12-1-2022

Systems Approach Explains Why Low Heart Rate Variability Is Correlated with Depression (and Suicidal Thoughts)

Francisco Zapata
The University of Texas at El Paso, fcozpt@outlook.com

Eric Smith
The University of Texas at El Paso, esmith2@utep.edu

Vladik Kreinovich
The University of Texas at El Paso, vladik@utep.edu

Comments:
Technical Report: UTEP-CS-22-122

Systems Approach Explains Why Low Heart Rate Variability Is Correlated with Depression (and Suicidal Thoughts)

Francisco Zapata, Eric Smith, and Vladik Kreinovich

Abstract Depression is a serious medical problem. If diagnosed early, it can usually be cured, but if left undetected, it can lead to suicidal thoughts and behavior. The early stages of depression are difficult to diagnose. Recently, researchers found a promising approach to such diagnosis – it turns out that depression is correlated with low heart rate variability. In this paper, we show that the general systems approach can explain this empirical relation.

1 Formulation of the Problem

Medical problem. Depression is a serious medical condition. If it is diagnosed early, in most cases, it can be cured. However, early diagnosis is difficult. However, early diagnosis of depression is difficult. As a result, depression become severe and often leads to suicidal thoughts and behavior. As a result, at present, suicide is the second leading cause of death among adolescents. The situation is not improving, is getting worse: the number of suicide attempts have been rising exponentially; see, e.g., [1].

Towards a possible solution. Recent research seems to have found a way towards the early diagnosis of depression: namely, it turns out the depression is correlated with the so-called heart rate variability (HRV); see, e.g., [3, 4, 6]. To explain this result, let us recall what is HRV.

In the first approximation, heart beat looks like a perfectly periodic signal. Our heart rate increases when we perform physical activity or get stressed, it goes down when we calm down or go to sleep, but during short-time periods, when there are no changes in behavior and in emotions, the heart rate seem to be pretty stable. Interestingly (and somewhat unexpectedly), it turns out that even during such stable

Francisco Zapata, Eric Smith, and Vladik Kreinovich
University of Texas at El Paso, El Paso, Texas 79968, USA
e-mail: fcozpt@outlook.com, esmith2@utep.edu, vladik@utep.edu

1-minute intervals, the times between the two consequent heart beats somewhat change. These changes are not easy to detect – even trained medical doctors cannot detect them by listening to the heartbeats. The only way to detect such changes is by using specialized devices.

The existence of this heart rate variability has been known for some time. It has been actively used in cardiology, since it turned out that unusually large heart beat variations may be a signal of the forthcoming arrythmia – a serious condition when the heartbeat becomes irregular, so serious that it can cause death. From the cardiologist viewpoint, large heart rate variations indicate the possibility of a serious disease, while smaller variations – even variations which are much smaller than average – are one of the indications that the heart is functioning normally.

The papers [3, 4, 6] show that while, on the one hand, unusually small heart rate variability means a healthy heart, on the other hand, it indicates a high probability of another type of health problem: beginning depression.

Remaining challenge. An important open question is why there is a correlation between low heart beat variability and depression.

What we do in this paper. In this paper, we show that this correlation can be explained by a simple systems approach.

2 Systems Approach: A Brief Reminder

What a system wants – or what we want from a system. In general, a system has some objective: to reach a certain state, maybe to stay in a current comfortable state, etc. For example:

- an airplane wants to reach its destination,
- the electric grid wants to supply all needed electricity to the customers,
- an economy wants to reach desired GDP growth while keeping unemployment, inflation, and other undesirable phenomena under control.

Ideal case of perfect knowledge. In the ideal case, when we have full information about the world, we can find the corresponding optimal trajectory, i.e., we can determine how all the quantities $x_1, \ldots, x_n$ describing the state of the system should change with time t.

In practice, a system needs to be stable. Real-life situations are more complicated: there are usually many difficult-to-predict disturbances that deviate the system from its planned trajectory. We therefore need to make sure that the system takes care of these unexpected deviations and returns to its desired state. In system theory, this is known as *stability*. For example:

- When an airplane encounters an unexpected thunderstorm straight ahead, it deviates from the original trajectory to avoid this thunderstorm, but then it needs to get back to the original trajectory.

- Similarly, if a storm downs electric lines, disrupting the electricity flow, the electric grid needs to get back to the desired state as soon as possible.

How can we describe the system's reaction to unexpected deviations. If the actual values $X_i(t)$ of the corresponding quantities starts deviating from the desired values $x_i(t)$, i.e., if the difference $d_i(t) \stackrel{\text{def}}{=} X_i(t) - x_i(t)$ becomes different from 0, then we need to change the values of the corresponding quantities, so that at the next moment of time, the system will be closer to the desired value. For example:

- an airplane need to adjust its direction and velocity,
- the electric grid needs to change the amount of electricity going to different hubs and to different customers, etc.

In other words, we need to apply some changes $c = (c_1, \ldots, c_n)$ – depending on the observed deviations $d(t) = (d_1(t), \ldots, d_n(t))$. Then, at the next moment of time $t' = t + \Delta t$, the deviations will take the form

$$d(t + \Delta t) = d(t) - c(d(t)). \tag{1}$$

Possibility of linearization. Deviations $d(t)$ are usually reasonably small: e.g., an airplane may move a few kilometers away from the trajectory of a 10000 km intercontinental flight. Situations when deviations are small are ubiquitous in physics; see, e.g., [2, 5]. In such situations, terms which are quadratic or of higher order with respect to these deviations can be safely ignored: e.g., the square of 1% is 0.01% which is indeed much smaller than 1%. Thus, the usual approach to such situations is to expand the dependence $c(d)$ in Taylor series and to ignore quadratic and higher order terms, i.e., to keep only linear terms in this expansion:

$$c_i(d) = c_{i0} + c_{i1} \cdot d_1 + \ldots + c_{in} \cdot d_n.$$

When all deviations are 0s, there is no need for any corrections, so $c_{i0} = 0$. Thus, the formula (1) takes the following form:

$$d_i(t + \Delta t) = d_i(t) - c_{i1} \cdot d_1(t) - \ldots - c_{in} \cdot d_n(t). \tag{2}$$

Ideal control and real control. In the ideal case, we should take $c_{ii} = 1$ for all i and $c_{ij} = 0$ for all $i \neq j$. In this case, at the next moment of time, the deviation will get to 0.

However, such an exact control is rarely possible:

- First, we usually have only an approximate understanding of the system, so even if we aim from the exact changes, the actual deviation can be somewhat different.
- Second, we may not be able to implement such a change right away:
  - a plane cannot immediately get back since would mean uncomfortable accelerations for passengers,

– an electric grid may take to repair an electric line if it was damaged in a faraway area, etc.

As a result, the actual control is different from the desired one. What are the consequences of this difference?

Let us first consider the 1-D case. To illustrate how the difference between the ideal and the actual control affects the system's behavior let us first consider the simplest 1-D case, i.e., the case when the state of the system is determined by only one quantity x_1.

In this case, the formula (2) takes the form

$$d_1(t + \Delta t) = d_1(t) - c_{11} \cdot d_1(t) = (1 - c_{11}) \cdot d_1(t). \tag{3}$$

So, if no other disturbances appear, at the following moments of time, we have:

$$d_1(t_k \cdot \Delta t) = (1 - c_{11})^k \cdot d_1(t). \tag{4}$$

If c_{11} is close to 1, the original deviation decreases fast. But what if the coefficient c_{11} describing our reaction is different from 1?

- If c_{11} is much larger than 1 – e.g., larger than 2 – then $c_{11} - 1 > 1$ and thus, the absolute value of the deviation increases with time instead of decreasing – and increases exponentially fast:
$$|d_1(t_k \cdot \Delta t)| = |1 - c_{11}|^k \cdot |d_1(t)|. \tag{4}$$
In this case, the system is in immediate danger.
- On the other hand, if c_{11} is much smaller than 1, i.e., close to 0, we practically do not get any decrease, so the original deviation largely stays. As we get more and more outside-caused deviations, the system will move further and further away from the desired trajectory – and the system can also be in danger.

General multi-dimensional case is similar. In general, we have a similar behavior if we use a basis formed by eigenvectors. In this case, in each direction, we have, in effect, the 1-D behavior.

3 How This Can Explain the Empirical Correction

Let us show how the above facts about general systems explain the empirical correlation between heart rate variability and the potential for several depression and suicide thoughts.

Indeed, a human body is constantly affected by different outside (and inside) disturbances. As a reaction, the body changes the values of quantities; for example:

- it changes the body temperature,

- it changes the muscle tension, and
- it changes the heart beat rate.

Some changes are inevitably slower: e.g., it is not possible to change the temperature fast. However, the heart beat rate can be changed right away. The average heart rate variability describes the healthy reaction to these disturbances, corresponding – in the notations of the previous section – to $c_{11} \approx 1$.

If the hear rate variability is much larger than the average, this means that the body's reaction is too strong, $c_{11} \gg 1$. We have already shown that in systems' terms, this overreaction leads to a disaster – this is why high values of heart rate variability may indicate a potential life-threatening heart condition.

On the other hand, if the heart rate variability is much smaller than the average, this means that the body's reaction is too weak. In other words, it means that the body practically does not react to outside phenomena. In clinical terms, this indifference to everything that occurs outside is exactly what is called depression. This explains why empirically low heart rate variability and depression are correlated.

Acknowledgments

This work was supported in part by the National Science Foundation grants 1623190 (A Model of Change for Preparing a New Generation for Professional Practice in Computer Science), and HRD-1834620 and HRD-2034030 (CAHSI Includes), and by the AT&T Fellowship in Information Technology.

It was also supported by the program of the development of the Scientific-Educational Mathematical Center of Volga Federal District No. 075-02-2020-1478, and by a grant from the Hungarian National Research, Development and Innovation Office (NRDI).

References

1. Center for Disease Control, *Web-Based Injury Statistics Query and Reporting System (WISQARS)*, National Center for Injury Prevention and Control, Atlanta, Georgia, 2019.
2. R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Addison Wesley, Boston, Massachusetts, 2005.
3. T. Forkmann, J. Meessen, T. Teismann, S. Sütterlin, S. Gauggel, and V. Mainz, "Resting vagal tone is negatively associated with suicide ideation", *Journal of Affective Disorders*, 2016, Vol. 194, pp. 30–32.
4. D. C. Sheridan, S. Baker, R. Dehart, A. Lin, M. Hansen, L. G. Tereshchenko, N. Le, C. D. Newgard, and B. Nagel, "Heart Rate Variability and its ability to detect worsening suicidality in adolescents: a pilot trial of wearable technology", *Psychiatry Investigations*, 2021, Vol. 18, No. 10, pp. 928–935.
5. K. S. Thorne and R. D. Blandford, *Modern Classical Physics: Optics, Fluids, Plasmas, Elasticity, Relativity, and Statistical Physics*, Princeton University Press, Princeton, New Jersey, 2017.

6. S. T. Wilson, M. Chesin, E. Fertuck, J. Keilp, B. Brodsky, J. J. Mann, C. C. Sönmez, C. Benjamin-Phillips, and B. Stanley, "Heart rate variability and suicidal behavior", *Psychiatry Research*, 2016, Vol. 240, pp. 241–247.