



***2019 NSCA TACTICAL  
ANNUAL TRAINING***

# Conflict of Interest Statement

I currently have, or I have had in the past 2 years an affiliation or financial interest with

the United States Army (NSRDEC/CCDC)

Tufts University CABCS

National Academies of Sciences, Engineering and Medicine

West Virginia University's Rockefeller Neuroscience Institute

around this presentation, including:

- Consulting
- Employment
- Research funding
- Scholarship



*The National  
Academies of*

SCIENCES  
ENGINEERING  
MEDICINE

**WVU** Rockefeller  
Neuroscience Institute

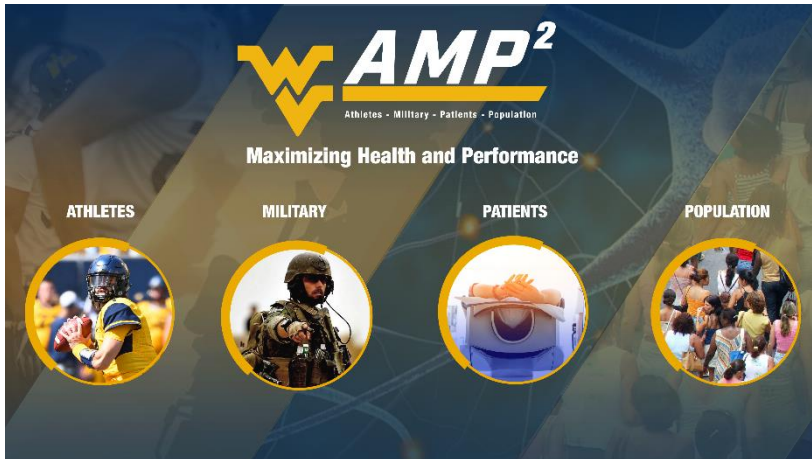
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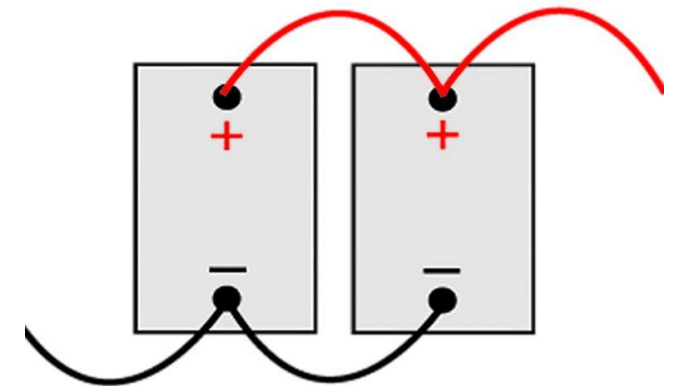
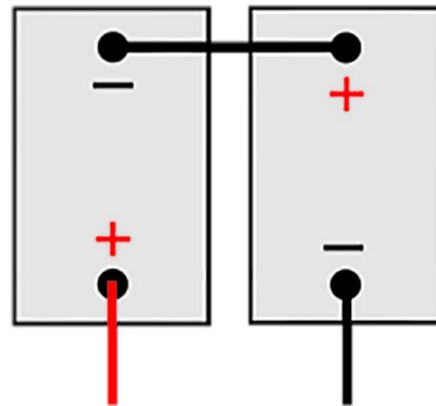
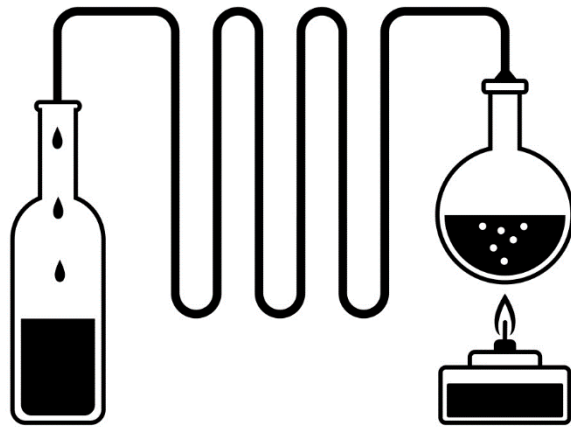
 AndrewG.Thompson@hsc.wvu.edu

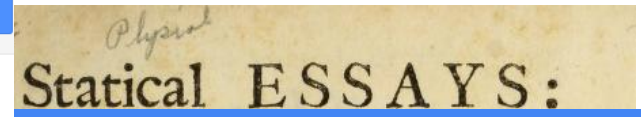


# The Infamous Heart Rate Variability: What, Why, How (a redemption song)

## What should I expect to learn?

- Clear up several common misconceptions about HRV and the inferences it affords
- Learn how to apply HRV in tactical athlete testing and training programs
- Identify methods for transitioning from collection, to assessment, interpretation, and application





Articles About 3,090,000 results (0.09 sec)

- Any time
- Since 2019
- Since 2018
- Since 2015
- Custom range...

**Decreased heart rate variability and its association with increased mortality after acute myocardial infarction**

RE Kleiger, JP Miller, JT Bigger Jr, AJ Moss - The American journal of ..., 1987 - Elsevier  
 A high degree of **heart rate** (HR) **variability** is found in compensated hearts with good function, whereas HR **variability** can be decreased with severe coronary artery disease, congestive **heart** failure, aging and diabetic neuropathy. To test the hypothesis that HR ...  
 ☆ Cited by 4509 Related articles All 7 versions

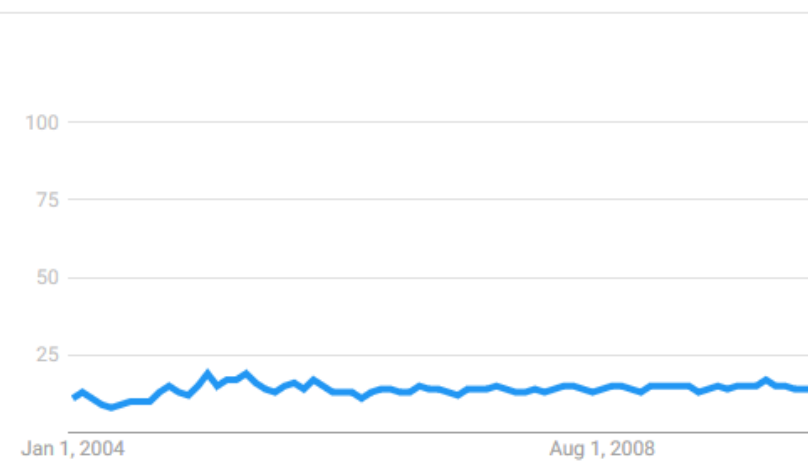
- Sort by relevance
- Sort by date

**Heart rate variability: origins, methods, and interpretive caveats**

GG Berntson, J Thomas Bigger Jr... - ..., 1997 - Wiley Online Library  
 Components of heart rate variability have attracted considerable attention in psychology and medicine and have become important dependent measures in psychophysiology and behavioral medicine. Quantification and interpretation of heart rate variability, however ...  
 ☆ Cited by 3139 Related articles All 17 versions

- include patents
- include citations

Interest over time ?



(Herophilus ca. 300 BC)

(Billman, 2011)

Articles About 32,500 results (0.12 sec)

- Any time
- Since 2019
- Since 2018
- Since 2015
- Custom range...

**[HTML] Autonomic response to tactical pistol performance measured by heart rate variability**

AG Thompson, DP Swain, JD Branch... - The Journal of ..., 2015 - journals.lww.com  
 ABSTRACT Thompson, AG, Swain, DP, Branch, JD, Spina, RJ, and Grieco, CR. Autonomic response to **tactical** pistol performance measured by **heart rate variability**. J Strength Cond Res 29 (4): 926-933, 2015—This study evaluated changes in autonomic tone during a ...  
 ☆ Cited by 19 Related articles All 6 versions

- Sort by relevance
- Sort by date

**Seasonal changes in physical performance and heart rate variability in high level futsal players**

RS Oliveira, AS Leicht, D Bishop... - ... journal of sports ..., 2013 - thieme-connect.com  
 ... competition season when the majority of the training time is devoted to **tactics** and training ... assessment in the morning (9:00-11:00 h); Day 2) resting **heart rate variability** measurements and ... in [Table 1]) with the main objective to improve players' physical, **tactical** and technical ...  
 ☆ Cited by 115 Related articles All 11 versions

- include patents
- include citations

Create alert

FREE ACCESS

ARTICLE



Tools



Share

## Jump to

Background

Measurement of HRV

Physiological Correlates of HRV

Clinical Use of HRV

Future Possibilities

Appendix A

Appendix B

Appendix C

Selected Abbreviations and Acronyms

# Heart Rate Variability

## Standards of Measurement, Physiological Interpretation, and Clinical Use

Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology

Originally published 1 Mar 1996 | <https://doi.org/10.1161/01.CIR.93.5.1043> | Circulation. 1996;93:1043–1065

The last two decades have witnessed the recognition of a significant relationship between the autonomic nervous system and cardiovascular mortality, including sudden cardiac death.<sup>1234</sup>

Experimental evidence for an association between propensity for lethal arrhythmias and signs of either increased sympathetic or reduced vagal activity has spurred efforts for the development of quantitative markers of autonomic activity.

HRV represents one of the most promising such markers. The



Details



Related



References



Figures

Circulation

March 1, 1996  
Vol 93, Issue 5

## Article Information

### Metrics



HRV Measure	Units	Description
-------------	-------	-------------

**Time Domain**

★ 1	SDNN	ms	Standard deviation of all NN intervals
2	SDRR	ms	Standard deviation of RR intervals
3	SDANN	ms	Standard deviation of the averages of NN intervals in all 5-minute segments of the entire recording
4	SDNN Index	ms	Mean of the standard deviations of all the NN intervals for each 5 min segment of a 24 h HRV recording
5	SDSD	ms	Standard deviation of differences between adjacent NN intervals
6	NN50		Number or pairs of adjacent NN intervals differing by more than 50 ms; total, longer leading pair; longer trailing pair
7	pNN50	%	NN50 count divided by total number of all NN intervals
★ 8	RMSSD	ms	Root mean square of differences between adjacent RR intervals

**Geometric**

9	Triangular Index		Total number of all NN intervals divided by the height of the histogram of all NN intervals measured on a discrete scale with bins of 7,8125 ms (1/128 seconds)
10	TINN	ms	Baseline width of the minimum square difference triangular interpolation of the highest peak of the histogram of all NN intervals
11	Differential Index	ms	Difference between the widths of the histogram of differences between adjacent NN intervals measured

**Frequency Domain**

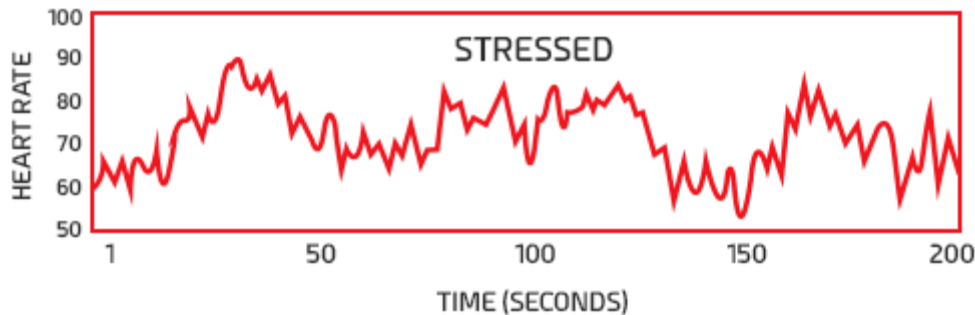
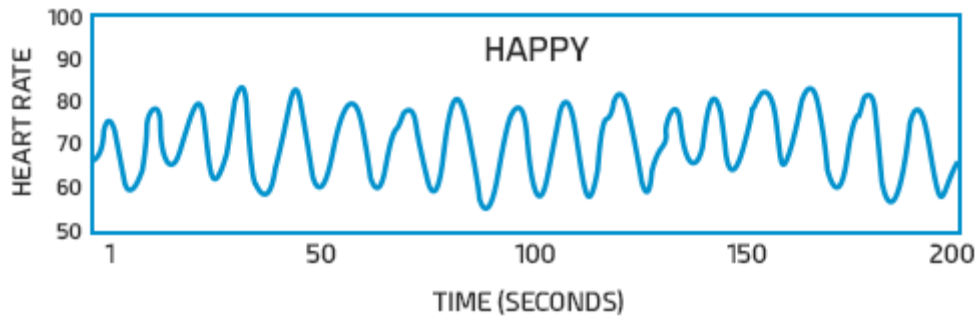
★ 12	TP	ms <sup>2</sup>	Total power across all frequency ranges/bands
13	ULF	ms <sup>2</sup>	Absolute power of the ultra-low-frequency band ( $\leq 0.003$ Hz)
14	VLF	ms <sup>2</sup>	Power in the very low frequency range ( $\leq 0.04$ Hz)
15	LF	ms <sup>2</sup>	Power in the low frequency range (0.04-0.15 Hz)
★ 16	HF	ms <sup>2</sup>	Power in the high frequency range (0.15-0.40 Hz)
17	LF norm	nu	LF power in normalized units: $LF/(TP-VLF) \times 100$
18	HF norm	nu	HF power in normalized units: $HF/(TP-VLF) \times 100$
19	LF/HF		Ratio of LF power to HF power
20	LF peak	Hz	Peak frequency of the low-frequency band (0.04–0.15 Hz)
21	HF peak	Hz	Peak frequency of the high-frequency band (0.15–0.4 Hz)
22	LF	%	Relative power of the low-frequency band (0.04–0.15 Hz)
23	HF	%	Relative power of the high-frequency band (0.15–0.4 Hz)

**Nonlinear**

24	S	ms	Area of the ellipse which represents total HRV
25	SD1	ms	Poincaré plot standard deviation perpendicular the line of identity
26	SD2	ms	Poincaré plot standard deviation along the line of identity
27	SD1/SD2	%	Ratio of SD1-to-SD2
28	ApEn		Approximate entropy, which measures the regularity and complexity of a time series
29	SampEn		Sample entropy, which measures the regularity and complexity of a time series
30	DFA $\alpha_1$		Detrended fluctuation analysis, which describes short-term fluctuations
31	DFA $\alpha_2$		Detrended fluctuation analysis, which describes long-term fluctuations
32	D <sub>2</sub>		Correlation dimension, which estimates the minimum number of variables required to construct a model of system dynamics

(Acharya et al., 2006; Task Force, 1996; Kleiger, 1998; Shaffer & Ginsberg, 2017)

# What is HRV?



Higher HRV



Less physiologically stressed

Ready to perform

Lower HRV



More physiologically stressed

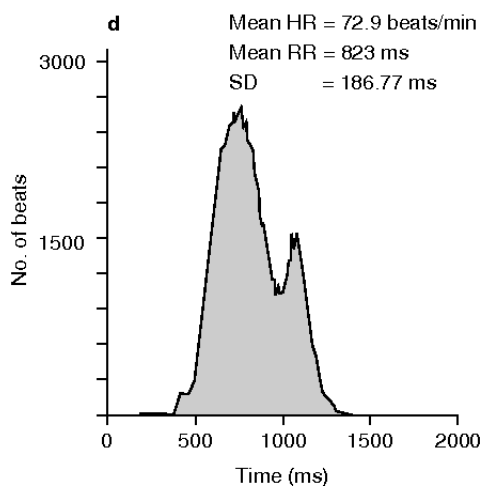
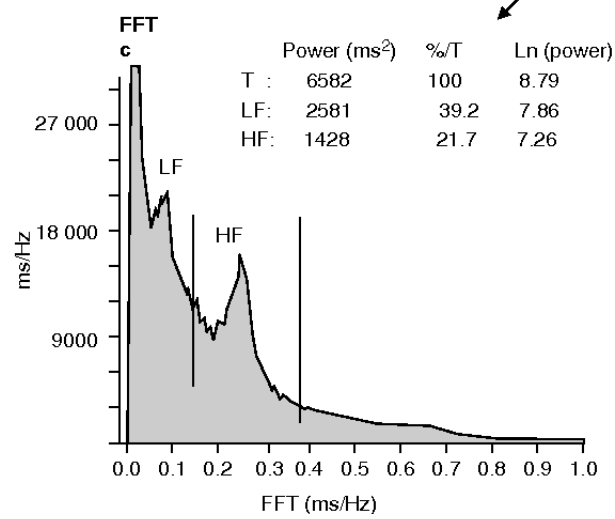
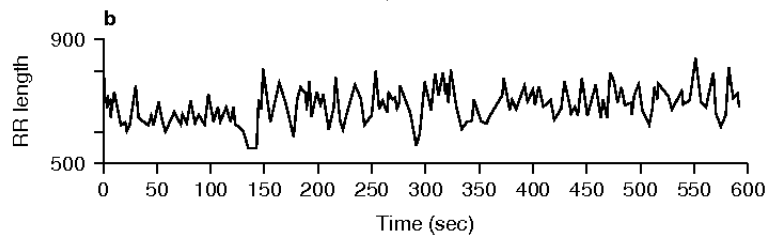
Tiredness

this slide is an oversimplification

# 5 HRV Theories (for Review see Shaffer et al., 2014)

- Neurovisceral Integration (Thayer & Lane, 2000; Thayer et al., 2009)
  - Connection from prefrontal cortex to heart through central autonomic network and vagus nerve
  - Heart-Brain connection
  - Higher vagal tone = better executive cognitive performance, emotion and health regulation
- Polyvagal (Porges, 2007)
  - Higher vagal tone = better social functioning
- Biological Behavioral Model (Grossman & Taylor, 2007)
  - Vagal tone primary role in regulation of energy exchange through cardiorespiratory synchronization during metabolic processes and behavioral changes
  - Higher resting vagal = more adaptive
- Resonance Frequency Model (Lehrer, 2013)
  - Connected to RSA
  - Increased vagal through slow paced breathing
- Psychophysiological Coherence Model (McCraty & Childre, 2010)
  - Slow paced breathing + positive emotions = broad range positive health outcomes

# What is HRV?



Time-domain



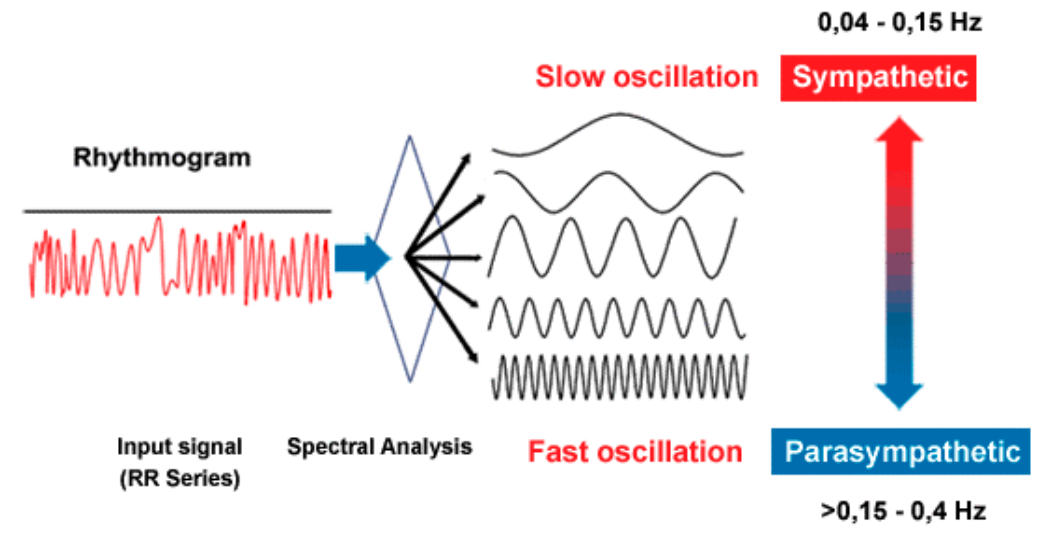
How many heartbeats in this timeframe?



Frequency-domain



How are the RR intervals modulated?

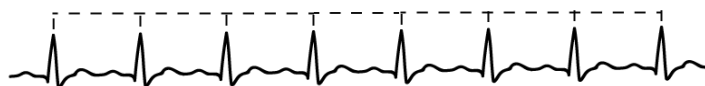


# What is HRV?

Time-domain



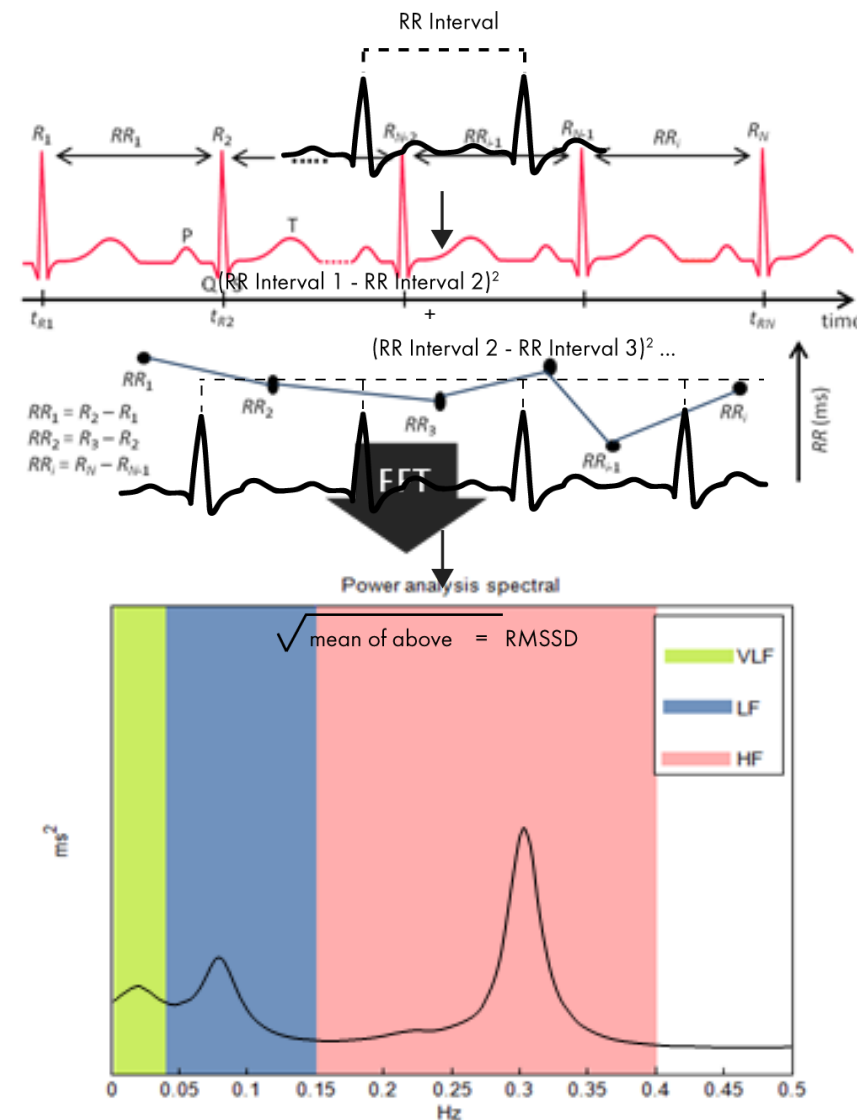
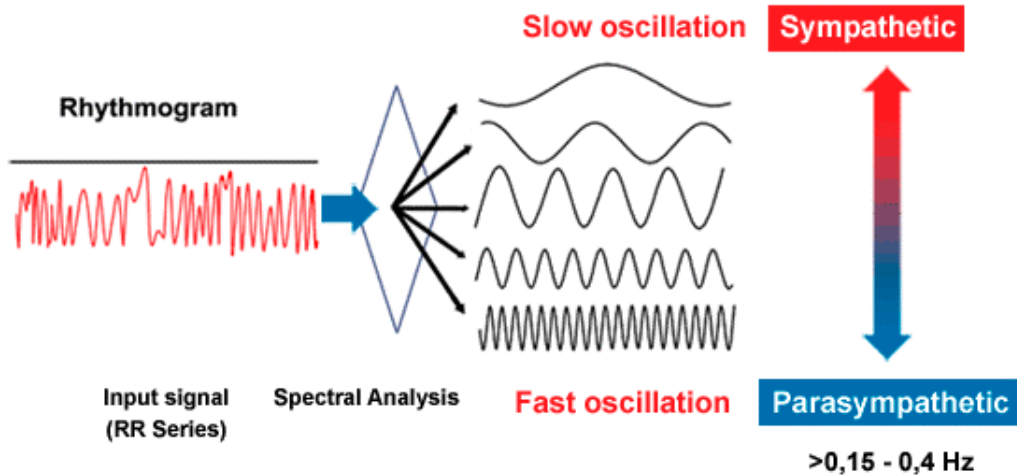
How many heartbeats in this timeframe?



Frequency-domain



How are the RR intervals modulated?



# OK, So.....What is HRV?

**WHAT IS HEART RATE VARIABILITY?**

Timing, frequency, and nonlinear based analytics, derived from consecutive, inter-beat intervals (R to R waves) of the cardiac cycle.

Quantifies the ebb and flow of autonomic nervous system resources (parasympathetic modulation) in response to environmental stimuli and adaptation/maladaptation

HRV is a valid and reliable predictor of autonomic nervous system (ANS) function  
Indicates physiological and psychological adaptability of the heart to meet sudden demands (body - environment)  
Is directly linked to all-cause mortality across all populations (higher HRV is better)

**PHYSIOLOGICAL**  
FUNCTION  
PULMONARY  
CIRCULATORY

**PSYCHOLOGICAL**  
COGNITIVE WORKLOAD  
DEPRESSION/ANXIETY  
ATTENTION ALLOCATION

**MOTOR**  
CONTROL  
SKILL ACQUISITION  
EXECUTION EFFICIENCY

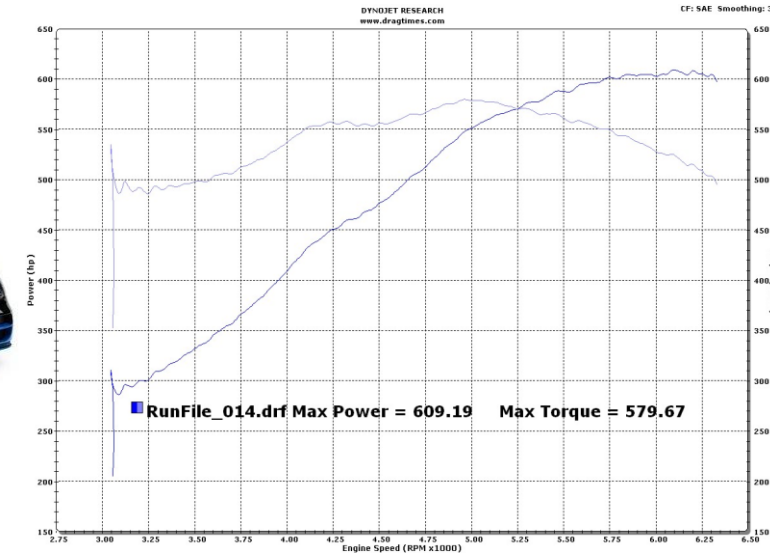
**PHYSICAL**  
WORKLOAD  
RECOVERY

**HOW IT WORKS**  
Electrocardiogram/heart rate monitor records timing between heart beats (minimum of 3-5 minutes) = R to R intervals. Uploaded to software through bluetooth, the cloud, or radiofrequency. Statistically processed by software that produces HRV metrics.

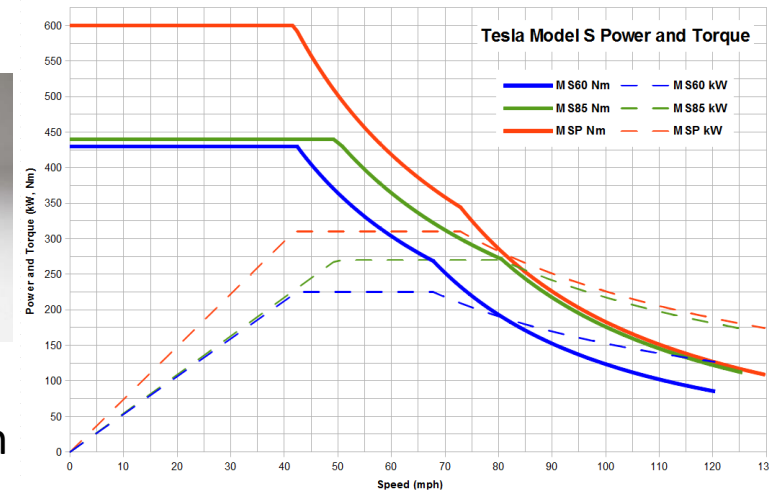
**APPLICATIONS**  
Monitor real-time workload (physical, cognitive, emotional, motor)  
Identify general readiness (for training, surgery, sports games, combat, scholastic, etc.)  
Track recovery (from training, sickness/negative medical event - heart attack, stroke, etc., mental stress, through sleep)



0-60 mph, 2.5 sec  
10.1 sec @ 142 mph  
\$1,700,000  
8/14 mpg

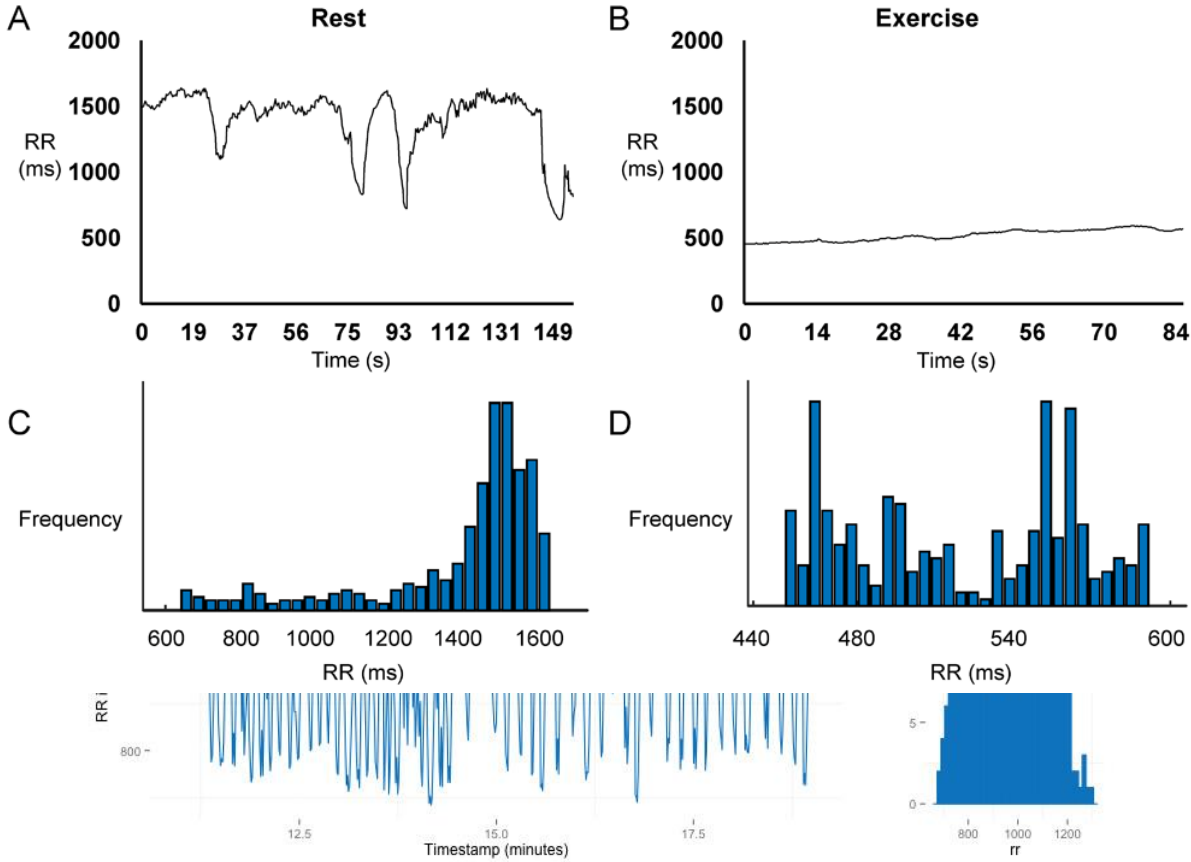


0-60 mph, 2.28 sec  
10.44 sec @ 124.2 mph  
\$133,000  
92/105 mpg\*



# Off -> Idle -> Drive -> Race

RR intervals timeseries and histogram for the 'public speaking' condition



**PRE-STAGE INDICATOR LIGHTS**  
warn drivers that they are approaching the starting line and the "staged" position.

**STAGE INDICATOR LIGHTS**  
Signal drivers that they are on the starting line ready for a run.

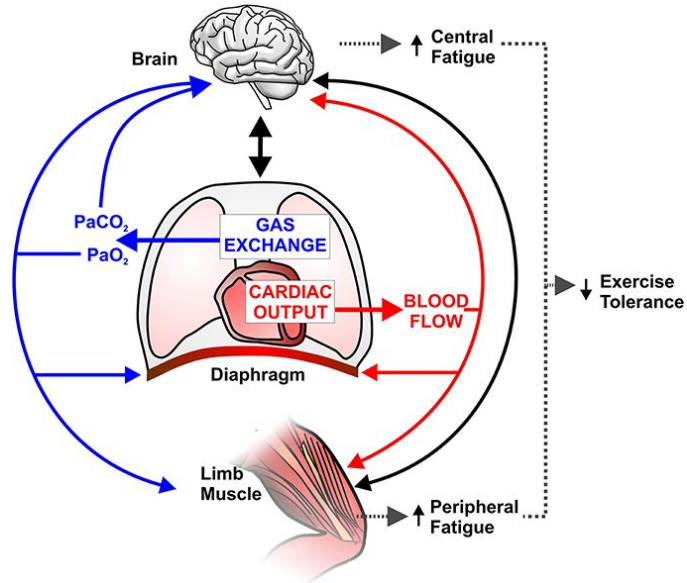
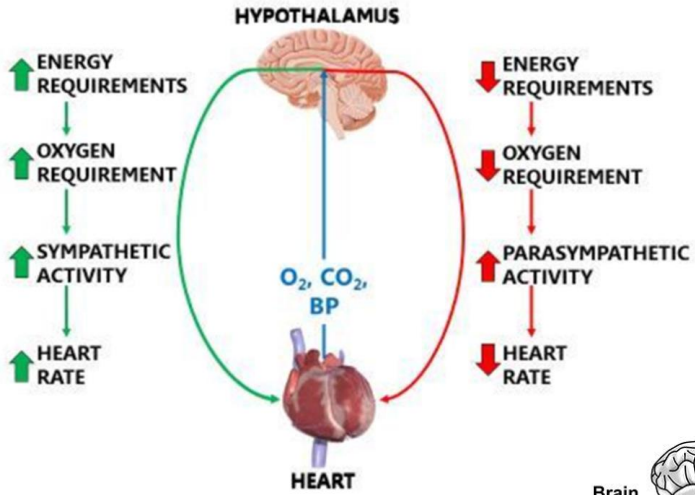
**THREE-AMBER STARTING SYSTEM**  
The three amber lights in a driver's lane flash at different intervals before the green depending on race class.

**GREEN LIGHT**  
Once the green light is flashed, the driver in that lane is free to make a run

**RED LIGHT**  
If a red light shows in a lane, the vehicle left before the green and is automatically disqualified



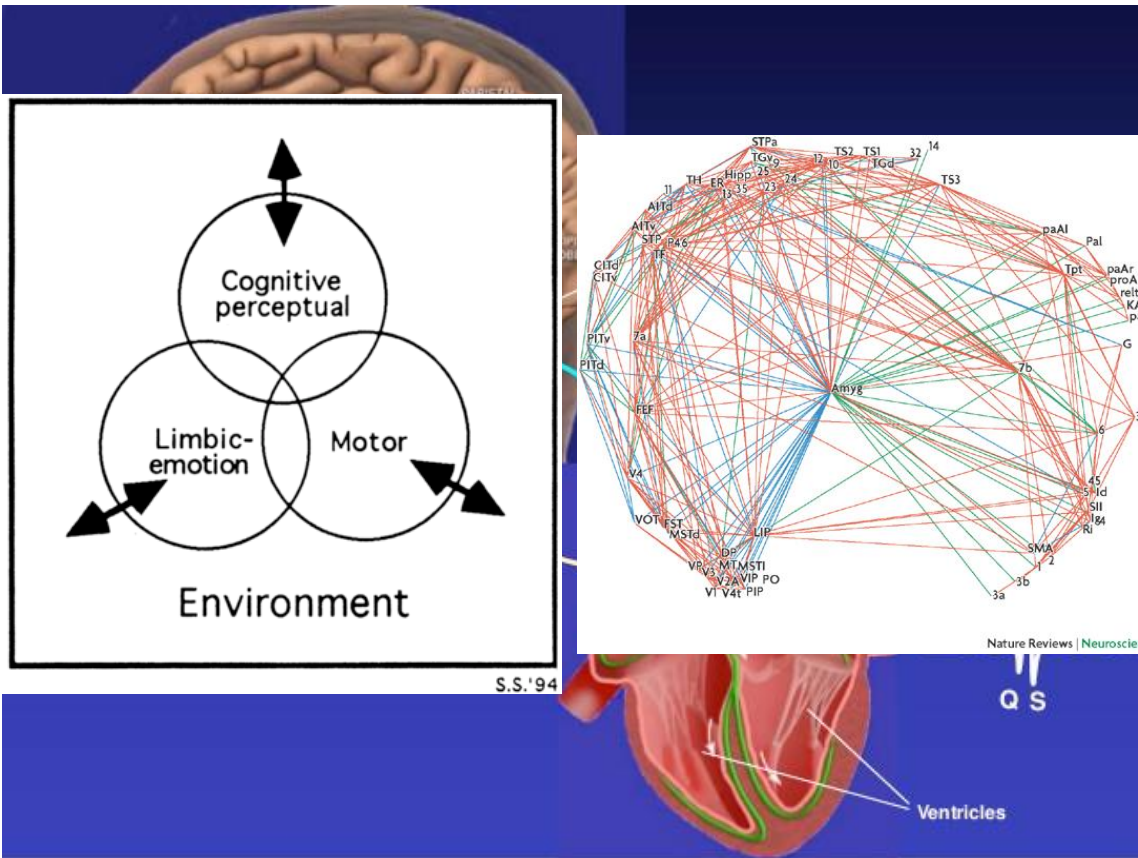
# Combustion Engine



(McArdle et al., 2006; Poirier, 2014)



# Computers & Electricity



Market Sale

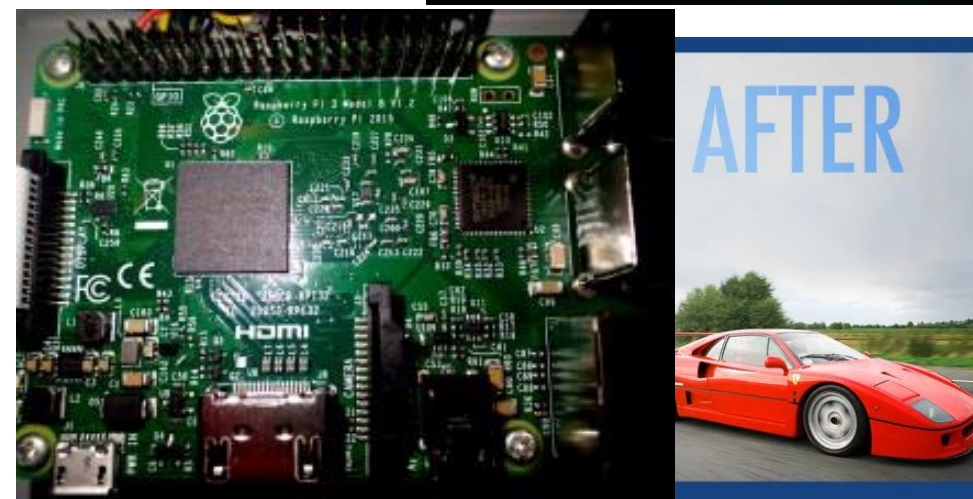
BOOST CONTROLLER 4

INTERCOOLER 3

TIRE WIDTH 10

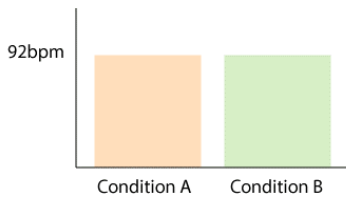
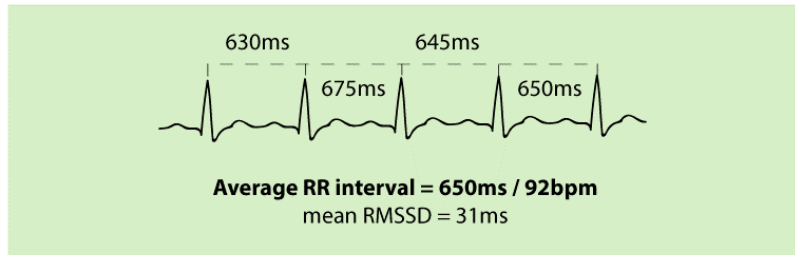
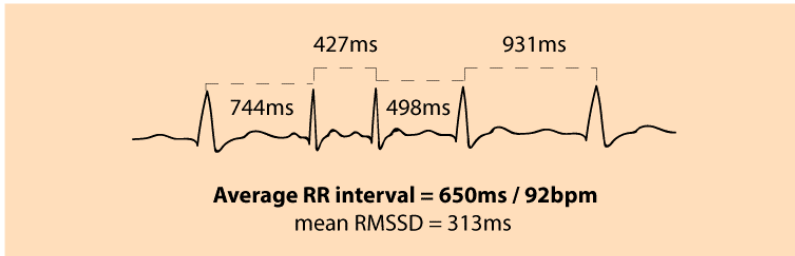
TIRE TREATMENT 16

**The higher the frequency, the higher the spark plug strength**  
frequency is adjusted at 1000-6000rpm/min

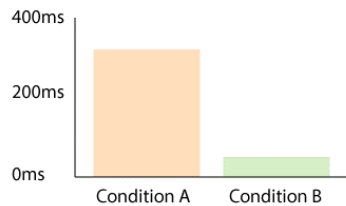


(Lane et al., 2009; McArdle et al., 2006; Pessoa, 2008; Thayer & Lane, 2000; Thayer et al., 2009)

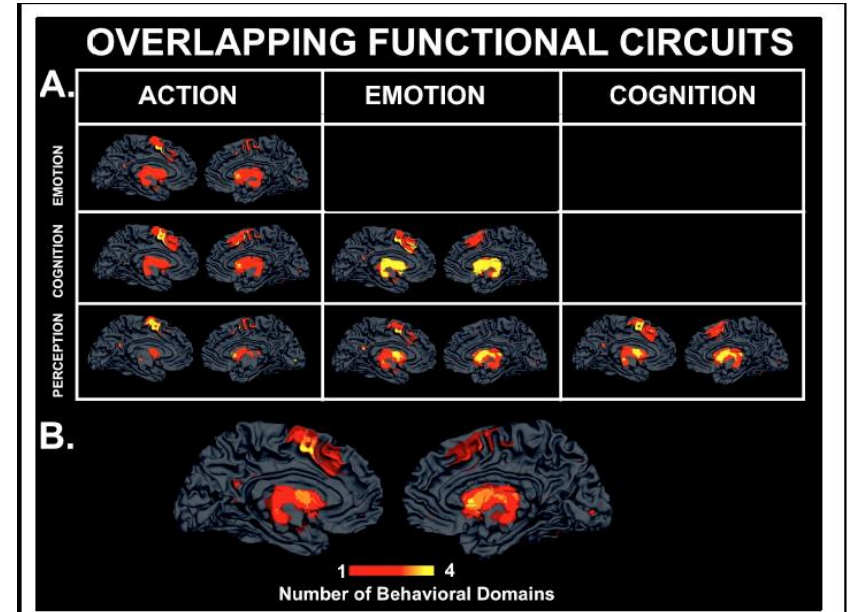
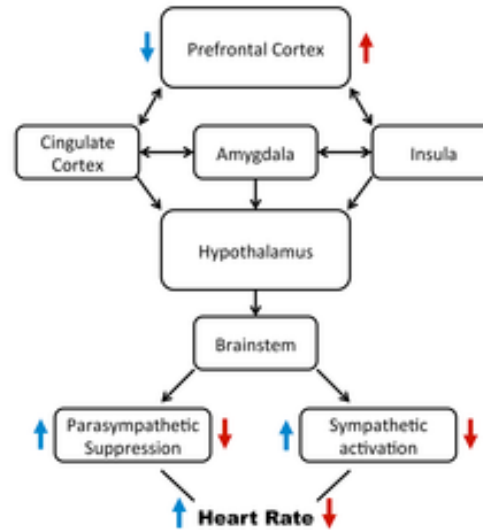
# Why should I care?



No difference discernible when compared across beats per minute (bpm), or RR interval.



The RMSSD values suggest that **condition B is more physiologically arousing than condition A** (lower HRV associated with increased physiological arousal).



(Lewthwaite & Wulf, 2010; McArdle et al., 2006; Poirier, 2014; Robinson et al., 2012)

# The Heart-Brain Connection

“Under any excitement there will be much mutual action and reaction between these, the two most important organs of the body” - Darwin (1872)

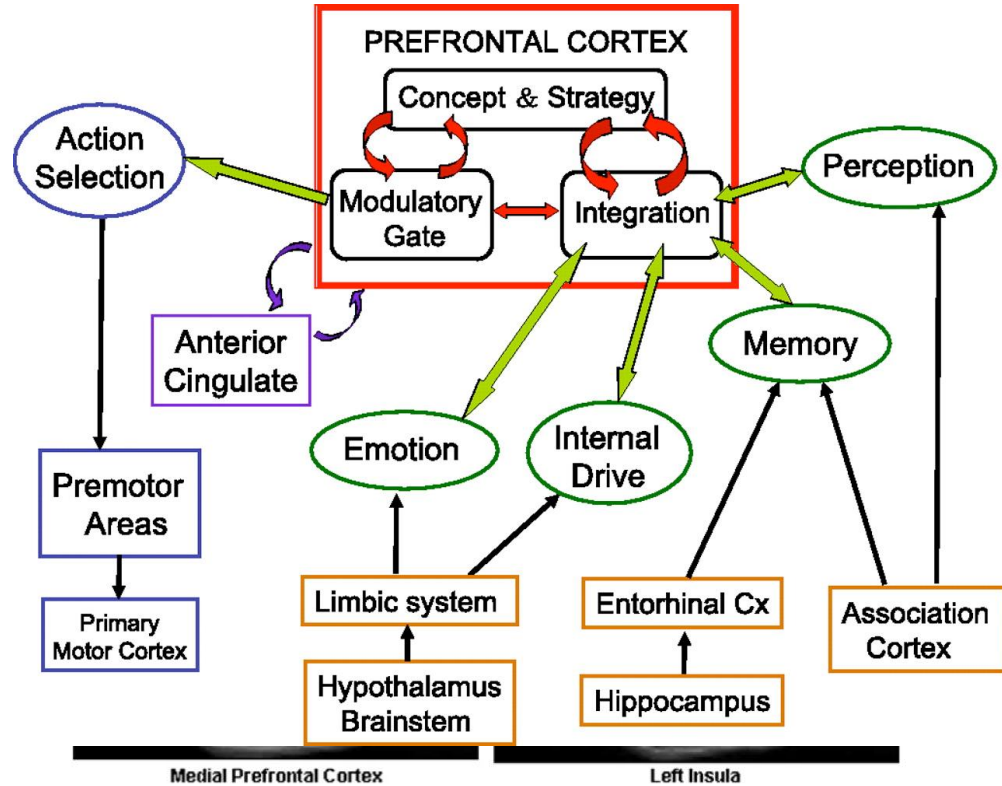


Fig. 4. Correlation of HF-HRV with emotion-specific rCBF. Brain areas where there is a significant correlation of HF-HRV with rCBF associated with the Emotion-minus-Neutral contrast. See Table 4. Sagittal and axial views of the correlation with HF-HRV in medial prefrontal cortex and coronal and axial views of the correlation with HF-HRV in the left insula are depicted.

(Lane et al., 2009; Pessoa, 2008; Thayer & Lane, 2000; Thayer et al., 2009)

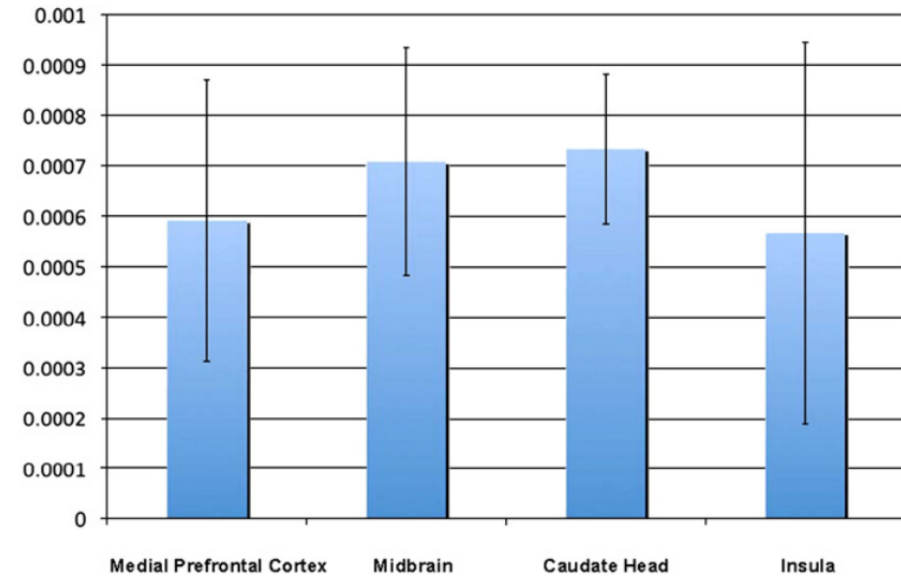
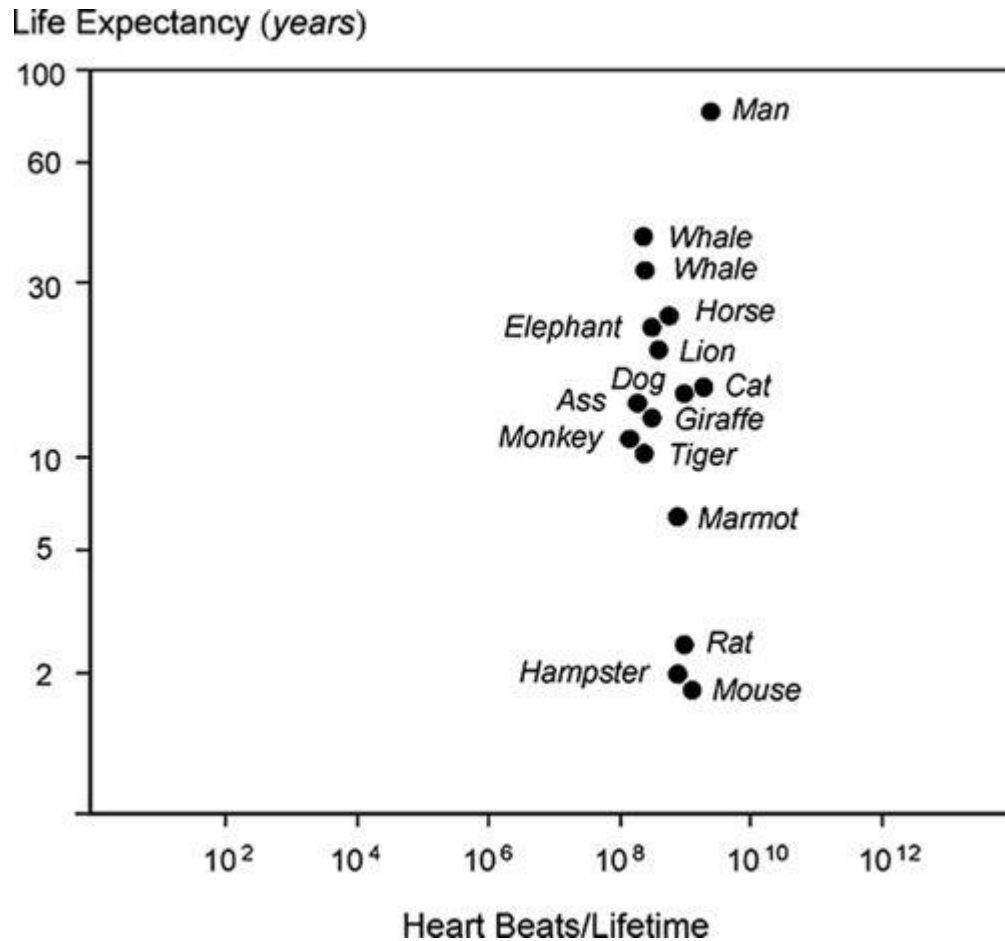


Fig. 5. Parameter estimates from the correlation of HF-HRV with emotion-specific rCBF. Parameter estimates from the correlation of HF-HRV with emotion-specific rCBF for the four areas shown in Table 4. Positive values for each parameter estimate indicate that there is a greater change in rCBF per unit of change in HF-HRV in the emotion conditions relative to the neutral conditions in that area. Units on the ordinate are arbitrary.

Perception  
 Risk/Reward  
 Self-awareness  
 Sensorimotor  
 Learning  
 Memory  
 Executive function

# Why should I care?



(Lewthwaite & Wulf, 2010; McArdle et al., 2006; Poirier, 2014; Robinson et al., 2012)





# Steps to HRV Data

## Steps to HRV Data

- 1) Design
- 2) Collect
- 3) Inspect
- 4) Correct
- 5) Calculate/Visualize
- 6) Interpret

## Practical Examples

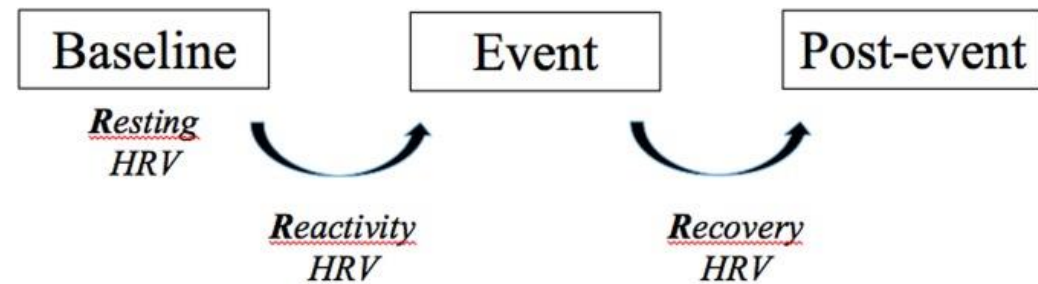
- 1) Acute Response/Biofeedback
- 2) Recovery Monitoring
  - 1) Acute
  - 2) AM to AM
  - 3) PM to AM
- 3) Training Effect/Habituation
- 4) Selection/Readiness

# Steps to HRV Data

## Steps to HRV Data

### 1) Design

- Time
  - Stamping events/segments
  - Recording period length
  - Acclimation phase
- Other Response Modalities
  - Objective
  - Subjective
- Outcomes Measures



(Quintana & Heathers, 2014)

# Steps to HRV Data

## Steps to HRV Data

- 1) Design
- 2) Collect
  - 500-1000 Hz sampling rate
  - Bandpass filter 0.5 -35 Hz
  - Skin prep
  - Secure electrodes
  - Body position\*

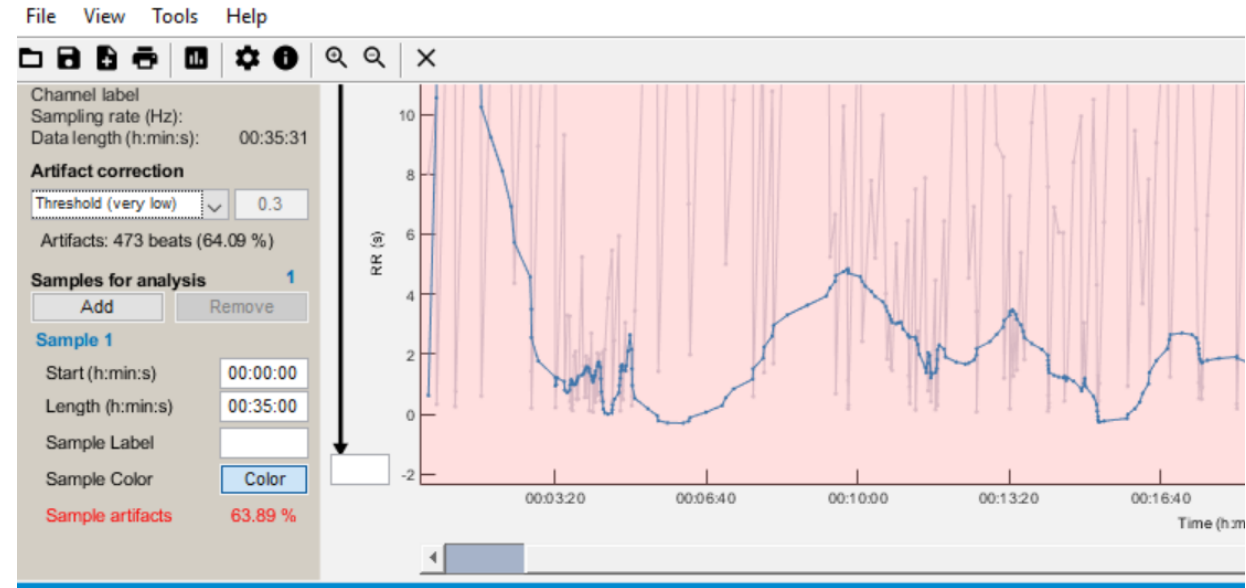
## Practical Examples

- 1) Acute Response/Biofeedback
- 2) Recovery Monitoring
  - 1) Acute
  - 2) AM to AM
  - 3) PM to AM
- 3) Training Effect/Habituation
- 4) Team Selection/Readiness

# Steps to HRV Data

## Steps to HRV Data

- 1) Design
- 2) Collect
- 3) Inspect
  - 1) Visually for artifacts/missed beats
  - 2) Filter ECG data
    - 1) 0.5 – 35 Hz
    - 2) Optimal coefficients =  $4 * (\text{sample rate} / \text{lowest frequency})$
  - 3) Visualize tachogram drift

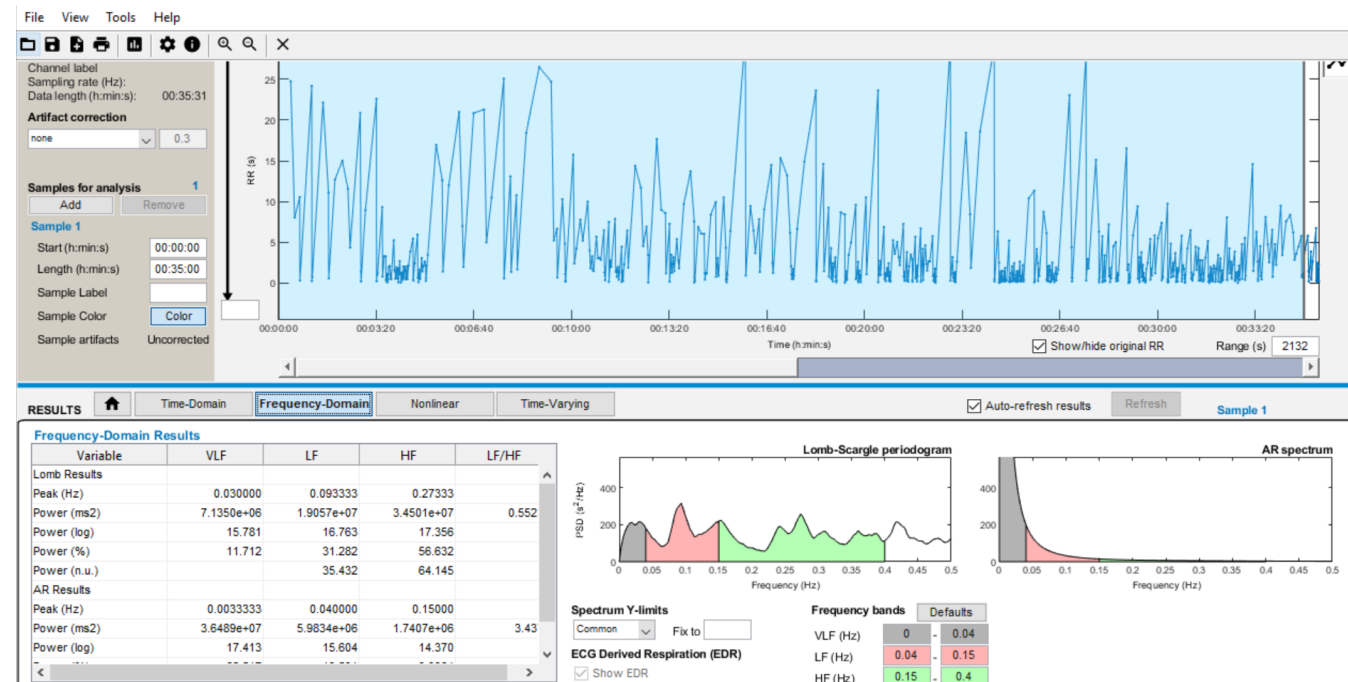
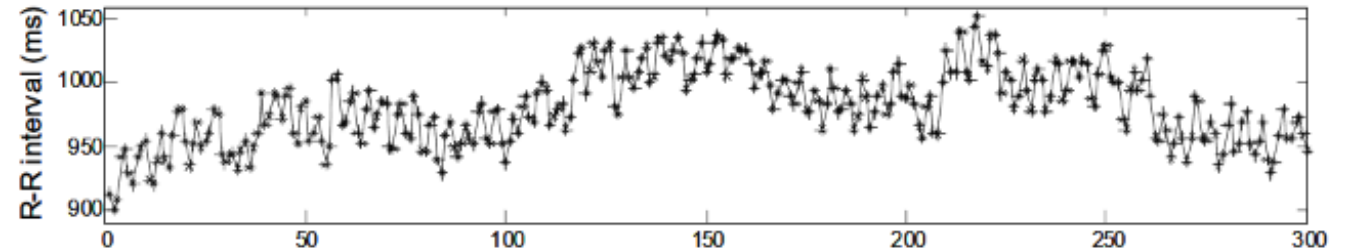


(Ruha et al., 1997)

# Steps to HRV Data

## Steps to HRV Data

- 1) Design
- 2) Collect
- 3) Inspect
- 4) Correct
  - 1) Reject artifacts
  - 2) Do not delete!
  - 3) Replace missed R peaks through interpolation of neighboring RR intervals
  - 4) Detrend drifts with wavelet

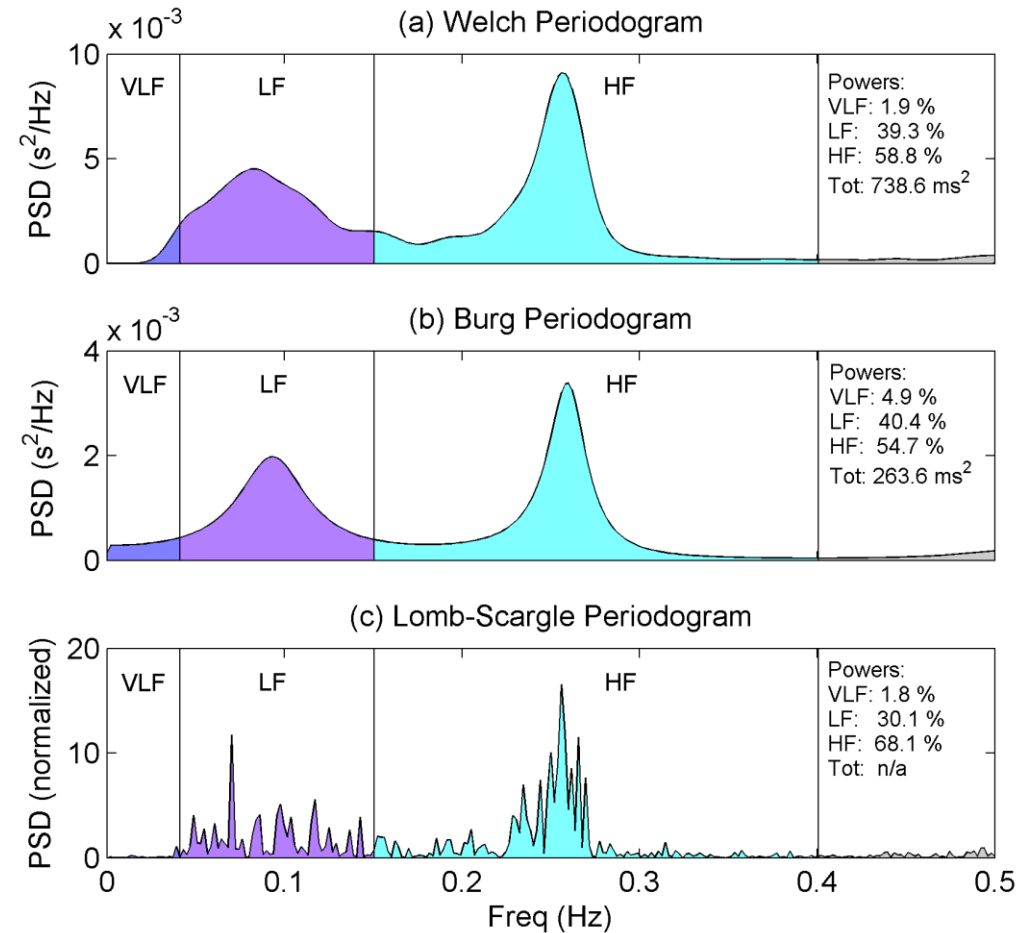


(Li et al., 2019; Malik & Camm, 1990)

# Steps to HRV Data

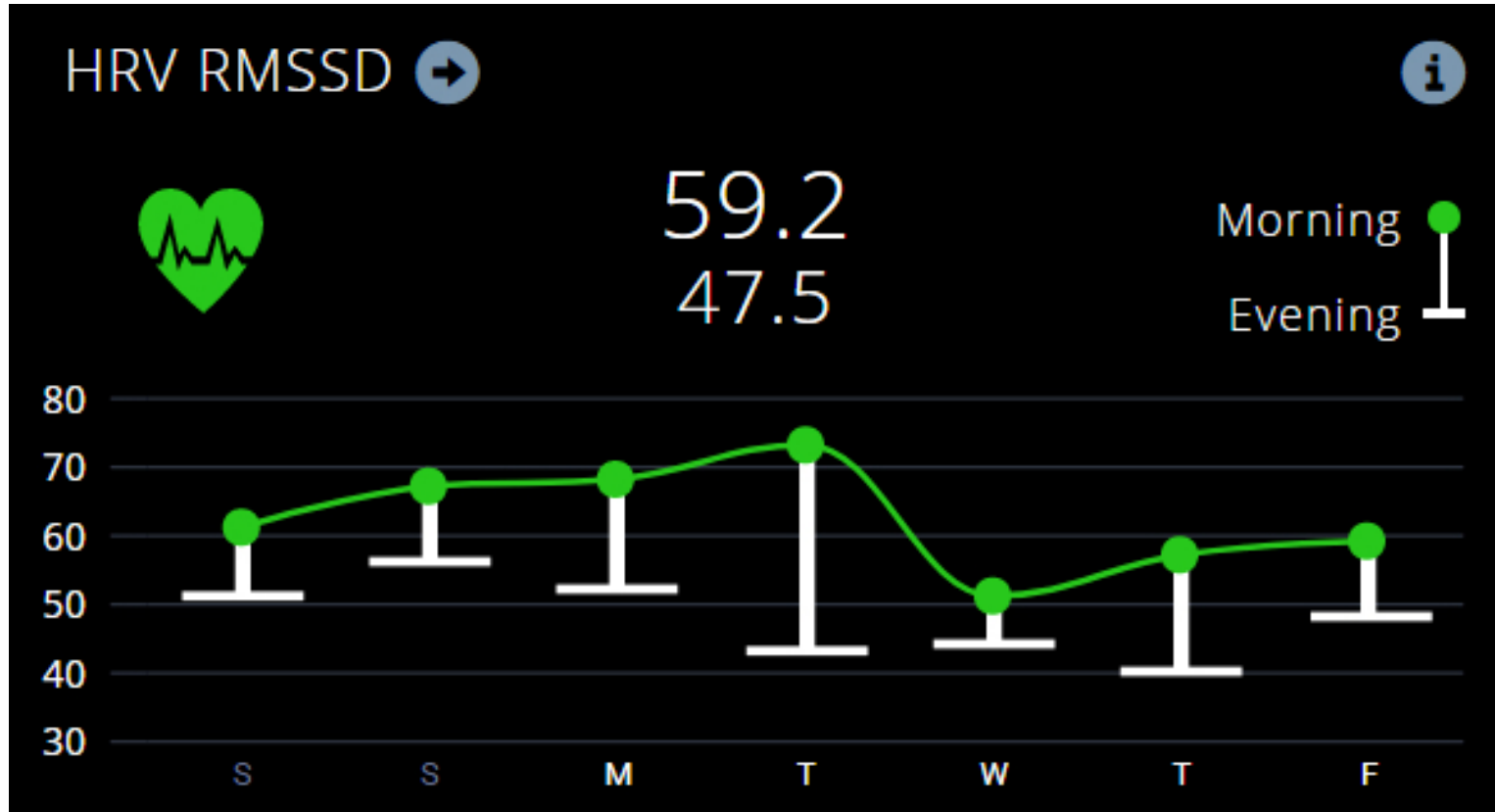
## Steps to HRV Data

- 1) Design
- 2) Collect
- 3) Inspect
- 4) Correct
- 5) Calculate/Visualize
  - Time Domain = RMSSD
  - Frequency Domain = HF, TP, HF/TP
  - Lomb Scargle > FFT
  - Natural Log

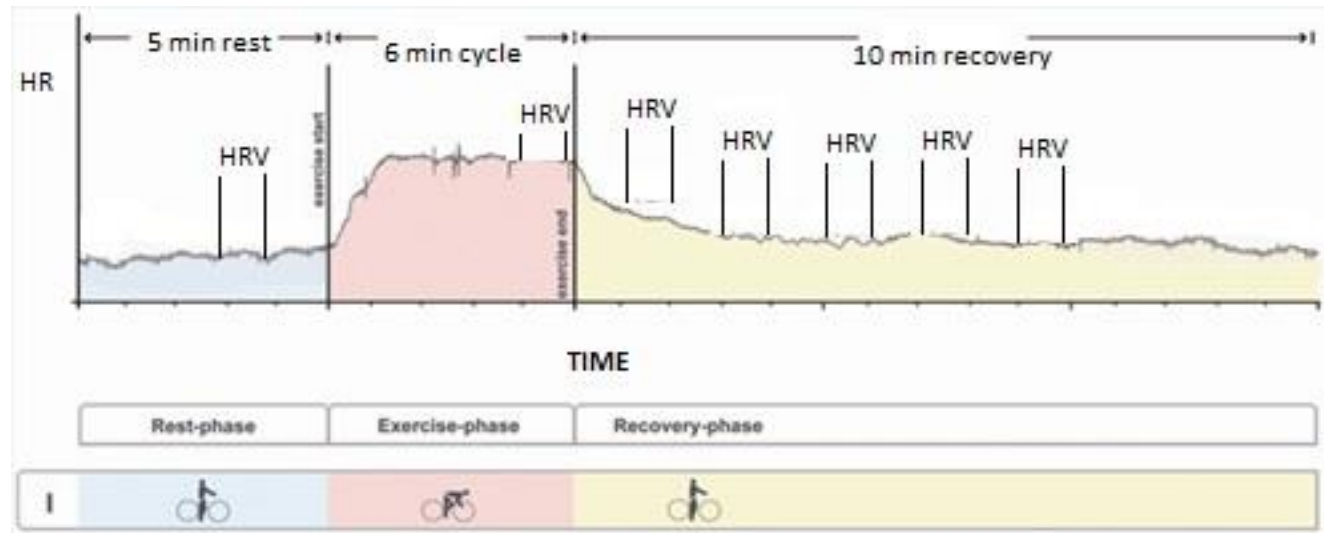
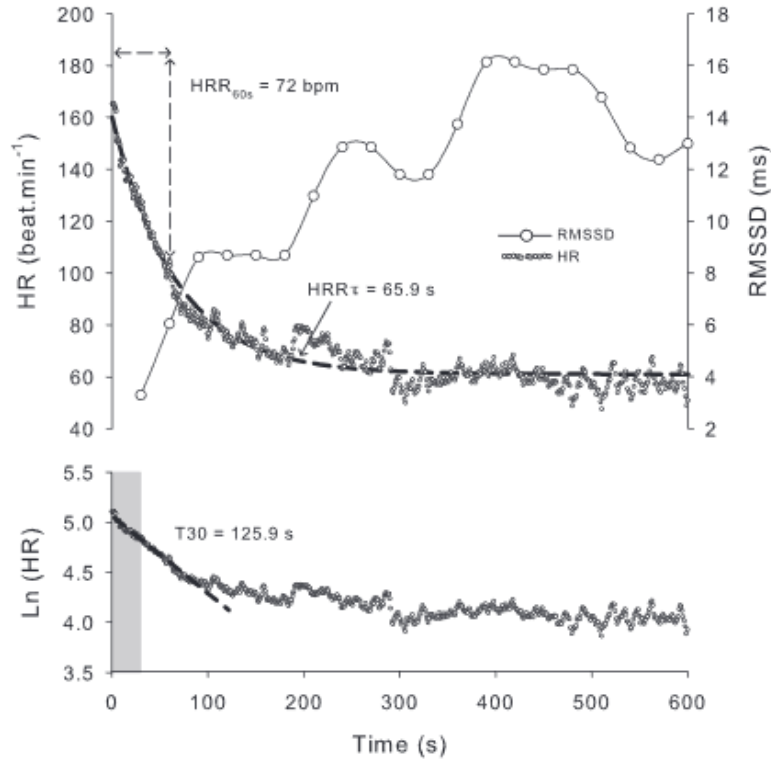


(Clifford & Tarassenko, 2005; Gang and Malik, 2008; Laguna et al., 1998; Lomb, 1976; Malik and Camm, 1990; Rajendra et al., 2006; Scargle, 1982)

# When to HRV?



# HRV Acute Response and Recovery



NEEDS CONTEXT!

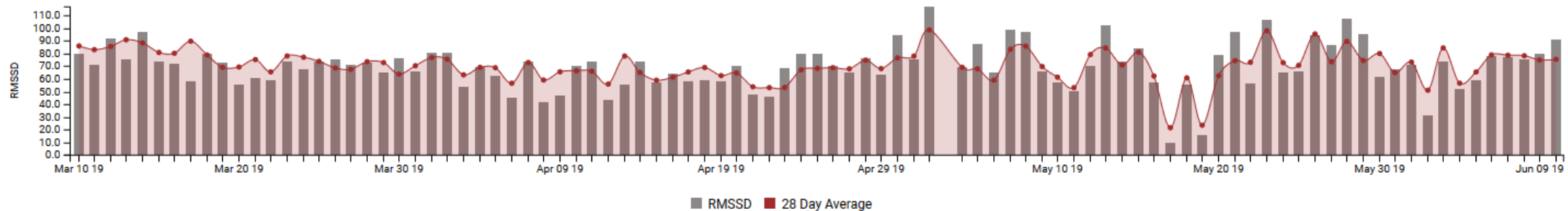
\*capture objective/subjective performance/health outcomes\*  
treat as predictors/outcome variables

(Chen et al., 2011; Lellamo et al., 2004; Pichot et al., 2002)

# HRV and Chronic Recovery

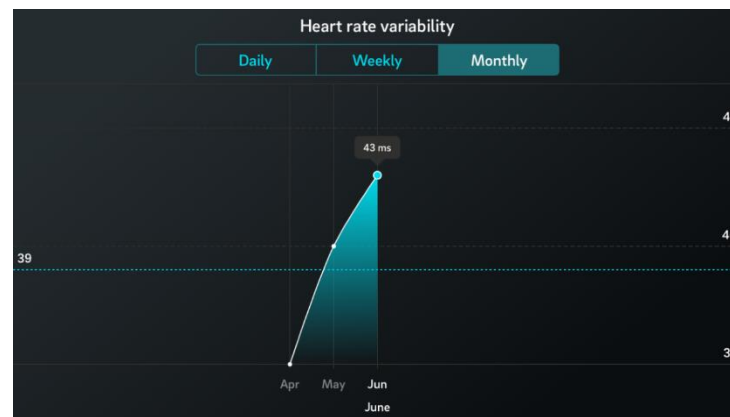
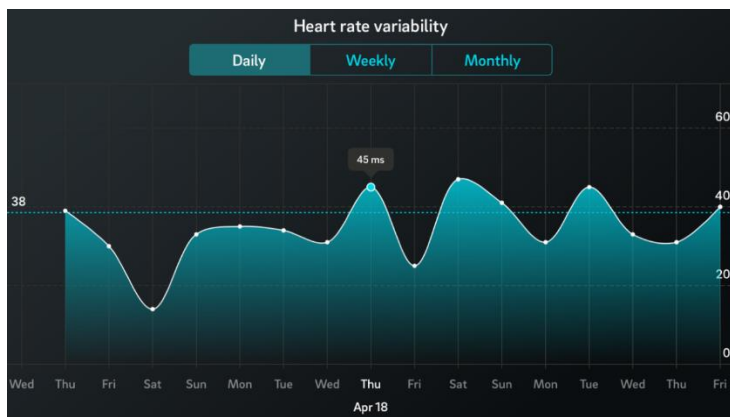
## RMSSD

Measure of heart rate variability. The higher the score the better.

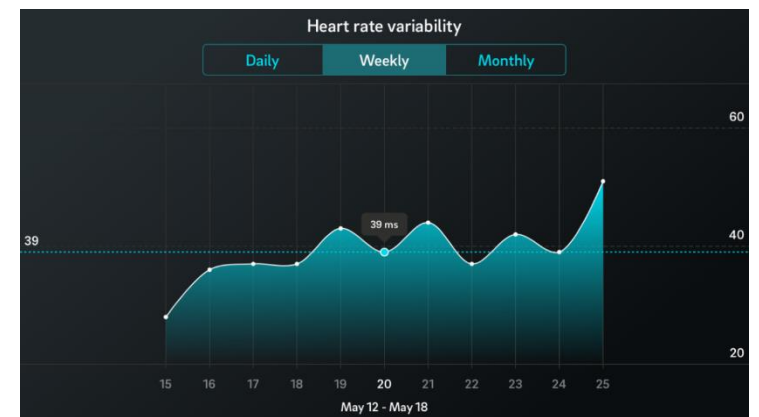


% RMSSD v. 28 Day Avg  
Most Recent

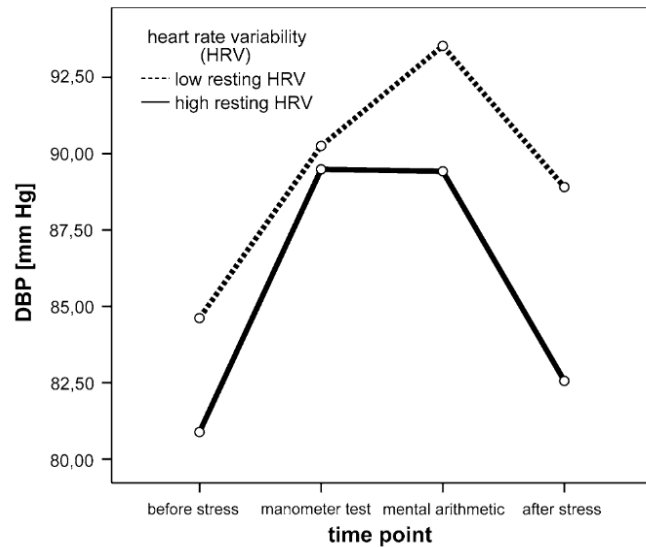
21



(Chen et al., 2011; Lellamo et al., 2004; Pichot et al., 2002)

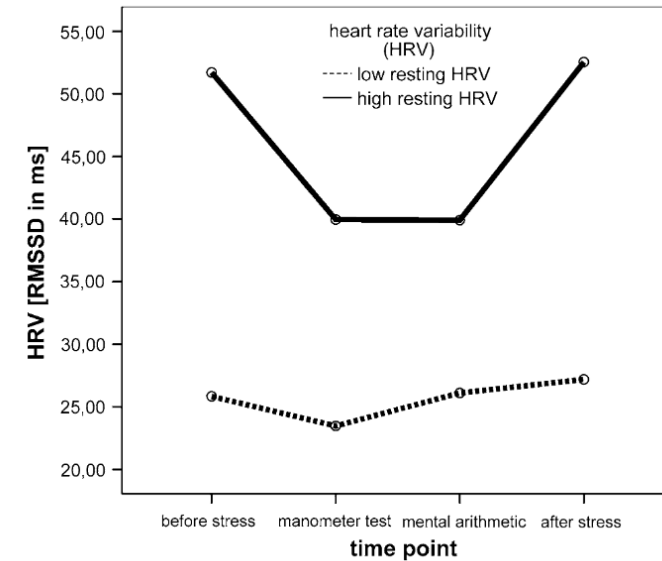


# HRV can be use to assess Recovery

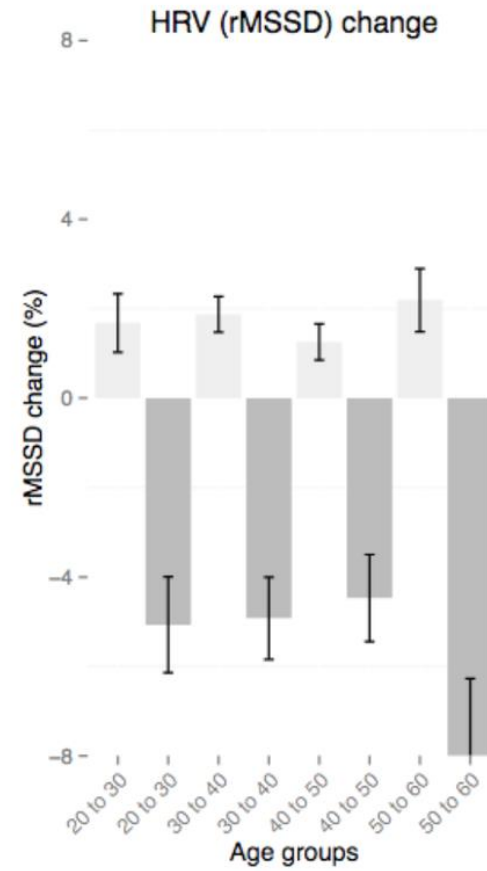
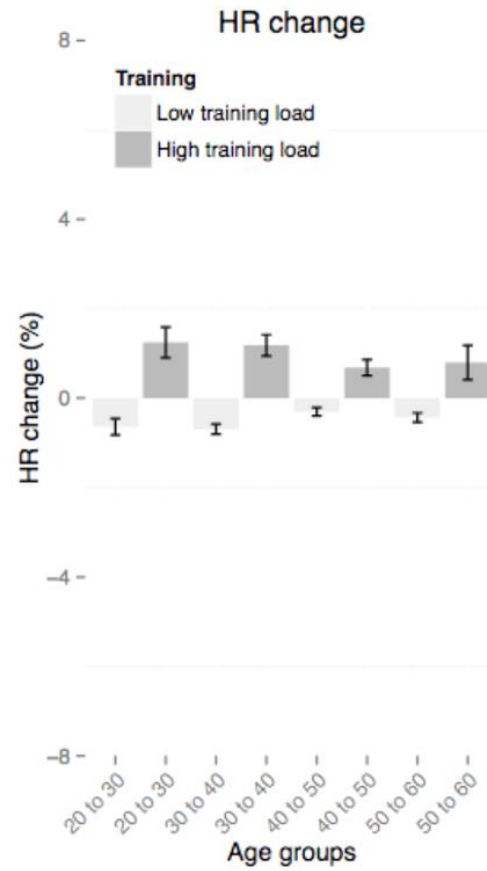


Post stressor  
AM to AM to AM  
PM to AM

- Musculoskeletal
- Cardiovascular
- Endocrine
- Immune



(Altini & Amft, 2016; Weber et al., 2010)



(Altini & Amft, 2016))

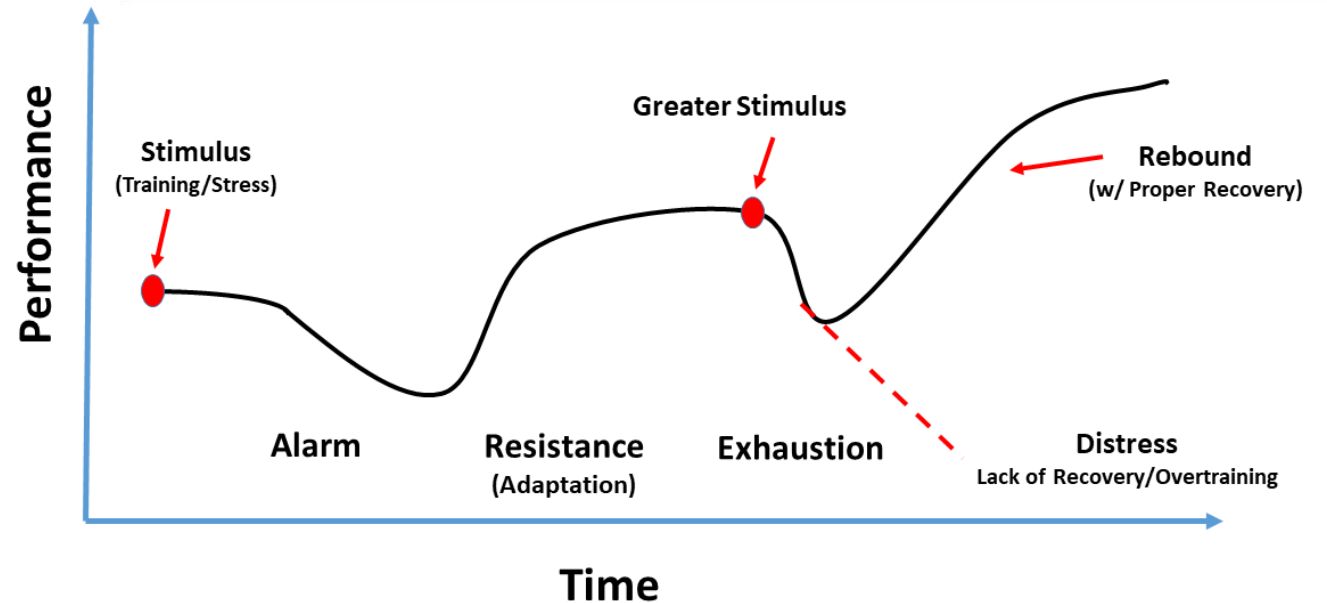
# Overtraining or Adaptation?

- HRV alone cannot determine
  - Both can increase resting HRV
- Need other metrics
  - Recent change in load/capability?
  - Subjective recovery

Addison - Parasympathetic  
Basedow - Sympathetic

Operators with one or more Flags

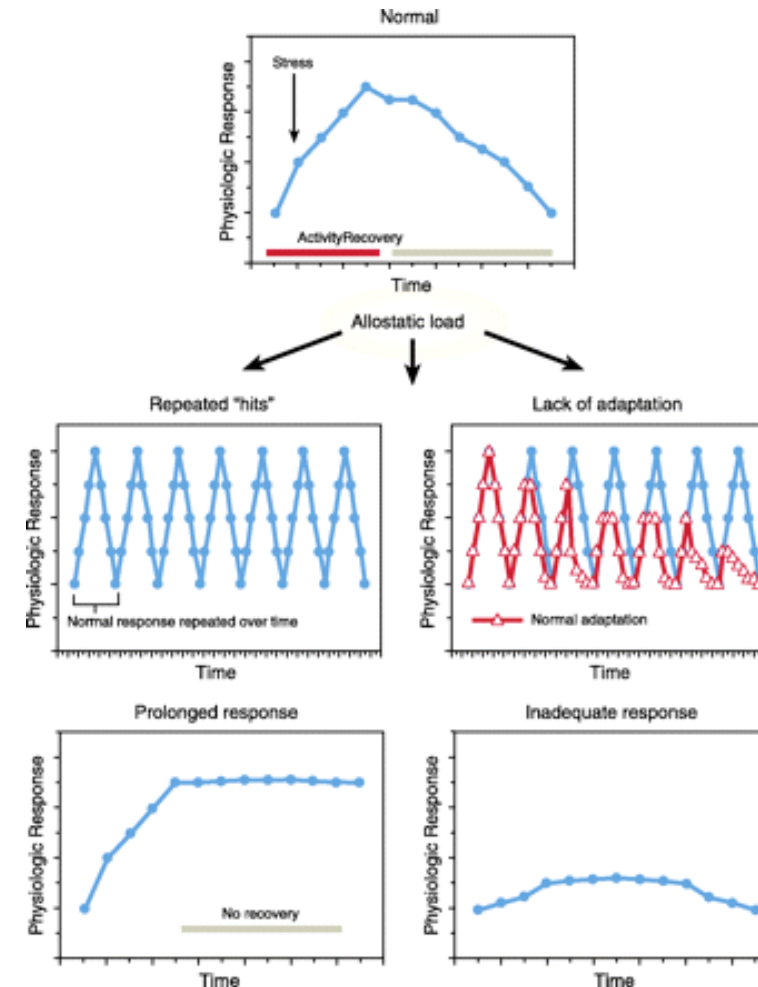
Date	Operator	Total Flags	Flag Details	RMSSD	RMSSD - Z SCORE
Jun 04 19	HP-052	3	- High Tension - Low Heart Rate Variability - High Stress / Low Recovery	63	-1.01
Jun 04 19	HP-001	2	- High Tension - High Stress / Low Recovery	97	1.17
Jun 04 19	HP-002	1	- Inefficient Recovery	53	-0.22



(Israel, 1976; Kuipers & Keizer, 1988; Kuipers, 1988; Lehmann et al., 1998; Selye, 1946)

# HRV to Predict Performance/Exercise Prescription

- Planning training load around HRV
  - Abnormally low? Take it easy
    - Individual differences
    - Track over time
- More effective than pre-planned



(Hedelin et al., 2001; Kiviniemi et al., 2007; Kiviniemi et al., 2010; McEwen 1998)

# Team Environment & HRV

- Physiological Compliance
  - HR, HRV

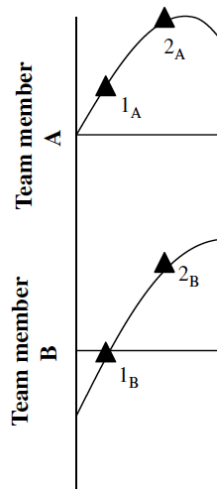


Fig. 3. Illustration

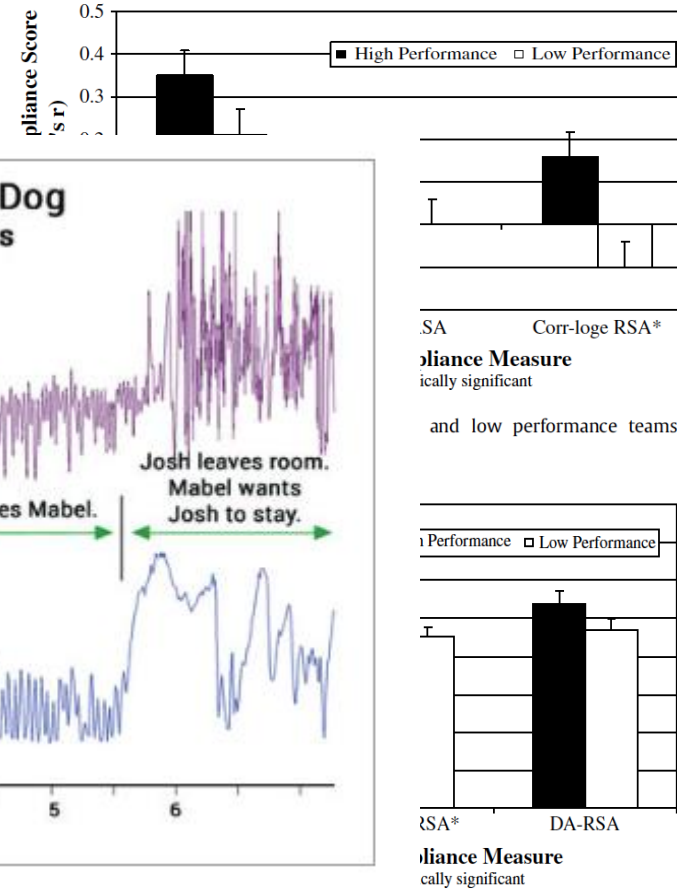
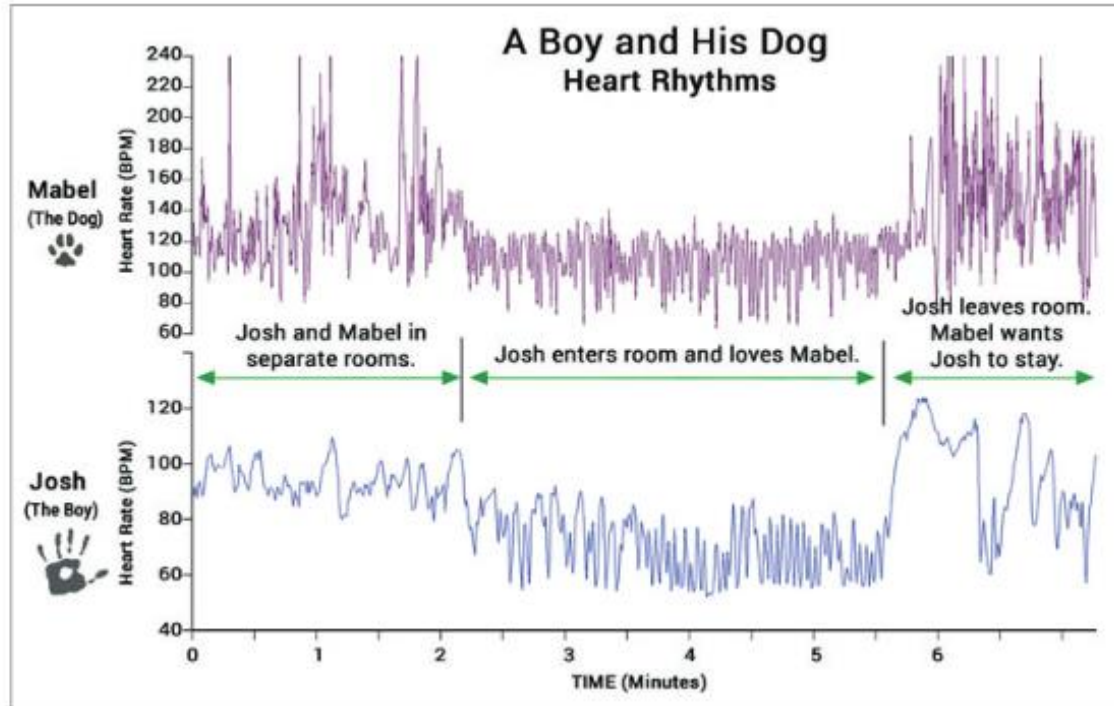


Fig. 5. Mean physiological compliance for high and low performance teams by correlation measure.

(Elkins et al., 2009)

# Practical example: The Fire House



## What?

HR  
RR  
RMSSD  
HF  
TP  
HF/TP

## How?

Logged ECG  
Routine testing  
Real-world  
Questionnaires  
Combined with biomarkers  
Mapped onto outcomes

## When?

Resting  
Active  
Recovery/Sleep  
Pre/Post training

## Why?

Predict Performance  
Monitor Load/Recovery  
Augmentation  
Adaptation



# The Fire House

Day 1



- Hiring process
- Written exams
- Physical tests
- Skill aptitude tests

Weekly “Baseline”  
Objective & subjective  
Record event/timing  
Transform HRV stats



Training effectiveness  
- Stress inoculation  
- Cognitive workload

- Acute response
  - Relationship to performance
- Recovery
  - Exercise
  - Stress
  - Sleep
- Training status
- Allostatic load



Sleep quality  
Team environment

# Take Home Messages

- HRV reflects autonomic resource allocation
  - Parasympathetic
  - General
  - Not Sympathetic
- HRV predicts recovery status
- HRV predicts performance (cognitive, physical, motor)
- HRV guided training > pre-planned
- RMSSD, HF, TP > SDNN, HR
- Jury still out on overtraining vs adaptation
  - Need more markers

# Additional resources for your reading pleasure

- G • Acharya, U. R., Joseph, K. P., Kannathal, N., Lim, C. M., & Suri, J. S. (2006). Heart rate variability: a review. *Medical and biological engineering and computing*, 44(12): 1031-1051.
- C • Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of general psychology*, 10(3): 229-240.
- G • Aubert, A. E., Seps, B., & Beckers, F. (2003). Heart rate variability in athletes. *Sports medicine*, 33(12): 889-919.
- T • Bellenger, C. R., Fuller, J. T., Thomson, R. L., Davison, K., Robertson, E. Y., & Buckley, J. D. (2016). Monitoring athletic training status through autonomic heart rate regulation: a systematic review and meta-analysis. *Sports medicine*, 46(10), 1461-1486.
- A • Berntson, G. G., & Stowell, J. R. (1998). ECG artifacts and heart period variability: Don't miss a beat!. *Psychophysiology*, 35(1), 127-132.
- G • Berntson, G. G., Thomas Bigger Jr, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., ... & Van der Molen, M. W. (1997). Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology*, 34(6): 623-648.
- A • Berntson, G. G., Quigley, K. S., Jang, J. F., & Boysen, S. T. (1990). An approach to artifact identification: Application to heart period data. *Psychophysiology*, 27(5), 586-598.
- H • Billman, G. E. (2011). Heart rate variability—a historical perspective. *Frontiers in physiology*, 2(86): 1-13.
- A • Burr R. L., Cowan M. J. (1992). Autoregressive spectral models of heart rate variability. Practical issues. *J. Electrocardiol.* 25(Suppl.), 224–233
- R • Chen, J. L., Yeh, D. P., Lee, J. P., Chen, C. Y., Huang, C. Y., Lee, S. D., ... & Kuo, C. H. (2011). Parasympathetic nervous activity mirrors recovery status in weightlifting performance after training. *The Journal of Strength & Conditioning Research*, 25(6), 1546-1552.
- A • Clifford, G. and L. Tarassenko, 2005. Quantifying errors in spectral estimates of HRV due to beat replacement and resampling. *IEEE Trans. Biomed. Eng.*, 52(4):630-638.
- C • Duschek S., Muckenthaler M., Werner N., Reyes del Paso G. A. (2009). Relationships between features of autonomic cardiovascular control and cognitive performance. *Biol. Psychol.* 81: 110–117. 10.1016/j.biopsycho.2009.03.003
- PC • Elkins, A. N., Muth, E. R., Hoover, A. W., Walker, A. D., Carpenter, T. L., & Switzer, F. S. (2009). Physiological compliance and team performance. *Applied ergonomics*, 40(6): 997-1003.
- A • Ellis R. J., Zhu B., Koenig J., Thayer J. F., Wang Y. (2015). A careful look at ECG sampling frequency and R-peak interpolation on short-term measures of heart rate variability. *Physiol. Meas.* 36: 1827–1852. 10.1088/0967-3334/36/9/1827
- R • Esco M. R., Flatt A. A. (2014). Ultra-short-term heart rate variability indexes at rest and post-exercise in athletes: evaluating the agreement with accepted recommendations. *J. Sports Sci. Med.* 13: 535–541.

A = Analysis

C = Cognitive

G = General Review

H = History M = Motor Control

O = Overtraining

PF = Performance

PC = Physio Compliance

R = Recovery

T = Training Load

# Additional resources for your reading pleasure

- A • Fagard R. H., Pardaens K., Staessen J. A., Thijs L. (1998). Power spectral analysis of heart rate variability by autoregressive modelling and fast Fourier transform: a comparative study. *Acta Cardiol.* 53: 211–218.
- G • Grossman P., Taylor E. W. (2007). Toward understanding respiratory sinus arrhythmia: relations to cardiac vagal tone, evolution and biobehavioral functions. *Biol. Psychol.* 74: 263–285. 10.1016/j.biopsycho.2005.11.014
- H • Hales, Stephen. "Statistical essays: concerning haemastatics; or, an account of some hydraulick and hydrostatical experiments made on the blood and blood-vessels of animals." *London: W. Innys and R. Manby* 1733 (1733).
- C • Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2003). Vagal influence on working memory and attention. *International journal of psychophysiology*, 48(3): 263-274.
- PF • Hedelin, R. I. K. A. R. D., Bjerle, P., & Henriksson-Larsen, K. A. R. I. N. (2001). Heart rate variability in athletes: relationship with central and peripheral performance. *Medicine and science in sports and exercise*, 33(8), 1394-1398.
- T • Iellamo, F., Pigozzi, F., Spataro, A., Lucini, D., & Pagani, M. (2004). T-wave and heart rate variability changes to assess training in world-class athletes. *Medicine & Science in Sports & Exercise*, 36(8), 1342-1346
- O • Israel, S. (1976). Problems of overtraining from an internal medical and performance physiological standpoint. *Med Sport*, 16, 1-12.
- C • Jennings J. R., Allen B., Gianaros P. J., Thayer J. F., Manuck S. B. (2015). Focusing neurovisceral integration: cognition, heart rate variability, and cerebral blood flow. *Psychophysiology* 52: 214–224.
- T • Kiviniemi, A. M., Hautala, A. J., Kinnunen, H., Nissilä, J., Virtanen, P., Karjalainen, J., & Tulppo, M. P. (2010). Daily exercise prescription on the basis of HR variability among men and women. *Medicine and science in sports and exercise*, 42(7), 1355-1363.
- T • Kiviniemi, A. M., Hautala, A. J., Kinnunen, H., & Tulppo, M. P. (2007). Endurance training guided individually by daily heart rate variability measurements. *European journal of applied physiology*, 101(6), 743-751.
- G • Kleiger, R. E., Stein, P. K., & Bigger Jr, J. T. (2005). Heart rate variability: measurement and clinical utility. *Annals of Noninvasive Electrocardiology*, 10(1): 88-101.
- O • Kuipers, H., & Keizer, H. A. (1988). Overtraining in elite athletes. *Sports Medicine*, 6(2), 79-92.
- O • Kuipers, H. (1998). training and overtraining1. txt *Medicine & science in sports & Exercise* (c) Williams & Wilkins 1998. All Rights Reserved. *Training*, 30(7), 1137-1139.
- A • Laguna, P., Moody, G., & Mark, R. (1998). Power spectral density of unevenly sampled data by least-square analysis: performance and application to heart rate signals. *IEEE Trans Biomed Eng*, 45(6): 698-715.
- C • Lane, R. D., McRae, K., Reiman, E. M., Chen, K., Ahern, G. L., & Thayer, J. F. (2009). Neural correlates of heart rate variability during emotion. *Neuroimage*, 44(1): 213-222.
- R • Lehmann, M. A. N. F. R. E. D., Foster, C. A. R. L., Dickhuth, H. H., & Gastmann, U. (1998). Autonomic imbalance hypothesis and overtraining syndrome. *Medicine and science in sports and exercise*, 30(7), 1140-1145.
- MC • Lewthwaite, R., & Wulf, G. (2010). Grand challenge for movement science and sport psychology: embracing the social-cognitive–affective–motor nature of motor behavior. *Frontiers in psychology*, 1, 42.

# Additional resources for your reading pleasure

- A • Li, K., Rüdiger, H., & Ziemssen, T. (2019). Spectral analysis of heart rate variability: time window matters. *Frontiers in Neurology*, 10.
- A • Li, L., Li, K., Liu, C., & Liu, C. Y. (2011). Comparison of detrending methods in spectral analysis of heart rate variability. *Res J Appl Sci Eng Technol*, 3(9): 1014-1021.
- A • Lomb, N. (1976). Least-squares frequency analysis of unequally spaced data. *Astrophys Space Sci*, 39(2): 447-462.
- G • Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European heart journal*, 17(3), 354-381.
- G • Malik, M., & Camm, A. J. (1990). Heart rate variability. *Clinical cardiology*, 13(8), 570-576.
- PC • McCraty R., Childre D. (2010). Coherence: bridging personal, social, and global health. *Altern. Ther. Health Med*. 16: 10–24
- O • McEwen, B. S. (1998). Protective and damaging effects of stress mediators. *New England journal of medicine*, 338(3): 171-179.
- A • Otzenberger H., Gronfier C., Simon C., Charloux A., Ehrhart J., Piquard F., et al. (1998). Dynamic heart rate variability: a tool for exploring sympathovagal balance continuously during sleep in men. *Am. J. Physiol.* 275(3 Pt 2), H946–H950
- C • Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature reviews neuroscience*, 9(2), 148.
- O • Pichot, V., Busso, T., Roche, F., Garet, M., Costes, F., Duverney, D., ... & Barthélémy, J. C. (2002). Autonomic adaptations to intensive and overload training periods: a laboratory study. *Medicine & science in sports & exercise*, 34(10), 1660-1666.
- G • Poirier, P. (2014). Exercise, heart rate variability, and longevity: the cocoon mystery? *Circulation*, 129(21): 2085-2087.
- G • Porges S. W. (2007). The polyvagal perspective. *Biol. Psychol.* 74: 116–143.
- G • Quintana D. S., Heathers J. A. (2014). Considerations in the assessment of heart rate variability in biobehavioral research. *Front. Psychol.* 5:805
- A • Ruha, A., Sallinen, S., & Nissila, S. (1997). A real-time microprocessor QRS detector system with a 1-ms timing accuracy for the measurement of ambulatory HRV. *IEEE Transactions on Biomedical Engineering*, 44(3), 159-167.
- A • Scargle, J. (1982). Studies in astronomical time series analysis. II-Statistical aspects of spectral analysis of unevenly spaced data," *Astrophys J*, 263: 835-853.
- G • Selye, H. (1946). The general adaptation syndrome and the diseases of adaptation. *The journal of clinical endocrinology*, 6(2), 117-230.
- A • Shaffer F., Combatalade D. C. (2013). Don't add or miss a beat: a guide to cleaner heart rate variability recordings. *Biofeedback* 41: 121–130.
- G • Shaffer F., McCraty R., Zerr C. L. (2014). A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Front. Psychol.* 5:1040

# Additional resources for your reading pleasure

- G • Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in public health*, 5: 258
- C • Smith, C. A., & Lazarus, R. S. (1990). Emotion and adaptation. *Handbook of personality: Theory and research*, 609-637.
- T • Stanley J., Peake J. M., Buchheit M. (2013). Cardiac parasympathetic reactivation following exercise: implications for training prescription. *Sports Med.* 43: 1259–1277
- R • Stein P. K., Pu Y. (2012). Heart rate variability, sleep and sleep disorders. *Sleep Med. Rev.* 16: 47–66.
- G • Stein, P. K., Bosner, M. S., Kleiger, R. E., & Conger, B. M. (1994). Heart rate variability: a measure of cardiac autonomic tone. *American heart journal*, 127(5): 1376-1381.
- PC • Strang, A. J., Funke, G. J., Russell, S. M., Dukes, A. W., & Middendorf, M. S. (2014). Physio-behavioral coupling in a cooperative team task: contributors and relations. *Journal of Experimental Psychology: Human Perception and Performance*, 40(1), 145.
- A • Tarvainen, M. P., Niskanen, J. P., Lipponen, J. A., Ranta-Aho, P. O., & Karjalainen, P. A. (2014). Kubios HRV—heart rate variability analysis software. *Computer methods and programs in biomedicine*, 113(1): 210-220.
- C • Thayer, J. F., Åhs, F., Fredrikson, M., Sollers III, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, 36(2): 747-756.
- C • Thayer J. F., Hansen A. L., Saus-Rose E., Johnsen B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. *Ann. Behav. Med.* 37: 141–153.
- G • Thayer J. F., Lane R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *J. Affect. Disord.* 61: 201–216
- PF • Thompson, A. G., Swain, D. P., Branch, J. D., Spina, R. J., & Grieco, C. R. (2015). Autonomic response to tactical pistol performance measured by heart rate variability. *The Journal of Strength & Conditioning Research*, 29(4), 926-933.
- R • Weber, C. S., Thayer, J. F., Rudat, M., Wirtz, P. H., Zimmermann-Viehoff, F., Thomas, A., ... & Deter, H. C. (2010). Low vagal tone is associated with impaired post stress recovery of cardiovascular, endocrine, and immune markers. *European journal of applied physiology*, 109(2), 201-211.

# Thank You!



comments, questions, and collaborations

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