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Dimensional causality and hidden drivers in cardiovascular and respiratory time series

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Cardiovascular and pulmonary diseases often arise from disturbances in the interactions among heart rate, blood pressure, and respiratory dynamics. In this study, we analyze parallel recordings of respiratory signals, ECG, and instantaneous blood pressure to uncover the underlying regulatory architecture.

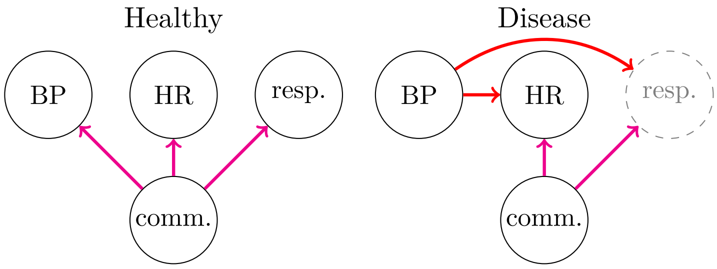
We apply a topological framework based on Takens' embedding theorem to reconstruct the joint state-space dynamics of these signals and to characterize interactions between subsystems using observation-only data. The presence of multiple feedback loops poses a fundamental challenge in complex systems analysis.

First, we introduce a novel method called Dimensional Causality (DC), which uniquely distinguishes all fundamental causal relationships between two subsystems: unidirectional causality, bidirectional interactions, hidden common causes, and independence. DC estimates the intrinsic dimension of the reconstructed state space and applies Bayesian inference to assign probabilities to competing causal structures. In comparative evaluations on simulated systems with known ground truth, DC consistently outperformed state-of-the-art methods, even under optimized conditions [1].

Our goal is to quantify the direction and strength of causal influences between cardiovascular and respiratory signals under resting conditions, both in healthy individuals and in patients with cardiovascular disease, with particular emphasis on hypertension.

We observe that the dimension of the respiratory dynamics changes significantly between the two groups. The dimension of respiration decreases in individuals with disease, and in parallel, the joint dimension of respiration/blood pressure (BP) and respiration/heart rate (HR) also decreases.

In the disease group, these dimensional changes alter the inferred causal relationships from a hidden common cause connecting the subsystems to cardiovascular signals (BP, HR) driving respiration.



In our interpretation, there is a hidden common cause that affects breathing, heart rate (HR), and blood pressure (BP). In the healthy case, all three are affected by other factors or possess their own intrinsic dynamics with degrees of freedom, which leads to the conclusion of a hidden common cause. However, in the diseased group, the other effects influencing blood pressure weaken, or the degrees of freedom in its intrinsic dynamics diminish. As a result, blood pressure becomes synchronized with the hidden common cause, becoming a direct driver of breathing and heart rate. It is also possible that blood pressure itself becomes the driver of both heart rate and respiration, effectively acting as their common cause. The observed decrease in the dimension of respiration requires further investigation.

Finally, we further analyze the joint dimensions to reveal the structure of pairwise hidden common causes or the existence of a higher-order hidden common cause.

Our dimensional approach has the potential to identify early markers of cardiovascular dysfunction, improve diagnostic algorithms for altered autonomic regulation, and deepen our understanding of physiological dynamics.

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[1] Benkő, Zs., Zlatniczki, Á., Stippinger, M., Fabó, D., Sólyom, A., Erőss L., Telcs, A. and Somogyvári, Z. Bayesian inference of causal relations between dynamical systems *Chaos, Solitons & Fractals* **185** (2024), 115142. doi: 10.1016/j.chaos.2024.115142