload and responsibilities, followed by a lifelong engagement with learning. Medical education is distinct in its combination of knowledge acquisition, technical skill development, and the intricate realm of human emotions (1-3). Unlike many other educational domains, medical training exposes students and healthcare professionals to intense emotional experiences in high-stakes situations. Trainees are exposed to emotionally intense incidents (i.e. negative: patient suffering, death, violence, etc.; positive: role models exhibiting compassion, empathy, etc.). The nature of this training process has the potential to evoke wider and more intense emotions when compared with most other educational fields.

Medical trainees must master competencies and skills that will be applied in high-stake situations, closely tied to professional credentialing, and patient outcomes. The complexity of medical training within emergency contexts is even more convoluted. These cases require the understanding of simultaneous cognitive, affective, and metacognitive (CAM) processes needed to work in a team to successfully care for the patient(4). For instance, medical trainees must depend on their cognitive abilities to gather, organize, and understand multiple sources of information simultaneously and rapidly within these high-pressure scenarios. They need to assess the patient's condition, analyze the data, to diagnose and make accurate decisions regarding treatment options. Moreover, affective processes are pivotal in emergencies. Trainees must regulate their emotions effectively, as progressively heightened stress can negatively impact their performance and decision-making abilities. Effective emotion regulation strategies allow trainees to maintain their focus and composure during challenging circumstances while providing compassionate care to the patients. Lastly, metacognitive processes involve monitoring and regulating one's thinking and learning strategies. Trainees must be aware of their knowledge gaps, limitations, and must be able to identify when to seek assistance. The simultaneous integration of CAM processes will enable trainees to adjust their medical approaches, decision-making, and technical skills, to improve patient outcomes.

Studies have demonstrated that the highly stressful nature of acute settings, such as emergencies, contributes to medical errors and adverse events due to communication challenges, diagnostic uncertainty, novelty of cases, and unique distractions in these contexts(4-7). Accordingly, these CAM processes have the potential to improve or hamper performance, hence, medical professionals and trainees must learn to regulate their thoughts, emotions, and behaviors, due to the potentially detrimental effects that poor self-regulation may have on patients' outcome (4). Effective management and regulation of these emotions are crucial for the well-being of medical learners and practitioners, as well as for providing optimal patient care.

Extensive research has explored the impact of stress, stemming from intense and negative emotions, on medical performance. Inadequate stress management has been linked to impaired performance, compromised patient care, and poor outcomes (5, 6, 8). Chronic stress has also been associated with psychological distress and mental health disorders (9-14).

Despite this, medical curriculums rarely address trainees' emotions directly, although compassion, respect, and collegiality are expected values in a physician. On the contrary, medical trainees are shown that emotional distance and detachment from the patient are appropriate and sometimes, necessary to deliver proper care (3, 15). Hence, the ability to remain level-headed without affecting performance and decision-making in the event of increasing mental and emotional demands, are fundamental qualities that reflect effective self-regulation and group ER strategies (16).

The upcoming sections and chapters of this thesis will provide an overview and explanation of the conceptual and theoretical frameworks that were used to inform and shape our research. We will delve into the significance of the CanMEDS framework and its roles in medical training, and its relevance to our research. Next, we will briefly describe how the Crisis Resource Management training is implemented within medical education to practice and assess CanMEDS roles such as Leader, Communicator, and Collaborator. Finally, as we approach the core of our research, we will learn how we can measure the trainees' emotional responses through their physiological signals, such as electrodermal activity (EDA) of the skin. These responses can be measured not only individually, but also on a group level by looking at the presence of physiological synchrony, the degree to which individual responses align with each other. This synchronization is believed to enhance communication, cooperation, and overall team performance (17-19). These sections aim to provide a foundation of understanding for readers by presenting a clear and concise explanation of key concepts necessary to comprehend the subsequent analysis and findings.

CanMEDS Framework

The CanMEDS framework was conceived in the 1990s to improve patient care by enhancing physician training. This framework identifies and describes the abilities physicians require to effectively meet the healthcare needs of the people they serve. These abilities are grouped under seven roles (Communicator, Collaborator, Leader, Health Advocate, Scholar, Professional, and Medical Expert). A ready-to-practice physician needs to smoothly integrate the competencies of all seven CanMEDS roles (20, 21) .

To efficiently work within teams, physicians need to be able to communicate effectively with everyone involved in the patient's care. Communication skills include mastering verbal and nonverbal communication; sustaining emotionally charged conversations; managing disagreements; and flexibility to adapt one's communication to the needs, culture, and clinical context of patients and team members. Likewise, good collaboration skills are essential to work with other healthcare professionals to provide safe, high-quality, patient-centered care. This requires shared decision-making among different individuals with complementary skills in different clinical settings across the continuum of care (22).

Finally, medical teamwork implies the presence of a leader. According to the CanMEDS framework, a physician must "demonstrate leadership skills to enhance healthcare", however, the core components of the leadership role are more oriented to resource stewardship skills than the role of the leader as the manager of human resources in practice. New trends on adaptive leadership for the new generations have emerged, aiming at incorporating concepts like teaming behaviors, in which leaders promote cohesiveness (23). Although the framework has been successfully implemented and improved over the years, there are still some skills that need more development, such as *communicator, collaborator, and leader*.

Crisis Resource Management in Emergency Training

Crisis Resource Management (CRM) is a set of skills outside of the medical knowledge that can be applied to a variety of crisis environments, including those encountered in medicine (24, 25). Medical emergencies are highly challenging for healthcare professionals, who need both, extensive medical knowledge, and effective self-regulatory and leadership skills. These are complex situations that also entail a higher risk for adverse medical events due to the complexity of invasive interventions needed, increasing the chances of cognitive errors in decision-making and communication difficulties. Leadership, communication, problem-solving, resource utilization, and situational awareness are CRM skills that are also paramount in clinical practice.

Therefore, CRM skills training programs have been developed to enhance trainees' dynamic decision-making, interpersonal skills, and team management in medicine. This training is implemented through simulations, allowing healthcare professionals to gain experience and learn from mistakes without exposing real patients to risks, do so within a safe environment, and facilitate the development of team-based competencies, including leadership, closed-loop communication, and adequate resource utilization. These competencies, in turn, contribute to improved decision-making, patient safety, and better outcomes. Given that real-life medical emergencies involve interdisciplinary teams working together towards a common goal (good patient outcomes) effective teamwork abilities are crucial. Accordingly, the interpersonal skills necessary to be a good leader, communicator, and collaborator, are related to the individual's ability to regulate their own and each other emotions within a team. However, since these emergency training programs occur in real time with unpredictable courses of action and outcomes, further research is needed to examine the nature of learning and team performance measurement within these unique situations (4, 26).

Theoretical Background

Our study draws from the Emotion Regulation in Achievement Situations (ERAS) model (16) proposed by J. Harley and colleagues, which combines two different frameworks, Gross's Process Model of Emotional Regulation (PMER) (27) and Pekrun's Control-Value theory (CVT) of achievement emotions (28).

Emotions are seen as a multi-component, coordinated processes of psychological subsystems including affective, cognitive, motivational, expressive, and physiological processes. The physiological component of emotion generation is the focus of our research.

Pekrun defined achievement emotions as the ones related to achievement activities and their success and failure outcomes. These emotions can influence one's achievement behavior and performance, and they can be modulated with the use of emotion regulation (ER) strategies. The PMER defines emotion regulation as the processes by which individuals influence which emotions they have, when they have them, and how they experience and express these emotions. This model posits that emotion regulatory mechanisms encompass dynamic changes that unfold over time in the behavioral, experiential, and physiological domains of emotions. These changes reflect the causes, outcomes and underlying strategies that generated the emotion in the first place, yielding the way to five families of ER strategies based on these three critical stages of emotion generation.

ERAS model notes that emotions can be regulated intrinsically and extrinsically and team situations, like the ones observed during CRM training, have distinct affordances and constraints from individual situations. It holds that achievement emotions are generated in a four-stage process (*situation, attention, appraisal, and response*). It starts with an achievement situation that is attended to and which gives place to a situation appraisal depending on how one's perceives its impact on one's goals, or *stakes*. This will generate emotional responses that can modify both, the situation and simultaneously one's appraisals and attention of the situation. Emotions can be generated in each one of these four stages, and they can loop back and modify each other. In addition, the ERAS model proposes that ER strategies can be classified into five families (*situation selection, situation modification, attentional deployment, cognitive change, and response modulation*) that reflect the five moments within the emotion-generation process where one can intervene to regulate one's emotions, including prior to and during a given situation. Within these four stages, there are core features (*individual vs social; timeframes and* *object foci; appraisals of control and value; achievement emotions*) that play a fundamental role in the emotion-generative process. These features can function as targets for specific ER strategies and most importantly, they can also determine the viability and limitations related to the implementation and effectiveness of these strategies. Finally, these core features can influence each of the five families of ER strategies, however, the ER strategies typically target their corresponding stage of the emotion-generative process in an achievement situation.

To illustrate, a resident could experience anxiety (*response)* before a CRM training (*social situation*) due to lack of knowledge regarding the content of the scenario (*appraisal of control*)*,* and the importance of the performance evaluation during said CRM training to advance in their academic goals or the repercussions of the performance score on the clinical rotation's grade (*appraisal of value: high stakes*). Conversely, the same resident could feel hopeful (*response*) when realizing that the training is addressing crisis situations, and they recently completed the Emergency Department rotation and anticipate a satisfactory performance (*appraisal of control*). Satisfactory performance could trigger *retrospective outcome* emotions, such as joy and pride. On the other hand, a previous substandard performance could trigger negative emotions such as shame and frustration, if the resident attributes their deficient performance to themselves for not having the knowledge required to manage given clinical scenario. The latter could trigger an ER strategy such as *situation modification*, motivating the resident to review the CRM skills topic before the upcoming CRM training day, to improve their performance.

Research has reported that positive emotions are related to more flexible and creative modes of thinking, as well as regulatory processes, such as planning, monitoring, and evaluation. In contrast, negative activating emotions (e.g. anger, anxiety) are linked with more rigid modes of thinking, such as rehearsal strategies. Duffy et al. (4) examined the nature of cognitive, affective, and metacognitive (CAM) processes within CRM training in medical residents. They reported that team members expressed negative emotions (i.e. anxiety, frustration, and hopelessness) more often than positive ones, and found that negative emotional states were preceded primarily with lower-order cognitive and metacognitive processes. The latter added to poor communication among team members, caused the persistence of negative affect, impacting the team's performance. In addition, they found that the emotions reported within training included those experienced during the task (*concurrent)*, and also those targeting the outcomes (*prospective)* (26). Nevertheless, these findings were based on the trainees' reports and qualitative analysis of the participants CAM processes exhibited during the CRM training. Given that the experiential and behavioral components of emotions can be modulated, these findings can be limited by the participants' efforts to modulate their emotions expression. For example, a resident, despite feeling overwhelmed and anxious due to the intense nature of the scenario, engages in deep breathing exercises to calm their racing heart and clear their mind. They remind themselves of the importance of staying focused and composed to provide the best patient care possible. This ER strategy used by the trainee to modulate their physiological response may help them to perceive this stressful scenario as less threatening, leading to a lesser physiological activation, and therefore, arousal level, due to changes in the balance between the sympathetic and parasympathetic nervous systems. By measuring psychophysiological signals, this study offers a deeper understanding of how physiological arousal reflects the unconscious perspective of the emotion generation process, without resorting to self-reported data. It is worth noting that the primary focus of this thesis was not to directly study discrete emotions (e.g. anxiety, frustration). Rather, the ERAS model served as a conceptual framework to investigate the shared patterns of emotional arousal from physiological responses, known as physiological synchrony, and its relationship with performance. By uncovering the interplay between shared physiological activation among team members and their performance, this study sheds light on the intricate dynamics that underlie collective emotional experiences which has implications for emotion regulation at the individual and group level.

Chapter 2: Measuring Emotional Responses: Psychophysiological Signals

Psychophysiological signals are measurable physiological responses that reflect the interaction between psychological processes, such as emotions, thoughts, and cognitive states, and the body's physiological functioning. In this section, we will explore the use of EDA as a robust tool for quantifying emotional responses and assessing physiological synchrony, shedding light on the dynamic interplay of physiological arousal between team members.

What are psychophysiological signals?

Emotions are multi-component, coordinated processes of psychological subsystems that include three key dimensions: The subjective experience, where the affective, cognitive, and motivational aspects play a role; the physiological response regulated by the autonomic nervous system, which is the focus of our study, and lastly, the expressive aspect, which is manifested through the behavioral response (e.g. fidgeting, laughing, furrowed brows, etc.)(28). Physiological signals are responses that reflect the degree of activation of *the autonomic nervous system* (ANS) and the excitatory *sympathetic* (SNS) and inhibitory *parasympathetic* (PNS) branches secondary to an individual's emotional states.

Conversely to behavioral expressions of emotions, which are culturally framed, and can be consciously modulated, psychophysiological signals are involuntary in nature, allowing researchers to have a look into an individual's internal emotional states, since the link between the latter and physiological activation has been established (29-34). Moreover, these signals can be measured within groups, allowing researchers to analyze interpersonal physiological synchrony among team members(17, 19, 35-40).

Across the literature, diverse signals have been measured to explore individuals' emotional states through physiological activation. *Electrodermal activity* (EDA), *heart rate* (HR), *heart rate variability* (HRV), *blood volume pulse*, *blood pressure*, *temperature, respiration rate*, *electrocardiogram*, *electroencephalogram* are among those. EDA and cardiovascular signals such as HR and HRV are most used in medical contexts given the availability of non-obtrusive sensing devices to measure them. For our study, we will look at EDA.

Electrodermal Activity (EDA)

EDA is the electrical activity seen as changes in conductivity on the skin surface secondary to sweat gland activity and is an extremely sensitive index of the SNS activation. Although, thermoregulation is the main function of sweat glands, it is mainly exerted by apocrine glands. Changes in skin conductivity are caused by the activity of the eccrine sweat glands, responsible for the *emotional sweating.* This phenomenon is more evident on hands and feet because of the high density of eccrine glands on these anatomical areas, which carry grasping functions (power grasp, precision grasp, cylindrical grasp, hook grasp, etc.) rather than thermal regulation. Therefore, EDA has been validated as a quantitative index of sympathetic-mediated sudomotor activity with the potential to be used to assess emotional arousal levels. The neurotransmitter involved in the eccrine sudomotor activity is acetylcholine. Despite acetylcholine being the primary neurotransmitter of the PNS, it is accepted that human sweat glands have cholinergic innervation linked exclusively to the SNS branch.

EDA has two components: The *tonic*, which represents slow changes in conductivity, expressed as *skin conductance level* (SCL), and the *phasic*, which denotes the changes of conductivity from the baseline with rapid responses, known as *skin conductance response* (SCR). Three main neurological pathways have been found to trigger SCRs: hypothalamic control, contralateral and basal ganglia, and the reticular formation in the brainstem. These pathways have distinct roles on central-mediate functions such as gross movements, thermoregulatory sweating, and affective, orienting, and attention processes.

These processes affect the EDA signal, triggering rapid and transient events displayed as peaks, known as *event-related skin conductance responses* (ER-SCR). These peaks are used to evaluate a subject's response to event-related experiments. The onset of the SCR is between 1 to 5s after a stimulus. They can be identified by measuring the amplitude of the signal, measured in microsiemens (µS). As a convention, a threshold of 0.05 µS change relative to the EDA level at the onset is commonly used to define an SCR. This threshold helps avoid erroneous readings caused by movement artifacts and experimental conditions(41, 42).

On the other hand, SCL serves to assess the response to tonic stimuli, and it reflects the slow changes of the EDA. These peaks, known as *non-specific skin conductance responses* (NS-SCR), appear spontaneously as a response to an ongoing sustained stimulus over a period. These peaks happen due to cognitive stress, workload changes, etc., and their frequency can vary between participants, correlating directly with the arousal level, meaning the higher the frequency the higher the arousal level of the ANS.

Concerning the measure of EDA for our study, the research team decided to use the whole EDA signal. This decision stems from our main objective to investigate whether physiological synchrony (PS) existed among team members, regardless of the intensity of their activation levels. Synchrony, in this context, focuses on the similarity of patterns or recurrence within the EDA signal rather than the intensity of the signal itself. Under this perspective, for this study we chose to use EDA as a whole instead of running analyses on its derived measures.

In conclusion, EDA as a response modulated by the SNS can be used as an objective index of emotional activation, despite individuals' potential efforts by participants to conceal behavioral responses and reports of emotions. These signals can give insight into an individual's subconscious level of emotional arousal in a real-time and non-obtrusive manner.

EDA Measurement: Empatica E4 Wristband

The non-invasive nature of EDA measurement and its ability to capture real-time changes make it a versatile tool for studying human behavior and affective experiences. Moreover, advancements in wearable technology have facilitated the integration of EDA sensors into various devices, enabling the continuous monitoring of individuals in naturalistic settings.

There are multiple EDA recording devices available for research, however, the Empatica E4 wristband has emerged as a valuable tool in electrodermal activity (EDA) research due to its advanced features and ease of use, during real-life conditions. It is a wearable device conceived to allow unobtrusive monitoring, obtaining accurate physiological data. It is equipped with sensors to measure blood volume pulse, temperature, heart rate, EDA, and it also provides the count of steps since it is equipped with a 3-axis accelerometer. E4 wristband was designed to capture physiological signals in a non-invasive and continuous manner in real-world settings, making it suitable for both laboratory studies and naturalistic research.

Multiple studies have employed the wristband to measure participants' physiological signals, and it has been tested against gold-standard devices, providing reliable and significant results, indicating the potential of the E4 wristband as a non-obtrusive tool to measure psychophysiological signals in research(17, 30, 43-46).

Consequently, CRM training within medical emergencies present a challenging context characterized by high-fidelity scenarios, where clinical cases evolve unpredictably and involve physically demanding activities such as cardiac massage that can cause artifacts, the use of non-invasive devices becomes paramount. In such dynamic and intense situations, the measurement of EDA using traditional devices becomes even more cumbersome due to environmental noise, posing significant obstacles to the accurate assessment of it. Moreover, in surgical tasks like performing a C-section, or during cardiac massage, hands-free movement is essential, thus, the use of conventional EDA measurement devices becomes impractical. These unique challenges demand the use of alternative methods and innovative technologies that can reliably capture EDA signals while accommodating the chaotic nature of CRM training within medical emergencies. To overcome these challenges, we used Empatica E4 wristbands to capture the EDA of the participants during the CRM training.

Measuring Physiological Synchrony

What is Physiological Synchrony?

Physiological synchrony (PS) refers to the spontaneous phenomenon where the physiological responses of two or more individuals become aligned or synchronized over time. It reflects coordinated patterns of physiological activity among individuals. It can be detected in several physiological signals such as heart rate, respiration, or electrodermal activity, menstrual cycles, facial micro-expressions, etc., among individuals who are in proximity or engaged in interpersonal interactions. PS is considered a herding behavior, stemming from the idea that humans are inherently social beings, and our physiological processes can be influenced by the presence and interactions with others. When individuals share an emotional experience, engage in cooperative tasks, or establish rapport, their physiological responses can exhibit similar patterns of activation.

Cooperation is one of human society's core pillars, distinguishing us from other species in its scale and complexity (35). Research has shown that emotional states and their consequent physiological responses tend to synchronize between partners. This synchronization is believed to reflect the level of interpersonal connection, empathy, and social bonding between individuals. PS has been studied in several contexts and disciplines, including romantic couples(47), parent-child interactions(48), therapist-client relationships(49), and group dynamics (friends, musicians, students, etc.)(37, 39, 50-54). Nonetheless, the social effects of it are still not apparent nor is a specific theoretical model available to effectively frame it. Additionally, there are contradictory findings regarding PS and group processes. For example, some studies found a positive relationship between PS and team cohesion, mental workload, and perceived task difficulty; conversely, other studies found negative or no relationship between PS and team cohesion, effective team communication, or emotions (17-19, 35, 38, 55-57). Additionally, studies looking at the relationship between PS and team performance have yielded inconsistent findings, ranging from positive, negative, to no association. These inconsistent findings could be explained by the fragmentation of the field, with an evident lack of consistency across terminologies, data collection methods, statistical analysis, and the interpretation of the findings(50).

Multidimensional Recurrence Quantification Analysis (MdRQA)

Across literature, multiple methods to examine PS have been reported. Multilevel modeling, pooled time-series analysis and dynamic cluster analysis are some examples; however, one big limitation of these analysis is the assumption of normally distributed and stationary data (time series where the statistical properties remain constant over time). Other authors have used Pearson's correlation(50), but these are not a good fit for continuous physiological data with sequential dependency violating general linear model assumptions. More recently, time-series analyses have been implemented to account for data dependency, allowing computing time domain and frequency domain analyses(50, 58). Nonetheless, most of these models assume stationarity, a quality not found in physiological data.

To measure PS, it is necessary to consider the difference between idiographic and nomothetic methods. Idiographic methods focus on units, for instance, one dyad or team, whereas nomothetic methods assess group-level trends (combining data from multiple dyads or teams). One commonly used idiographic method is the Pearson correlation between two variables. However, it is not well suited to analyze continuously measured physiological data since it shows autocorrelations and is non-stationary over time.

One approach to overcome this issue is nonlinear modeling. Nonlinear modeling is a broad term that encompasses analysis that detects patters that are unobservable through linear regression. One example of nonlinear modeling is cross-recurrence analysis(50). This phase space analysis graphs multiple time series, in which one axis represents one person and the other axis of the other person. This method visually represents the periods when both persons' states were identical. This class of recurrence plots' analyses, falls into the recurrence-based methods category, and have their roots in dynamical systems analysis and physics. They are multivariate correlational analyses, which make very few assumptions, making them very robust to stochastic systems' data, with extreme outliers(59, 60). These qualities allow it to analyze data from group contexts in semi-experimental and naturalistic settings.

Additionally, multidimensional recurrence quantification analysis (MdRQA) is a multivariate version of recurrence analyses and can be used to analyze the joint dynamics of groups with two or more participants. MdRQA uses multiple time series embedded in a phase-space, in which each of the time series provides one dimension of that phase-space. As its name implies, the core concept of this analysis lies in the repetition of patterns in a sequence or *recurrence*. These repetitions can be plotted in a recurrence plot or matrix. This plot not only allows the visualization of the similarities of two sequences, but also allows the quantification of their similarities.

Accordingly, multiple measures can be extracted from these plots to provide details about how the sequences are similar. The most commonly used are the percent recurrence (%REC) which is the sum of all recurrent points on the plot and quantifies the repetition of elements across the sequences (two or more); the percent determinism (%DET), results from counting all recurrent points that have other, diagonally adjacent recurrent points and dividing them by %REC and quantifies how many of the individual repetitions co-occur in connected trajectories; and the average diagonal line (ADL), results from counting the average length of all diagonal lines and quantifies how long the average repeating trajectory is(59).

MdRQA is a versatile tool that can be used to compare sequences of time series of nominal, ordinal, and interval data. It does not make assumptions of normality and is robust to non-stationary data. Finally, MdRQA allows quantifying the system dynamics at different grouping levels, for instance, one group with three participants can be analyzed as a unit in a group level, and it can be broken down into three dyads within the same group. This allows one to investigate differences in the members' interactions, whether there is uniformity across the group or whether there are stronger interactions among particular dyads within the group (19, 59, 60). These qualities make MdRQA an excellent option to analyze multiple EDA time series of participants (medical residents) undergoing CRM training (naturalistic, phase-space) to explore the presence of PS among team members.

For the purposes of this study, we used %REC to examine the presence of PS among medical residents and conducted the MdRQA on the groups and on the dyads within the groups. This decision was made considering that MdRQA is a measure of system-level recurrence and that our main objective was to determine the presence or absence of physiological synchrony among the medical residents.

By focusing on the %REC, we are specifically assessing the proportion of recurrent points in the phase space, which indicates the presence of synchrony. Other output measures of the MdRQA function such as DET and ADL capture various aspects of the system's dynamics, complexity, and temporality. However, since our study's main interest was determining the presence of PS rather than examining the more granular characteristics of it, focusing on %REC alone aligned with our research objectives. Further details will be provided in the methodology section.

Chapter 3: Objectives and Hypotheses

This thesis aims to enhance our understanding of physiological dynamics within medical teams, specifically focusing on the potential implications of PS for team performance in high-stress scenarios. This thesis contributes to the current body of knowledge by examining the EDA recordings of medical residents while they completed CRM simulated training, in a first analysis as members of a team, and in a second analysis, as dyads within their team. The objectives of this study were to examine the presence of physiological synchrony (PS) among medical residents in quasi-naturalistic CRM scenarios and evaluate whether PS among team members can predict overall team performance. We hypothesized that PS could be found among medical residents during the CRM simulated training based on previous reports on the literature of PS detected during collaborative tasks (17, 37, 56, 61, 62). Additionally, we predicted that the level of PS would positively correlate with the performance of the team on both, group and dyadic level(17, 36, 38, 39, 63, 64).

Chapter 4: Manuscript

Physiological Synchrony as Predictor of Performance of Medical Residents During Crisis Management Simulation Training

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Abstract

Medical training places significant cognitive and emotional demands on trainees, but often neglects addressing their emotions. Effective emotion self-regulation strategies are crucial for working within teams and meeting increasing mental and emotional demands, without affecting patient outcomes. Crisis Resource Management (CRM) simulated training has been incorporated into medical curriculums to develop teamwork skills, by reinforcing the trainees' leadership, communication, and collaboration skills. This study examined physiological synchrony (PS) among medical residents undergoing CRM simulation training and its impact on performance. Electrodermal activity (EDA) was used to measure the emotional arousal of the participants, and Multidimensional Recurrence Quantification Analysis was carried out to examine the presence of PS among them. Our results revealed the presence of PS among residents during both pre-training and training periods. Positive correlations were found between PS levels and group performance during training, and PS levels during training predicted performance within team dyads. These findings provide novel insights into PS among medical residents during CRM training, highlighting its influence on their performance. The study is the first examining physiological synchrony among medical residents and emphasizes the need to integrate emotion regulation education into medical curriculums. By addressing emotions, medical education can help enhance the well-being of practitioners, reduce burnout, mental health disorders, and mitigate suicide rates.

Keywords: physiological synchrony, medical education, electrodermal activity, recurrence analysis, MdRQA.

Word count:209 words.

Introduction and Background Literature

Medical training is cognitively, physically, and emotionally demanding. It requires years of training with a progressively increasing workload and responsibilities, followed by a lifelong engagement with learning. Trainees are exposed to a range of emotionally intense incidents that can be either positive or negative (i.e. positive: role models exhibiting compassion, empathy, etc.; negative: patient suffering, death, violence, etc.) (2). The nature of this training process has the potential to evoke a wider array of and more intense emotions when compared with other educational fields. Medical trainees must develop competencies and skills that will be applied in high-stake situations, closely tied to professional credentialing and patient outcomes.

Emergencies pose greater complexity due to the heightened demands they place on trainees, requiring the mastery of simultaneous cognitive, affective, and metacognitive (CAM) processes needed to work in a team to successfully care for the patient(4, 5, 7, 21, 65-67). The urgency and high-stakes nature of emergencies amplify the challenges faced by medical professionals, requiring them to manage intense emotions(3, 68) while simultaneously making rapid decisions and coordinating actions seamlessly in a dynamic and often unpredictable environment. Under this perspective, these CAM processes have the potential to improve or hamper performance. Hence, medical professionals and trainees must learn to regulate their thoughts, emotions, and behaviors, due to the potentially detrimental effects that poor self-regulation may have on patients' outcomes (15, 26, 29). In our context, regulation refers to the ability to manage and control one's emotional and cognitive states. It involves the conscious or unconscious processes and strategies that an individual uses to influence and modulate their emotional experiences and thought patterns.

Additionally, to understand and regulate emotions, it is necessary to measure them. Electrodermal activity (EDA) is a signal that reflects the physiological component of the emotional response due to activation of the autonomic nervous system which cannot be consciously modulated (69). This psychophysiological signal is broadly used in research to establish the link between an individual's experienced emotional states, and the physiological responses in their body (31, 32, 44). Nonetheless, EDA is only informative on an individual level, limiting the understanding of physiological responses within teamwork dynamics.

Over the last decade, physiological synchrony (PS), defined as the spontaneous similarities in individuals' physiological responses over time, has been gaining traction in social-psychological research as it has been observed in different social interactions(35, 48, 49, 51, 53), and has been linked to group cohesion, learning quality, and performance (39, 50). While a few studies have explored PS in educational settings, none have done so to date in medical education settings, despite the importance of cohesion and performance in medical teams. Thus, our study aims to provide further insight regarding shared emotional arousal within medical teams and its relationship with performance.

Emotions in Medical Education

Medical education combines the simultaneous acquisition of knowledge and the development of technical skills with the complex intricacies of human emotions(2, 3). Unlike other educational disciplines, medical training immerses trainees and healthcare professionals into intense emotional experiences, within situations where the stakes are extraordinarily high. For example, during a simulation in which a pregnant woman presents with a cardiac arrhythmia and consequent cardiac arrest, the residents from different specialties, obstetrics and gynecology and anesthesiology, must act promptly and skillfully to treat both, the mom, and the baby. While the anesthesiology team is leading the resuscitation efforts, the obstetrics team must perform an urgent C-section to prevent the fetus's death or long-term neurological consequences due to brain hypoxia. The actions of the medical teams will determine the prognosis of the mom and the baby and will also determine if both survive. This and other situations such as major trauma cases, organ transplantation, and complex surgery, in which the consequences can significantly impact patients' lives or even their survival, are some examples that highlight the intense emotional nature and high-stakes critical decision-making that medical practitioners face on a regular basis.

The ability to feel and effectively regulate these emotions becomes crucial in ensuring both the personal well-being of medical learners and practitioners and the provision of optimal care for patients, rendering medical education a distinct niche in which being aware of one's own and others' emotions and being able to manage them is crucial. Across the literature, the effects of stress as a response to intense situations (e.g. the death of a patient, breaking bad news, overwork, etc.) on medical performance have been studied, linking the inability to manage stress to impaired performance and poor patient care and outcomes (9, 11, 14, 65, 70). Additionally, besides the detrimental effects of stress on performance, it has been reported that stress also affects trainees' learning and skill acquisition, since stress has been found to impair memory retrieval, working memory and attention(5-8, 71-73). Moreover, the cumulative effect of stress has been linked to psychological distress and mental health disorders (9-14).

Research has shown that the highly stressful nature of acute settings, increases medical errors and adverse events due to communication difficulties, diagnostic uncertainty, case novelty, and frequency of distractions unique to these contexts (4, 7, 74). Additionally, while the prevalence of stress in medical education has been established, little research has been done to examine the impact of acutely stressful events on clinical performance within simulation contexts.

Crisis Resource Management (CRM) training programs have been developed to promote dynamic decision-making, interpersonal skills, and team management within various crisis environments, including medical emergency training (24). The implementation of CRM training within high-fidelity medical simulation environments allows trainees to gain experience and learn from errors without harming patients, while also developing team-based competencies critical for effective teamwork, a key skill for healthcare professionals working in multidisciplinary teams (26). These high-fidelity simulation scenarios allow an immersion of the trainees into complex medical situations without risking the patient's safety. The manikins emulate physiological functions such as breathing and cardiac sounds, blinking, and their vital signs can be monitored in real time, which can be adjusted by the facilitators accordingly to the evolution of the clinical case and in response to the interventions carried out by the trainees.

These qualities, in addition to an unpredictable evolution and outcome of the clinical case, since the scenarios will evolve depending on the actions and interventions of the trainees, constitute a quasi-naturalistic approach. However, there is a gap in research regarding the nature of the emotions that arise under these circumstances, and their role in learning and team performance within these trainings.

To approach this gap, we used the Emotion Regulation in Achievement Situations (ERAS) (29) model as the primary theoretical framework for our study. This model seeks to explain how emotions are generated and regulated within the individual and team-based achievement situations. Emotional arousal, a component of emotions, can be used to explore the physiological responses of the trainees triggered by emotionally stressful situations.

Emotion Expression and Psychophysiological Signals

To understand others' emotional states, we often rely on the behavioral aspect of emotional expression. However, cultural norms impose display rules that require us to conceal our emotional expressions accordingly (75-77). Nevertheless, it is important to note that physiological responses associated with emotional activation cannot be consciously controlled. These responses provide insights into the level of autonomic nervous system (ANS) activation, involving both the excitatory sympathetic (SNS) and inhibitory parasympathetic (PNS) branches. For instance, the SNS, also known as "fight of flight" response, is activated during stressful of threatening situations. It will rapidly prepare the body for action, by triggering the release of stress hormones like adrenaline and cortisol. These hormones will cause responses all over the body with the intention of enhancing alertness, focus, and physical readiness to respond to the perceived threat. This can be observed in responses such as increased sweating to regulate body temperature, faster heart rate, dilated pupils, increase of blood flow to big muscular groups, and decrease of "non-vital" functions, such as digestion. On the other hand, the PNS, known as the "rest and digest" response, predominates during calm and non-threatening situations. It promotes relaxation and recovery and restoration functions of the body. Accordingly, it facilitates digestion, salivation, supports bowel and bladder functions, restful sleep, overall healing, and immune system responses. This can be observed in a slower heart rate and constricted pupils. The permanent interplay of these two branches allows the body to adapt to diverse stressors and maintain physiological balance. Because of these characteristics, psychophysiological signal measurement has been widely used in research to explore the connection between individuals' emotional and cognitive states and their physiological responses.

Electrodermal activity (EDA) is one of the most extensively studied psychophysiological signals. It refers to the variations in the electrical properties of the skin secondary to the "emotional" sweating produced by the eccrine glands, providing a reliable measure of sympathetic arousal without interference from parasympathetic activity. EDA has been widely linked to autonomic emotional processes, making it a valuable index for assessing emotional processing(33, 34, 43, 78). These signals can be measured within groups, enabling researchers to examine the physiological interpersonal dynamics among team members.

Physiological Synchrony and Team Performance

In recent years, there has been a growing interest in studying physiological synchrony (PS) in psychological research. PS refers to the similarities in physiological processes among individuals over time and provides insights into the physiological interpersonal interactions between two or more people. Various populations have been investigated in the literature to understand PS, including mother-child(48) and therapist-client dyads(49), as well as different types of groups like friends, dancers, musicians, and students (17, 18, 36, 38, 54). These studies have explored diverse patterns, domains, and analysis techniques related to PS and it has been found to be associated with cohesion, collaboration quality, and overall performance(19, 37, 38, 53).

To date, no studies have directly examined PS among medical trainees undergoing simulated training, further underscoring the need to investigate this crucial aspect of the educational experience. As PS reflects the coordination of physiological responses between individuals, it can be an indicator of effective communication, teamwork, and social cohesion among medical trainees. Likewise, it could potentially inform about disrupted team dynamics, performance, and overall learning outcomes. Therefore, our research aims to fill this gap by using EDA and a multivariate recurrence quantification analysis to assess and explore the presence and implications of PS in the context of medical training. Understanding the factors that influence PS in medical trainees can potentially provide insights into the effectiveness of simulated training and their impact on team dynamics. It could also inform the further development of interventions or training strategies aiming at enhancing PS to improve teamwork, cohesion, and overall performance among medical trainees.

Objectives and Research Questions

The primary aim of this study was to determine whether PS, as an index of shared emotional arousal, could be detected among team members training under quasi-naturalistic settings. Furthermore, this study sought to establish whether the presence of PS among team members can be a predictor of the team's performance. To achieve these objectives, the following research questions were formulated, and tested in two different analyses to account for PS at the full-team level and dyadic (pairs of team members) level.

Analysis 1: Team Level

Research Question 1. Can PS be detected before or during a CRM training scenario? We hypothesized that PS could be found among medical residents during a CRM simulated training based on prior literature where PS was detected in other settings and among other participants. Based on previous reports of PS being found before the actual experiments (19), we hypothesized that PS could be found among medical residents before the CRM scenarios, however, in a lesser degree than during the scenarios.

Research Question 2. Is the PS level before or during the simulation scenarios associated with the overall performance of the team? We predicted that the level of PS positively correlates with the performance of the team based on previous reports of this positive association (19, 38, 39).

Analysis 2: Dyadic Level

Research Question 3. If PS is detected in dyads, is it associated with the team's overall performance? We predicted that a positive correlation could be found between dyads' PS levels and team performance, based on previous literature reports of PS associated with performance (17, 36, 38, 39, 63, 64).

Materials and Methods

Participants

Medical residents (*N=29)* belonging to different residency programs (14 in Internal Medicine, nine in Emergency Medicine, three in Critical Care, and three in Anesthesiology) from a North American university participated in this study. Participants had a mean age of 28.42 years (SD=3.15), 55.2% were female, and 24.1% self-identified as Caucasian (other ethnicities included Aboriginal, Arab, African descent, Asian, and others) (Table 1).

—insert Table 1 here—

Study Design

This was an observational study. We collected data from the medical residents while they took part in one of nine Crisis Resource Management (CRM) simulated training sessions from March 2022 to January 2023 at a North American Hospital-affiliated University Simulation

Centre. The residents were divided into ten groups (seven groups of three residents, and two groups of four residents) and each group had an appointed leader.

There were no specific roles preassigned to the participants before the simulations, other than the leader. During the simulation, one of the objectives of the CRM training for the appointed leader was to use the resources at hand, including their team. Thus, it was expected from the leader to assign tasks to their team members throughout the simulated scenario. These tasks were different actions including gathering information from the patient or the patient's relatives, reviewing the chart, examining the patient, performing procedures on the patient (e.g. orotracheal intubation, defibrillation), etc. The research team classified the supporting roles (other roles than leaders) as *Examiner*, being the participant asked to perform physical examination or any procedure on the patient, and as *Assistant*, being the participant performing other tasks not directly related to the patient, such as gathering information, reviewing the chart, or assisting procedures.

For the analyses on the dyadic level, the participants within each group were divided into dyads. For instance, in a team with three members, one leader (L), one examiner (E), and one assistant (A), the possible dyads would be three: L-E, L-A, and E-A. Additionally, in a team with four team members, one leader (L), one examiner (E), assistant one (A1) and assistant two (A2), the possible dyads would be six: L-E, L-A1, L-A2, E-A1, E-A2, and A1-A2.

Every data collection session consisted of a brief CRM training offered to the residents by the faculty facilitators. The training consisted of a lecture about the CRM concept applied to medical scenarios, the five major principles (leadership, problem-solving, situational awareness, resource utilization, and communication), the principles' performance standards, the application of the principles in simulated code blue or deteriorating patient cases, and lastly, how to apply these principles in real-life situations. Next, the facilitators would explain the organization of the simulation scenarios, and the debriefing sessions, focusing on the leadership role. Finally, a member of our team explained the research study and gave the consent form to the residents. However, the principles evaluated during the simulations observed by the research team were leadership and communication. Once the residents were ready to enter the simulation room, they were asked to fill out a pre-simulation survey(43). Then, the Empatica E4 wristbands were placed on residents' wrists to capture their EDA signals, aiming to capture a pre-simulation window as a "baseline" reference to compare with the participant's EDA levels during the simulation windows. Next, the participants underwent the scenario, which was audio and video recorded. Scenarios lasted from 10 to 20 minutes. After the simulation, residents went to the debriefing session in which they filled out a post-simulation survey, and then proceeded to discuss about the learning objectives with the facilitator.

The CRM simulation training was part of residents' standard medical education. Accordingly, we had no control over the scheduling of the scenarios, selection of the participants, size of the groups, content, or duration of the simulations. Additionally, all the participants in our sample participated only once on the scenarios and they did not have repeated exposure to the training, and all teams performed only one scenario. All participants consented to their inclusion on our study, and our research protocol was approved by the IRB.

CRM Simulation Training

The CRM simulation training sessions consisted of nine high-fidelity medical simulated scenarios, employing programmable manikins as patients, which can mimic physiological activity (i.e. breath sounds, heart sounds, blinking, etc.) and interact with the residents through speakers controlled by simulation educators. CRM training scenarios are designed to allow residents to be exposed to and practice managing complex medical situations in a controlled and safe environment. The CRM learning goals for the resident appointed as leader of the team are to effectively lead the team through the complex clinical cases; to demonstrate effective communication skills by using closed-loop communication and listening to team input throughout the case; and to maintain a global perspective whilst making use of all the human and material resources on hand.

The medical learning objectives varied across simulated scenarios, but the overall goals were to be able to demonstrate a systematic approach to the assessment of the medical problem, to be able to promptly recognize the clinical challenges, and to treat them, hence, varying the content of the simulated scenarios would not affect the generalization of the CRM skills across medical scenarios (4). All the simulations were audio and video recorded for synchronization with the participants' physiological data, to have a qualitative description of each scenario to contextualize the physiological signals, and lastly, to code the performance of the participants. (See Appendix A in the supplemental material for a description of the scenarios).

Measures

Ottawa Global Rating Scale (GRS): This scale is employed to assess performance in crisis resource management skills. The Ottawa GRS is divided into five categories of CRM skills (problem solving, situational awareness, leadership, resource utilization, and communication). Each category is measured on a seven-point anchored ordinal scale with a description of every point to avoid personal bias. A score of one corresponds to the performance of a novice. A score of three corresponds to the performance of a novice with some CRM and resuscitation experience. A score of five corresponds to the performance of a physician with sufficient CRM and resuscitation experience to manage critical events competently, and lastly, a score of seven corresponds to the performance of an experienced physician in CRM and resuscitation (See Appendix B on supplemental material).

Construct validity from the perspective of content validity, response process, internal structure, and relationship to the variable of training, has been established for the Ottawa GRS (25). Accordingly, given that the learning objectives for the CRM simulated training were focused on the leadership and communication skills of the residents appointed as leaders, the Ottawa GRS was adapted by the research team by eliminating the categories outside of the scope of the simulation training (overall, problem solving, situational awareness, and resource utilization). This abbreviated version of the Ottawa GRS, referred to henceforth as CRM score (See Appendix C), was used across all simulated scenarios as CRM skills required to manage critically ill patients are expected to be generalizable across medical emergency cases, and not influenced by differences in residents' medical knowledge (e.g. year of residency) or program.

The CRM training was intended to reinforce the CRM leadership skill of the residents, thus, every team had different scenarios during the same day, allowing all the team members to play the role of leader. Since the performance of all team members depended on the leader's instructions and task distribution, the team's overall performance was dependent on the leader's performance. Hence, the research team decided to assign the leader's CRM performance score as a proxy performance measure for the entire team. This approach provided an assessment metric for the team's performance, acknowledging the influence of leadership on overall outcomes. It is important to note that the research team selected only one simulation per team, guaranteeing a sample of unique participants, meaning that none of the participants of the sample was repeated or repeated scenarios.

Every category and item on the modified CRM score were assessed by two experienced Emergency Medicine physicians, members of the research team (L.P.M. and O.N). In the first iteration, both physicians scored each video individually, focusing on the team leader's performance, guided by learning objectives of each scenario. After the first iteration, both raters reviewed the videos and their ratings, and negotiated the differences in scores. Cohen's Kappa was 0.77 before negotiation, representing moderate to strong agreement with perfect agreement reached after deliberation. Once the scoring was completed, all the item scores in every category of both *Leadership* and *Communication* were averaged to get one global CRM score.

Collection and Pre-Processing of the Physiological Data

We collected participants' electrodermal activity (EDA), using Empatica E4 wristbands(43). Participants wore the wristband before and during the simulation scenarios. Empatica E4 wristband provides four data points per second (sampling rate: 4 Hz) measured in micro-Siemens (uS). All the EDA recordings were visually inspected in the Empatica platform to explore the integrity of the signals, identify artifacts or data loss. After inspection, EDA recordings were synchronized with the times in the audiovisual recordings. Once the simulation window was defined, a three-minute window starting immediately before the simulation scenario was extracted and used as the baseline state of each participant (19). Finally, all the raw data was transformed into z-scores, using RStudio (version 2022.12.0+353, packages *tidyverse, ggplot2,* and *stats4*), then preprocessed using the Ledalab function (version V3.4.9) from MATLAB (version R2023a) by applying a *Butterworth* low-pass filter (0.03) to attenuate high-frequency noise, and finally, manually removing artifacts using the linear interpolation method (36, 45, 56, 79, 80).

To examine the presence of PS, we used the Multidimensional Recurrence Quantification Analysis (MdRQA) method, which is an extension of univariate recurrence quantification analysis (RQA)(81, 82), which measures the degree of synchrony between two or more time series. To perform recurrence analysis, the time-series data are transformed into a phase space using the method of time-delayed embedding (83). The time series are then plotted against themselves with a time lag determined by a delay parameter, and with a dimension parameter that determines the number of times the data points are plotted against themselves. It is particularly helpful when dealing with complex and stochastic signals like EDA due to its robustness to non-normally distributed data and outliers. For a practical introduction to the process of deriving the parameters, see (59).

MdRQA is particularly helpful for analyzing collaborative work, since it allows the analysis of multiple EDA signals simultaneously, where individuals' physiological signals interact and influence each other. The more recurrence we observe in a system, the more we can say that the system demonstrates a particular behavior. MdRQA produces various output measures that explore various aspects of PS. However, for the purposes of this study, we focused on the recurrence rate (%REC) outcome measure, since it allows one to assess the proportion of recurrent points in the phase space, indicating the presence of synchrony. While other output measures capture system dynamics, our study's main objective was to determine the presence of physiological synchrony rather than explore finer characteristics. Thus, focusing on %REC aligns with our research goals (59, 60).

We conducted the analysis in RStudio (version 2022.12.0+353, packages *crqa, entropy, nonlinearTseries, plot3D, SDMTools, tserieschaos, matrix)* as per Wallot et al. guidelines (See (59, 60)). As stated in the objectives section, we aimed to capture both, teams' PS levels, and dyads' PS levels (details regarding the distribution of the dyads within teams can be found in the Supplemental material). To conduct this analysis, we applied the following parameters: 1) Groups: *emb:* 1, *del*=21, *rad*=0.2, *norm:* Euclidean; 2) Dyads: *emb:* 2, *del*=21, *rad*=0.2, *norm:* Euclidean. Additionally, the *radius (rad)* parameter was defined running iterations of the MdRQA with different threshold values until obtaining %REC outputs ranging from 5 to 20%, as suggested for stochastic systems, and the same value was applied throughout all the data analysis. This was done to procure the comparability of the MdRQA results across data sets (59)

Finally, to answer the RQ1, we generated surrogate data sets to compare against real data sets. The surrogate data sets were false data matrices created by randomizing the EDA z-scored values of each participant within a group. Using the MdRQA function with the same parameters as the real data sets, we obtained surrogate %REC values for both the pre-simulation and simulation windows. This process was applied to all teams and dyads within teams. These surrogate data sets served as reference values to assess synchrony levels in the real data sets, as they were expected to lack significant synchrony or %REC due to their randomized nature (cf. (84)).

Statistical Analysis

Data were analyzed using IBM SPSS 29. Normality was assessed with the *Shapiro Wilk*'s test, and some of the variables were not normally distributed. Significance was defined at the $p < 0.05$ level. For analysis 2, in a dyadic level, we conducted multilevel modeling (MLM) using STATA 17 to account for the nesting of the dyads within teams, and significance was defined at the $p < 0.05$ level. A description of the study variables' definitions and their descriptive statistics can be found in Table 2.

—insert Table 2 here—

Using *GPower* 3.1, we calculated the number of groups needed to meet statistical power. A retrospective power analysis indicated that a sample size of 9 groups**,** with an effect size of 0.80, an error probability of 0.05, 1 tested predictor and 1 total predictor, produced a nominal power of 0.70. Same calculations were computed at a dyadic level, and a retrospective power analysis indicated that a sample size of 29 participants, with 33 dyads, a medium effect size of 0.25, an error probability of 0.05, 1 tested predictor and 2 total predictors, produced a nominal power of 0.74. Results indicate that this sample is sufficiently powered to meet statistical assumptions.

(Refer to Supplemental Material on Appendix B to see %REC values on team level, and to Appendix C to see %REC values on dyadic level.)

Results

Analysis 1. Group Level

Research Question 1: Is there PS before or during the simulation scenarios?

After running the MdRQA, the presence of PS was found across all teams in both, pre-simulation, and simulation windows. Therefore, to determine if PS levels were significant, we conducted a Wilcoxon signed-ranked test comparing the %REC levels of the pre-simulation and simulation windows, between the surrogate data sets of each team, and each team's real data sets (Table 3).

—insert Table 3 here—

The Wilcoxon signed-rank test result of the pre-simulation window analysis revealed that there is a statistically significant difference between surrogate %REC and real data %REC

PreSim values of all teams, with the real teams exhibiting higher %REC than surrogate data. (Wilcoxon Surrogate %REC and real %REC= T = -2.66, p .008.)

Likewise, the Wilcoxon signed-rank test result of the simulation window analysis revealed that there is a statistically significant difference between surrogate and real data %REC Sim values of all teams, with the real teams exhibiting higher %REC than surrogate data. (Wilcoxon Surrogate %REC and real %REC= T = -2.66, p .008.) Hence, we can conclude that there is physiological synchrony among team members before and during the simulation scenarios, with higher levels during the simulation window.

Research Question 2. Does PS correlate with the overall performance of the team?

To answer this question, we ran Kendall's tau correlation to determine the relationship between %REC levels during PreSim and Sim windows and the CRM scores. We found a statistically significant, moderate, positive correlation between During Sim real data %REC and CRM score. (τ_b = .535, p = .046). We conducted assumption tests to determine if a regression could be done, however, four of the assumptions to conduct regressions were not met, thus no regressions were conducted (See Table 4).

—insert Table 4 here—

Analysis 2. Dyadic Level

Research Question 3. If PS is detected in dyads, does it correlate with the teams' overall performance? To answer this question, accounting for the presence of nesting of the dyads within the teams in our sample, we fit a multilevel model to investigate the effect of the dyads' %REC during presimulation and simulation windows, and their CRM Scores (Figure 1). The model consisted of two levels, with dyads nested within teams.

—insert Figure 1 here—

The model showed that the dyads' %REC during simulation window was a positive predictor of performance measured by CRM Scores (B=0.073, p=0.032), indicating that higher physiological synchrony levels during the CRM training were associated with higher CRM scores or performance (See Table 5).

—Insert Table 5 here—

To gain a deeper understanding of the PS levels among teams and dyads within teams in relation to their performance assessed by CRM scores, readers can refer to Figure 2. This visual depiction offers an organized representation of the data, illustrating the varying levels of PS based on the roles played by participants during the simulations. By examining this figure, the reader can have a better understanding of our results and the correlations between synchrony levels and performance outcomes.

—insert Figure 2 here—

Discussion

This study aimed to investigate PS among medical residents during CRM simulated training and its potential correlation with team performance. We used EDA as a measure of sympathetic activity and computed MdRQA function to explore the presence of PS among team members. Teams' performance was assessed indirectly by using the CRM score scale, which assigned scores based on the leadership and communication skills exhibited by the teams' leader during the training session.

The first key finding of this study concerning the successful application of the MdRQA technique to medical education in a quasi-naturalistic approach is the empirical evidence of PS among medical residents during CRM training. Our results address a notable gap in the existing literature and demonstrate the presence of PS both before and during the CRM scenarios, indicating that medical residents undergoing CRM training exhibit spontaneous similarities in the pattern of their physiological responses. This key finding serves as a gateway for future research, enabling the application of other recurrence-based analyses to examine synchronization properties, types of synchrony and changes in synchrony as a function of experimental manipulations. Moreover, using MdRQA derived analyses to examine PS within teams, such as cross-recurrence quantification analysis (CRQA) and diagonal cross-recurrence profile (DCRP), which focus on bivariate dynamics like the ones present in dyads, could shed light on co-regulated (DCRP: leader-follower interactions) and shared-regulated (CRQA: interaction between peers others than leaders) learning mechanisms (59).

The second key finding of this study is that significant correlations were observed between performance scores and PS at the group level, while PS at the dyadic level emerged as a predictor of performance scores. This echoes prior research associating PS positively with performance in various domains. Although some prior studies in education have reported inconsistent results, linking PS to relationship quality, monitoring activities, and perceived task difficulty during learning activities rather than performance itself (39, 61, 85, 86), our findings underscore the potential of utilizing PS as a predictive tool for performance in medical education and CRM training. We believe that our finding of PS associated with performance can be attributed to the high-stakes nature of the scenarios involved, which encompassed complex medical cases. This aligns with the ERAS model, since individuals' emotional and physiological responses are closely linked to the level of stakes of importance they attribute to a given situation(16).

This unique quality of our study sets it apart from previous research on PS and performance within educational contexts. Unlike previous studies primarily focusing on students of other educational fields with lower stakes, the high-stakes nature of medical scenarios triggers heightened physiological arousal among team members, potentially leading to increased synchronization. The latter can facilitate efficient communication, coordination, and shared understanding among team members, as seen during the simulations of the groups with better performance scores.

Additionally, as previously mentioned, the overall performance of the teams depended on the leader's performance. This is relevant since, a leader who is able to remain calm, who maintains a global perspective anticipating who crisis early on, who delegates tasks strategically, set task priority, is open for suggestions, and ask for help when needed encouraging input from team members(24), can definitely foster a positive team environment and dynamic, enhancing the PS within the team. This synchronization may be secondary to the leader's ability to effectively manage the high-stakes environment, thereby influencing team members' physiological responses, highlighting the pivotal role of the leader on the overall team performance.

Importantly, our findings provide a compelling rationale for the integration of stress management training into medical education, as also suggested by previous research (2, 66, 70, 71, 74, 87, 88). The incorporation of emotion regulation training as part of medical curriculums would enhance performance by equipping medical residents with effective emotion regulation strategies, and by attenuating the negative effects of stress on residents' learning, performance, and overall well-being, both in the short and long term.

Limitations and Future Directions

It is important to acknowledge the limitations of our study. First, a larger sample size would increase the confidence in our findings. Although the study breaks new ground, it warrants a replication with a larger sample size and, ideally, a more homogeneous design/selection of groups (e.g. Same scenario across all teams, same experience level, etc.).

Moreover, the impact of different simulation scenarios on team coordination and its relationship to performance outcomes is still largely unknown. Similarly, having varying group sizes alone can modify the interaction potential among team members, contributing to higher variability of EDA measures, in our case, without being an indicator of a looser coordination within the group. Hence, besides increasing sample size, there is also a need to specifically recruit more teams with the same number of people that perform in the same settings in order to draw general conclusions, and additionally, to assess what might make certain situations special regarding the role of physiological synchrony in team performance (i.e. influence of leadership styles, roles performed during the simulation, etc.).

Also, although the CRM skills are validated as independent from knowledge level and medical experience, a bigger sample size would allow us to examine with more detail if there are differences between trainees from different specialties and PGYs. The sample size at the group level limited our ability to run regression analyses, but the positive correlation between PS level and team performance is still a meaningful contribution. Nonetheless, small sample sizes are a common limitation in studies involving highly specialized populations like medical residents, who have complex schedules. Additionally, our observational design limited our recruitment efforts to only the residents who were required to undergo CRM training as part of their curriculum and learning objectives. We are continuing data collection from this population to bring more participants into the analysis.

Second, the CRM training design and learning objectives of the simulations restricted the participants' performance measure to the leaders' performance. CRM skills constitute one measure of performance within crisis situations; however, future research should expand on additional CanMEDS competencies, and procedural skills, including measures of performance for all team members. Additionally, it is important for future research to include the examination of emotion regulation (ER) strategies alongside physiological synchrony (16, 29). By collecting additional data, we would be able to answer different research questions grounded in complementary theoretical models, such as the Framework for Regulation of Emotions in Collaborative Learning (FRECL) (81), which provides a more comprehensive understanding of the complex regulatory dynamics observed in educational collaborations. For instance, the interpersonal components of emotion formation (cognition, motivation, emotions, and behaviors), could help inform how the individual's pre-existing factors and emotional responses (e.g. behaviors and physiological responses), potentially shape the leadership styles and consequently, team synchrony and performance. By including the examination of ER strategies selected and implemented, researchers can gain valuable insights into how trainees within medical teams modulate their emotional responses during critical situations. This approach would further inform the development of emotion regulation training interventions in medical education.

In conclusion, our research findings provide novel insights into the potential of utilizing PS to discern the shared emotional states of teams in medical education and its predictive potential for team performance. Although this study represents the first of its kind to demonstrate the feasibility and potential utility of this approach in this context, the implications of our findings extend beyond medical education, as the application of these methods could have important implications for understanding and enhancing team collaboration and performance in various domains.

Tables and Figures

Table 1. Participants' demographics.

Participants' Demographics

		N	Mean ± SD	Min-Max
Age		**24**	**28.5 ± 3**	**24 - 33**
	Missing	**5**		
Gender	**Female**	**16**		
	Male	**13**		
Ethnicity	**Caucasian**	**7**		
	Minority	**19**		
	Missing	**3**		
Program	**Int. Med.**	**14**		
	ER	**9**		
	Anest.	**3**		
	Critical Care	**3**		
	Residency year	**27**		
PGY	**Missing**	**2**	**2.27 ± 1.62**	**1 - 6**
	Leader	**9**		
Role	**Exam**	**9**		
	Assisting	**11**		

[1]*Ethnicty* was reported by the participants under two categories, *Caucasian,* or *Minority* (*First Nations, Arabic, Black, Chinese, Korean, Japanese, South Asian,* and *others*).

[2]*Program* refers to the specialization program to which the participants belonged. *Int. Med*. is Internal Medicine; *ER* is Emergency Medicine; *Anest*. is Anesthesiology; and *ICU* is Critical Care.

[3]*PGY* stands for postgraduate year, which goes from year 1 to year 6, being PGY1 a junior resident and PGY6 a senior resident.

[4]*Role* refers to the role assigned to the participants during the simulations. *Leader* is the leader; *Exam* refers to the participant assigned to perform the physical examination or any other physical intervention on the patient. *Assisting* refers to the participant assigned to perform other activities than the physical exam or interventions, such as helping with the procedures, making phone calls, and gathering information. The only role preassigned was the Leader. The other two roles were categorized by the research team based on the activities that the team leader assigned the team members to do. Occasionally, some team members temporarily changed roles, from examining to assisting or vice versa, so the role in which the participant spent most of their time during the simulation was the role assigned.

Table 2. Descriptive statistics for all study variables.

Variables' Descriptive Statistics							
	N		Mean	SD	Range	Min	Max
	Valid	Missing					
1. Surrogate PreSim%REC	9	0	0.69	0.25	0.60	0.25	0.85
2. PreSim %REC	9	0	7.23	3.61	10.66	3.60	14.26
3. Surrogate Sim%REC	9	0	0.71	0.27	0.62	0.23	0.85
4. Sim%REC	9	0	6.72	2.66	6.87	3.92	10.79
5. CRM Score	9	0	6.24	0.78	2.36	4.51	6.87

Variables description: 1. *Surrogate PreSim %REC*: Percentage of recurrence resulted from MdRQA of surrogate data sets during the pre-simulation (PreSim) window. 2. *PreSim %REC*: Percentage of recurrence resulted from MdRQA of participants' real data during PreSim window. 3. *Surrogate Sim %REC*: Percentage of recurrence from surrogate data sets of the simulation (Sim) window. 4. *Sim %REC*: Percentage of recurrence from participants' real data of the Sim window. 5. *CRM Score*: Team's performance score on a 7-point Likert scale from 1 to 7 (1= novice, 7= clearly superior).

Table 3. Wilcoxon Signed-Rank test. Difference between surrogate data and real data during PreSim and During-Sim in group level.

Wilcoxon Signed-Rank test				
		N	**Mean Rank**	**Sum of Ranks**
PreSim %REC - Surrogate PreSim %REC[1]	Negative Ranks	0[a]	0.00	0.00
	Positive Ranks	9[b]	5.00	45.00
	Ties	0[c]		
	Total	9		
Sim%REC- Surrogate Sim%REC[2]	Negative Ranks	0[d]	0.00	0.00
	Positive Ranks	9[e]	5.00	45.00
	Ties	0[f]		
	Total	9		

a. Presimulation %REC <PreSim Surrogate %REC
b. Presimulation %REC> PreSim Surrogate %REC
c. Presimulation %REC = PreSim Surrogate %REC
d. During Simulation %REC <During Sim Surrogate %REC
e. During Simulation %REC> During Sim Surrogate %REC
f. During Simulation %REC = During Sim Surrogate %REC

Variables description: [1]*PreSim Surrogate %REC* and *During Sim Surrogate %REC* refers to PreSim and During Sim surrogate data, respectively. [2]*Presimulation %REC* and *During Simulation %REC* refers to PreSim and During simulation real data.

Table 4. Kendall's tau correlations between study variables.

Correlations					
		1	**2**	**3**	**4**
Kendall's tau_b	**1. Surrogate PreSim %REC**	-			
	2. PreSim%REC	-0.056	-		
	3. Surrogate Sim%REC	0.444	0.278	-	
	4. Sim%REC	-0.111	.611*	0.333	-
	5. CRM Score	-0.085	0.310	0.254	.535*
	N	9	9	9	9

*. Correlation is significant at the 0.05 level (2-tailed).

Variables description: 1. *Surrogate PreSim %REC*: Percentage of recurrence resulted from MdRQA of surrogate data sets during the pre-simulation (PreSim) window. 2. *PreSim %REC*: Percentage of recurrence resulted from MdRQA of participants' real data during PreSim window. 3. *Surrogate Sim %REC*: Percentage of recurrence from surrogate data sets of the simulation (Sim) window. 4. *Sim %REC*: Percentage of recurrence from participants' real data of the Sim window. 5. *CRM Score*: Team's performance score on a 7-point Likert scale from 1 to 7 (1= novice, 7= clearly superior).

Table 5. Dyad's PS and Performance: Multilevel Modeling Results.

Dyad's PS and Performance: Multilevel Model

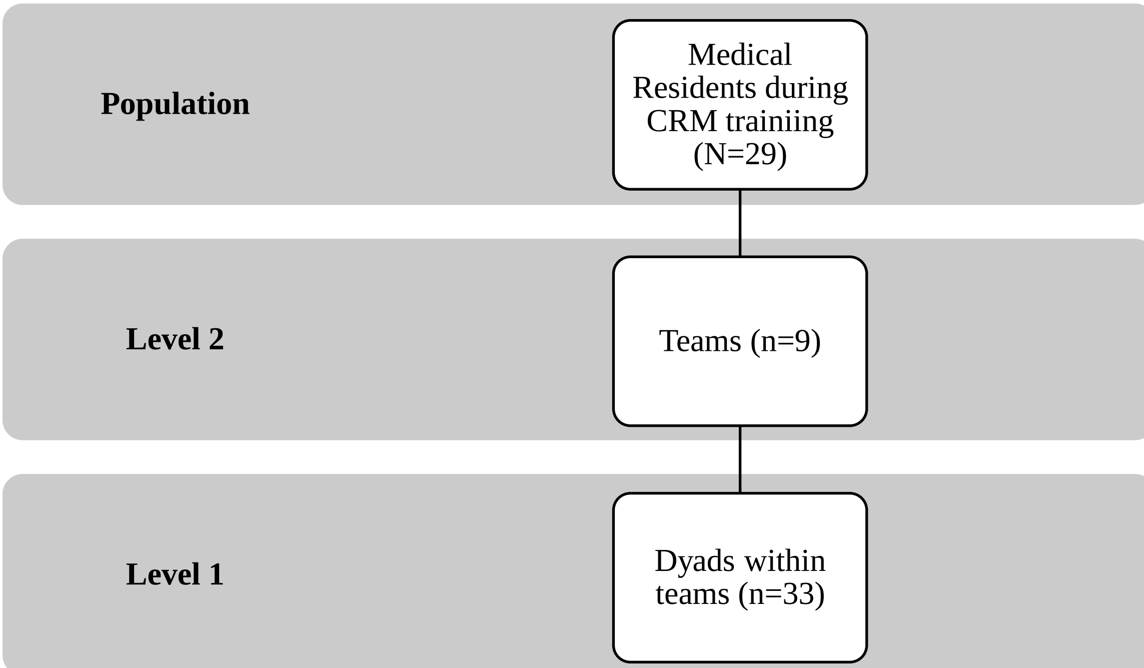
	Dyads' CRM Score[1]					
	Null model (n=33)			*Final model (n=33)*		
	(95% CI)			(95% CI)		
	B	**SE (B)**	***p***	**B**	**SE (B)**	***p***
Intercept	6.83*	0.22	<0.001	5.63*	0.27	<0.001
PreSim %REC[2]				0.05	0.28	0.853
Sim %REC[3]				0.073*	0.034	0.032
Log likelihood		-35.95			-31.36	

Random-effects parameters		**Estimate**	**SE**	**[95 % CI]**	
_all: Independent[4]					
	var (team_id)	3.99^{-11}	9.20^{-08}	0	-
	var (cons)	9.06^{-11}	3.51^{-09}	9.45^{-44}	8.69^{22}
dyad_role: Identity[5]					
	var (cons)	9.99^{-10}	6.07^{-09}	6.77^{-15}	0.0001
	var (Residual)	0.391	0.096	0.24	0.63

*. Effect is significant at the 0.05 level (2-tailed).

[1]Dependant variable: CRM score. [2,3] Independent variables: PreSim %REC and Sim %REC. [4,5] Model levels: Level 1, Dyads by role; Level 2, Teams.

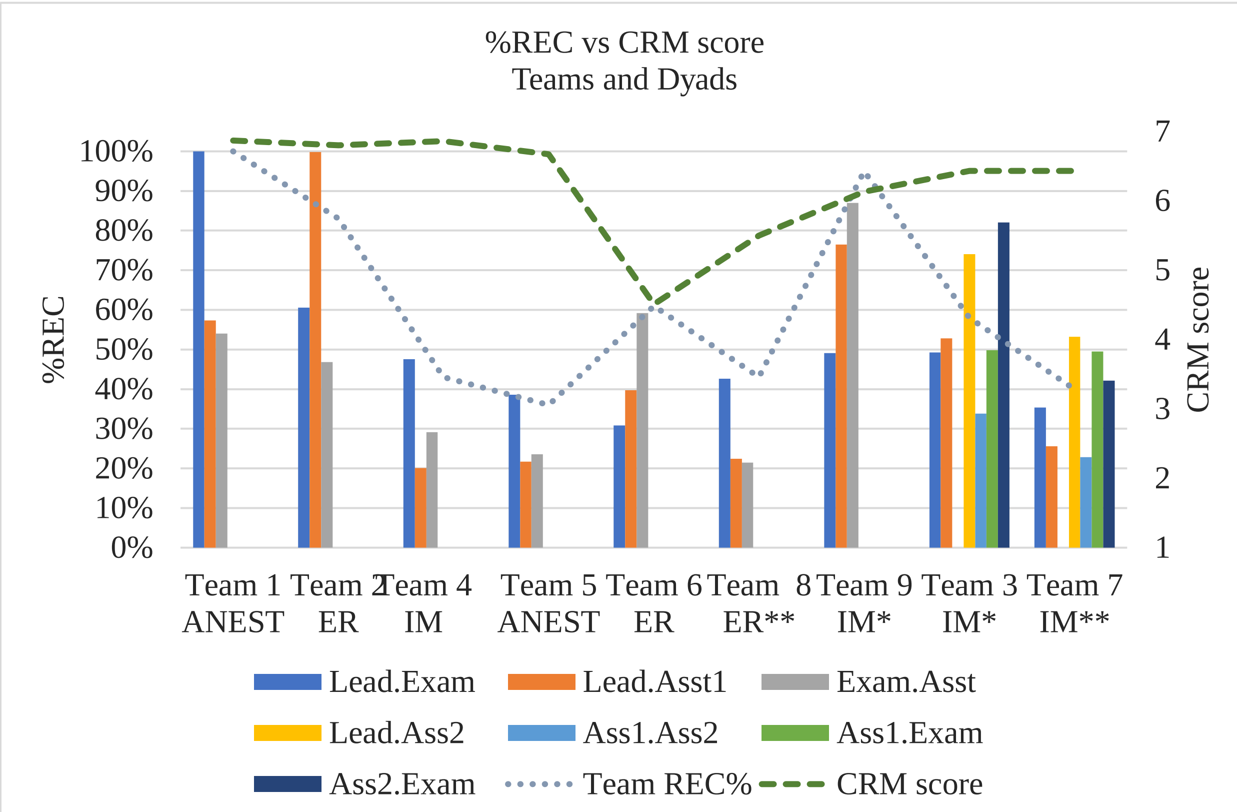
Figure 1. Flowchart diagram for multilevel model structure.



This diagram visually depicts the nested structure of the multilevel model, highlighting the relationships between groups and dyads within the teams of medical residents undergoing CRM training. The model consists of two hierarchical levels. At the first level, we have the dyads nested into the teams and on the groups, and on the second level, the teams.

Figure 2. Diagram of the PS and performance scores on both group, and dyadic levels.

%REC vs CRM score of Teams and Dyads



On the left vertical axis, labeled as *%REC*, is the PS level measured as the recurrence rate on a scale from 0 to 100%, in which higher values represent higher synchrony. The values of %REC were normalized relative to the smallest value of synchrony and then transformed as percentages to facilitate the understanding of the results.

On the right vertical axis, labeled as CRM score, is the performance score calculated with the CRM adapted checklist, on a scale from 1 to 7 in which 1 is the performance score of a novice, and 7 is the performance score of an experienced physician with CRM skills knowledge.

On the horizontal axis, are the ten teams organized by the number of participants within each team. The teams with a curved line, one asterisk, and two asterisks are teams who underwent the same clinical scenarios. All the teams had three participants, except team 3 and team 7, which are depicted on the extreme right of the graph.

Below the team's number, the program of the participants is described: *ANEST* is Anesthesiology; *ER* is Emergency Medicine; *IM* is Internal Medicine. Team 4 also labeled as IM, was composed of PGY 6 residents on the Critical Care fellowship.

The bars represent the dyads within teams, and they are coded by the roles of the participants during the simulation. Four roles were defined by the research team, based on the activities performed by the residents during the simulations: Leader (*Lead)*: the appointed leader of the team and focus of the CRM skills performance score; Examinator (*Exam)*: the participant was commissioned by the leader to perform the physical examination or any procedure on the patient; Assistant 1 and Assistant 2 (*Ass1* and *Ass2*): Participants assigned to other activities such as gathering information, making phone calls, assisting procedures, etc. On teams of three participants, only three dyads were possible: Leader-Examinator (royal blue), Leader-Assistant (orange), and Examinator-Assistant (light gray). On teams of four participants, six dyads were possible: Leader-Examinator (royal blue), Leader-Assistant1 (orange), Leader-Assistant2 (yellow), Assistant1- Assistant2 (light blue), Examinator-Assistant1 (green), and Examinator-Assistant2 (navy blue).

The %REC of the dyads is seen on the color-coded bars as previously explained. The %REC of the teams is represented with the dotted line. The CRM score of the teams is represented with the dashed line. This descriptive graph allows an overall view of the recurrence values of the teams against the dyads, differentiated by their programs and roles during the simulations.

Supplemental Material

Appendix A. Crisis Resource Management (CRM) training scenarios description.

Team	Specialty	Case Description
1	**Anesthesiology**	A hospitalized pregnant woman, treated for high blood pressure during her pregnancy, presents sudden shortness of breath, chest pain, and rapid clinical deterioration. The first team (OBGYN team) responds to the nurse call. The leader must gather information from the patient and nurse. The patient then presents cardiac arrest, so the leader needs to activate the Code Blue protocol, which is the cue for the Anesthesiology team to enter the simulation and lead the resuscitation of the patient, while the OBGYN team performs an urgent C-section simultaneously. Both teams need to work together to maintain, both Mother and fetus alive, and decide further treatment and/or interventions.
2	**Emergency Medicine**	A young female is brought to the Emergency Department (ED) as trauma activation case after being bucked off her horse and presenting head and pelvic trauma. Resident Leader needs to effectively lead the trauma team during the complex scenario delegating tasks, to recognize the need to intubate and the brain herniation, and timely consult the proper specialties for definite management.
3	**Internal Medicine**	Hemodialysis patient, admitted for gastrointestinal bleed, has a witnessed fall in the hospital, and does not feel well since. Patient's potassium is high and besides their hemodialysis catheter, there are not other intravenous lines to deliver treatment. Resident Leader and team need to detect the hyperkalemia (high potassium blood levels) as a medical emergency promptly, start medical treatment, and call the medical teams that can provide a solution to the catheter issue to promptly deliver medications and prevent further clinical deterioration of the patient.
4	**Internal Medicine**	Residents are called to a room to perform CPR on a hospitalized patient. The nursing team has already started the protocol, and the residents need to take over the resuscitation efforts and diagnose the etiology of the cardiac arrest to treat it.
5	**Anesthesiology**	Residents are called to ED to care for a child brought after drowning for several minutes. The team needs to carry the resuscitation, gather information from the patient's relatives, and progress in the treatment sequence to minimize potential negative effects of sustained hypoxia on the patient's brain.

Continuation of Appendix A. Crisis Resource Management (CRM) training scenarios description.

Team	Specialty	Case Description
6	**Emergency Medicine**	An elderly man presents to the ED with palpitations and malaise. The patient had an LVAD (left ventricular assist device) placed within the last month, which makes it complicated to obtain vital signs from the patient. The Resident Leader and team need to find a way to assess the patient's vitals. The patient LVAD line site has infection signs, and electrocardiographic signs of hyperkalemia. The patient progress to cardiac arrest and the team needs to resuscitate the patient and manage the causes of it.
7 **8**	**Internal Medicine** ** **Emergency Medicine** **	**A young pregnant woman admitted for hypertension (high blood pressure) of pregnancy. The team is called because the patient complains of chest pain and shortness of breath and is found to have hypotension (low blood pressure) on exam, and neurological deterioration. The fetus also presents signs of suffering. The patient shows progressive clinical deterioration. The Resident Leader and team need to identify the possible diagnosis and start treatment. They need to be able to progress in the complexity of the treatment sequence for the dyad mother-fetus.
9	**Internal Medicine**	See description for Team 4.

Appendix B. Table of teams' %REC values of surrogate and real data sets, in both, PreSim and Sim windows.

	PreSim Window1		Sim Window2	
Team ID	**Surr%REC[3]**	**%REC[4]**	**Surr%REC[3]**	**%REC[4]**
1	0.80	14.26	0.85	10.79
2	0.81	5.70	0.85	8.98
3	0.26	5.69	0.23	6.29
4	0.85	4.37	0.85	4.64
5	0.82	3.60	0.83	3.92
6	0.79	9.96	0.84	6.62
7	0.25	3.94	0.23	4.36
8	0.82	10.46	0.84	4.61
9	0.81	7.08	0.82	10.28

[1]PreSim Window is the 3 min period immediately before the start of the simulations. [2]Sim Window is the simulation window, which length varied according to the content of the scenario. [3]Surr%REC is the surrogate value of the recurrence rate. [4]%REC is the real recurrence rate value of the team. %REC is the measure accounting for the percentage of recurrence or synchrony during pre-and simulation moments.

Appendix C. Table of dyads' %REC values in both, PreSim and Sim windows.

Team ID	Dyads by Roles5	PreSim Window1		Sim Window2	
		Surr%REC3	%REC4	Surr%REC3	%REC4
1	1 Lead.Exam	0.22	13.47	0.24	10.09
	2 Lead.Asst	0.23	26.26	0.24	17.60
	3 Exam.Asst	0.23	12.24	0.24	9.51
2	1 Lead.Exam	0.25	11.80	0.24	17.56
	2 Lead.Asst	0.24	3.17	0.24	10.65
	3 Exam.Asst	0.23	3.54	0.25	8.25
3	1 Lead.Exam	0.22	6.77	0.23	13.02
	2 Lead.Asst	0.23	4.93	0.24	9.29
	3 Lead.Asst_2	0.24	4.61	0.24	8.67
	4 Asst.Asst_2	0.25	3.96	0.24	5.95
	5 Asst.Exam	0.24	9.33	0.23	14.44
	6 Asst_2.Exam	0.23	4.95	0.23	8.76
4	1 Lead.Exam	0.23	3.85	0.25	8.37
	2 Lead.Asst	0.26	3.69	0.25	3.54
	3 Exam.Asst	0.25	3.96	0.24	5.12
5	1 Lead.Exam	0.24	3.03	0.24	6.79
	2 Lead.Asst	0.24	2.71	0.25	3.81
	3 Exam.Asst	0.24	3.25	0.24	4.14
6	1 Lead.Exam	0.24	11.24	0.24	6.98
	2 Lead.Asst	0.24	7.00	0.24	5.42
	3 Exam.Asst	0.23	9.23	0.23	10.41
7	1 Lead.Exam	0.25	3.53	0.23	4.50
	2 Lead.Asst	0.23	9.49	0.23	9.36
	3 Lead.Asst_2	0.25	4.63	0.24	6.22
	4 Asst.Asst_2	0.23	7.30	0.24	8.71
	5 Asst.Exam	0.26	5.23	0.23	7.42
	6 Asst_2.Exam	0.23	3.11	0.23	4.02

Continuation of Appendix C. Table of dyads' %REC values in both, PreSim and Sim windows.

Team ID	Dyads by Roles	PreSim Window		Sim Window	
		Surr%REC	%REC	Surr%REC	%REC
8	1 Lead.Exam	0.25	9.41	0.24	7.50
	2 Lead.Asst	0.22	12.39	0.24	3.95
	3 Exam.Asst	0.22	9.05	0.24	3.78
9	1 Lead.Exam	0.25	4.64	0.24	8.64
	2 Lead.Asst	0.22	9.92	0.24	13.45
	3 Exam.Asst	0.22	6.92	0.24	15.31

[1]PreSim Window is the 3 min period immediately before the start of the simulations. [2]Sim Window is the simulation window, which length varied according to the content of the scenario. [3]Surr%REC is the surrogate value of the recurrence rate. [4]%REC is the real recurrence rate value of the team. %REC is the measure accounting for the percentage of recurrence or synchrony during pre-and simulation moments. [5]Dyads by roles were based on the four roles or activities performed by the residents during the simulations: Leader (*Lead)*: the appointed leader of the team and focus of the CRM skills performance score; Examinator (*Exam)*: the participant was commissioned by the leader to perform the physical examination or any procedure on the patient; Assistant 1 and Assistant 2 (*Ass1* and *Ass2*): Participants assigned to other activities such as gathering information, making phone calls, assisting procedures, etc.

Chapter 5: Discussion and Conclusion

Our study sought to investigate the presence of PS among medical residents undergoing CRM training and its impact on performance. Our findings are the first of their kind reported in the literature by successfully applying the MdRQA technique to medical education yielding novel evidence of the presence of PS among medical residents undergoing CRM training.

We found the presence of PS both, before and during the CRM scenarios, suggesting that medical residents undergoing CRM training exhibit spontaneous similarities in their physiological responses over time, providing novel evidence that similar patterns of emotional activation occur within this specific population. Our findings align with previous research that showed that performing collaborative tasks often leads to similar physiological responses among collaborators. These findings have been reported in various fields, but specifically in education, it has been found present during shared cognitive and metacognitive processes such as monitoring of learning and group progress, task interest, and engagement with the task (36, 37, 61, 63, 85, 89-91). However, we did not measure shared-regulated learning processes, highlighting the importance of conducting future studies to account for these factors in the dynamics of physiological synchrony.

Furthermore, as one could interpret the PS presence during the simulation was directly related to the participation on the training (86), explaining the PS before the scenarios requires higher inference levels. For instance, Golland et al. (92) reported that mere co-presence could cause emotional transmissions resulting in shared emotional experiences in the absence of direct communication, and they are mediated by autonomic synchronization. We could also argue that arousal during the pre-simulation period could be triggered by the general anticipation to the scenario, due to the high-stakes nature of the latter, even more when it would carry an evaluation of performance and medical knowledge, however, we lack the data to support that inference.

Additionally, we found that some dyads and groups experienced higher levels of synchrony during the pre-simulation period in comparison with the simulation period. Although arguing that this could be explained by participants' familiarity (e.g. friendship, same cohort, etc.), we did not collect this data from the participants, thus, we cannot arrive to conclusions on this regard. It would be useful to incorporate this information in future research since these findings could help inform the impact of interpersonal factors on the mechanisms of emotion generation on achievement situations. We calculated PS levels during the whole scenario, but we did not investigate more granular aspects of this synchronization. We did not observe any patterns in synchrony related to roles acted during the simulation. Nonetheless, looking into the system dynamics by using the recurrence plots could allow the examination of moments of stronger coupling, providing insight into the possible causes of PS (e.g. specific task, perceived task difficulty, shared decision-making, patient clinical deterioration or evolution, etc.)(59).

MdRQA offered a unique insight into medical teams' physiological patterns, allowing us to examine the whole group interaction, and the differences on the dyadic level, evidencing dyads within groups that tend to synchronize their EDA more with each other than when compared with other team members. Furthermore, considering that the way we measured performance of the team as a unit was to assign the leader's performance score to the team as a measure by proxy, we recognize the pivotal role that the leadership style plays into the team's dynamic. Using DCRP analysis would inform how synchrony behaves within dyads with a leader-follower dynamic. Using CRQA analysis would allow us to observe coupling dynamics among team members, and to understand the reasons behind stronger synchrony or even asynchrony of team members (59, 60). Moreover, refining research methods adding other emotion measurements and physiological data streams (i.e. facial expression analysis, heart rate variability, etc.), could help to look further into the emotion generation process, physiological synchrony, and how both affect team performance in medical education(52, 57, 85, 93).

Additionally, we found that performance scores were correlated with PS at the group level and predicted by PS at the dyadic level. We were not able to make predictions on a group level due to unmet statistical assumptions. But despite our small sample size, we had enough statistical power to support our conclusions, and our results on a group level are a meaningful contribution to the field (50). On a dyadic level, with a larger sample, predictive analyses could be run, aligning with the positive correlation on a group level. This emphasizes the importance of replicating our study with larger samples to increase the confidence of our findings. As mentioned before, no patterns emerged that could explain better performance, beyond the synchrony levels. Adding data regarding pre-simulation conditions, such as participation in previous CRM skills training should be included to control for this factor as an influence on performance.

However, what makes our contribution unique is the fact that we used a multivariate method to calculate PS in medical education that allowed us to examine PS using multiple EDA time series simultaneously during CRM simulations, whereas other studies in medical education have analyzed PS of a team by examining the dyads separately using linear regression models (50, 94), providing information about the dyads but missing the complex dynamics of all the team members as a unit. Individual factors could affect synchrony levels on a dyadic versus a group level, causing variations on the strength of the synchrony. This was seen in our results, as some dyads exhibited higher synchrony levels than the whole team together. Again, additional research is necessary to examine in more detail this phenomenon and this also underscores the feasibility of the application of MdRQA analyses into medical education field. One way to promote the use of these methods could be actively including them into current research methodology courses, facilitating the learning of it, and its multiple applications on diverse science fields.

Regarding our second key finding concerning the significance of PS in relation to performance outcomes, it is clear the potential of utilizing PS to predict performance outcomes in the context of medical education and training. Although our findings align with previous research (85), it is important to acknowledge that there are contradicting results in the existing literature concerning the correlation between PS and group performance that can be explained by variations in the methodology used and the characteristics of PS investigated. Furthermore, other studies have found that PS is associated with metacognitive activities but not necessarily with performance (46). Other studies have investigated the relationship of PS, cohesion, and collaboration quality, whereas others have found that in some situations less PS levels are beneficial for performance (17, 19, 35, 40, 45, 86). The differences in these findings could be accounted for by the different methodologies used and the distinct aspects of PS analyzed. Therefore, our study opens the gateway for future research and fills a significant gap in the literature on PS and performance by successfully applying the MdRQA technique into medical education.

This novel evidence of the association between PS and performance within this domain highlights the role of shared emotional activation in affecting performance outcomes. Our results indicate that to enhance performance, attention should be given to emotion regulation strategies, highlighting the importance of incorporating emotion regulation training in medical education.

Future research grounded on holistic models such as the FRECL model (95), which integrates both the generation and regulation of emotions with collaborative learning contexts is necessary to deepen our understanding of complex dynamics such as the ones observed in high-stakes medical scenarios. Examining individual factors and their impact into emotion generation and emotion regulation processes within medical training will provide further understanding of the role that emotions play into the complex dynamics of medical education and medical practice, and how they can whether hinder or enhance performance and patients' outcomes, paving the way for the incorporation of emotion regulation training in medical curriculums as an effort to reduce the negative effects of stress on medical residents' learning, performance, and well-being (66, 70, 71, 88, 96, 97).

Finally, the research findings presented herein offer novel insight into the potential of utilizing physiological synchrony to discern the emotional states of teams within medical education, and its predictive potential of team performance. Notably, this study represents the first of its kind to demonstrate the feasibility and potential utility of this approach in this context. The implications of these findings extend beyond the medical education domain, as the application of these methods could have important implications for understanding and improving team collaboration and performance in a wide range of contexts.

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