Music & Wearable Computing for Health and Learning:

a Decade-long Exploration on a Neuroscience-inspired Interdisciplinary Approach

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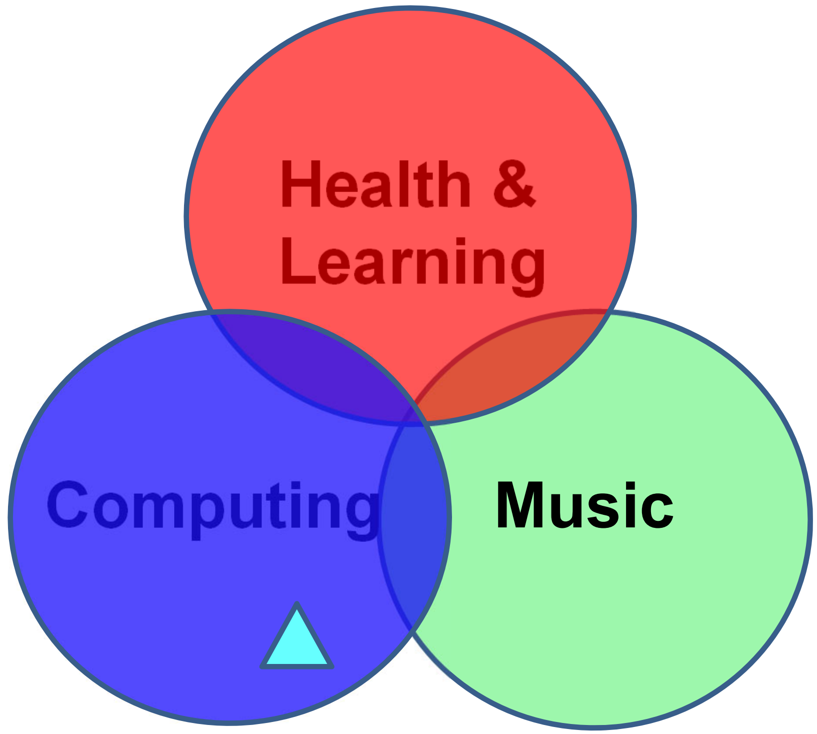
Outline

- **Motivation**
- **Music and wearable computing for motor functions**
- **Reflections, key insights and future directions**
- ***Advice based on a neuroscience-inspired & DL-based educational model***

What have attracted me to this particular unchartered water?



NGS (ISEP now) was established about 10 years ago to foster cross-disciplinary research.

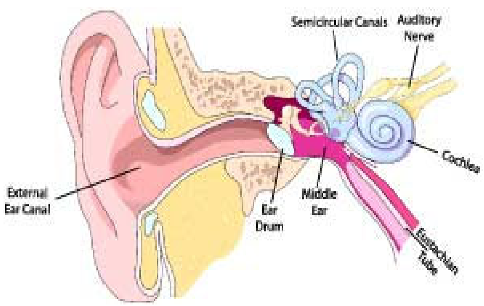
Roughly at the same time I have got to know a concept of **neurologic music therapy**.

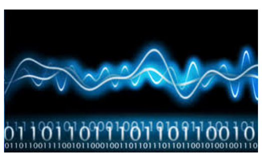
The freedom after P&T allowed me to step out of my comfortable zone to explore the boundary between computing, music and healthcare/learning.

Reinvent my research program via a multidisciplinary approach:

From audio signal processing to applied machine learning and real-world applications

Sound and Music Perception/Generation



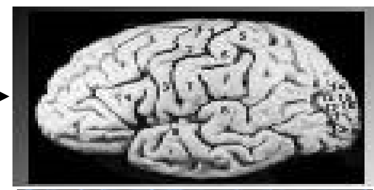


Audio Signal Processing

P& T
On 1 July 2011

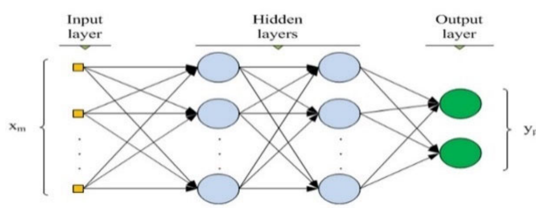
Neuroplasticity

Gottfried Schlaug: Can SMC help?
(my first sabbatical @HMS)



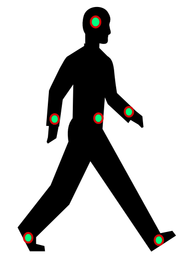
Synaptic

Connections



Applied Machine Learning

Motor Functions

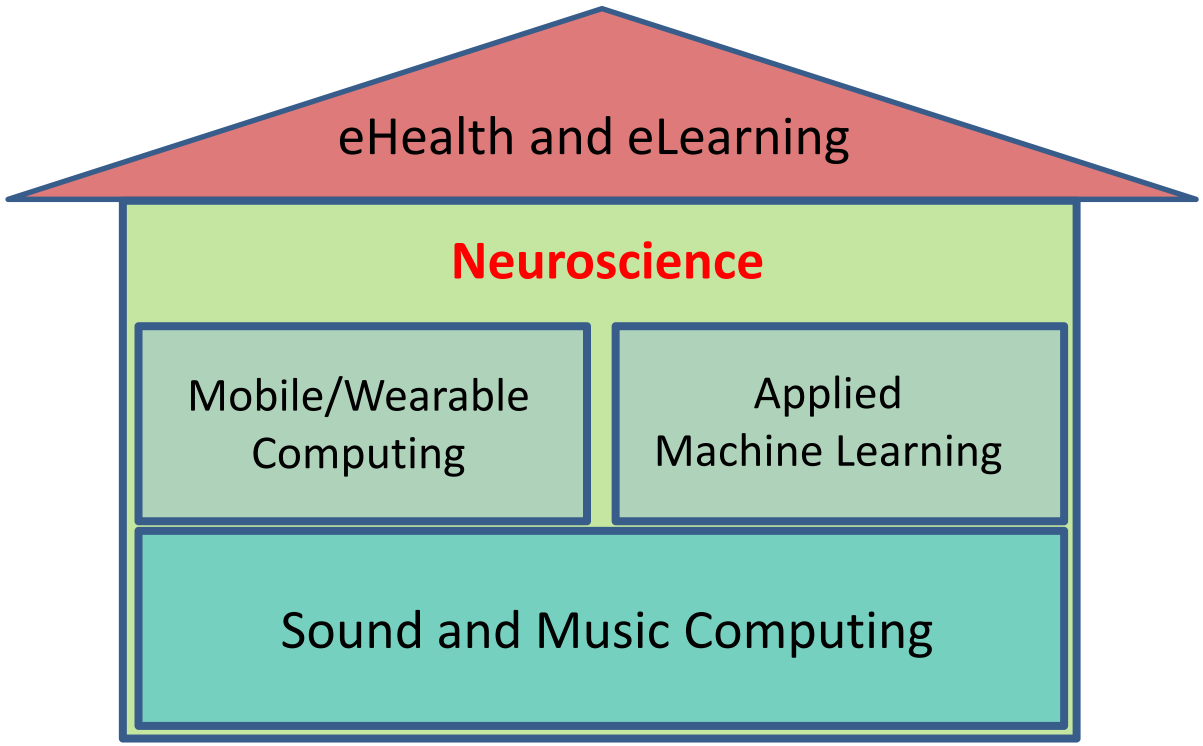


Learn to walk
(e.g., Parkinson's disease)

Learn to speak
(e.g., aphasia)

Real-world applications:
eLearning and eHealth

Starting to build a new hut:
Neuroscience-inspired and application-driven research program:
a multidisciplinary approach – connecting the dots



This hut represents what we do (the research themes) in the NUS SMC lab.

Reinvent my research program via a multidisciplinary approach:

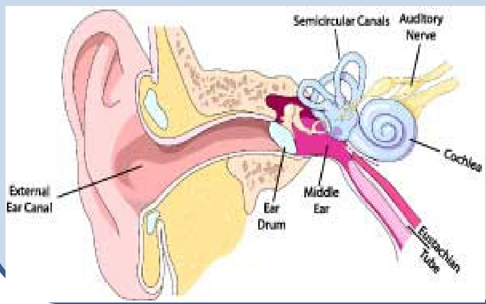
From audio signal processing to applied machine learning and real-world applications

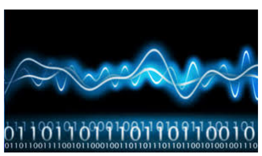
Sound and Music Perception/Generation

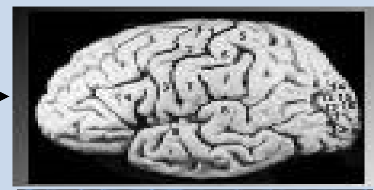
Neuroplasticity

Motor Functions

Entrainment

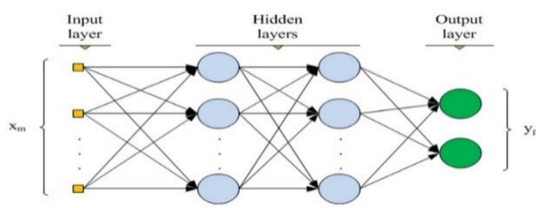


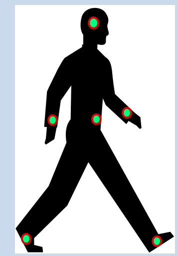




Synaptic

Connections





Learn to walk

(e.g., __gait__ of people with Parkinson's disease Ref. Keynote 3)

Learn to speak

Audio Signal Processing

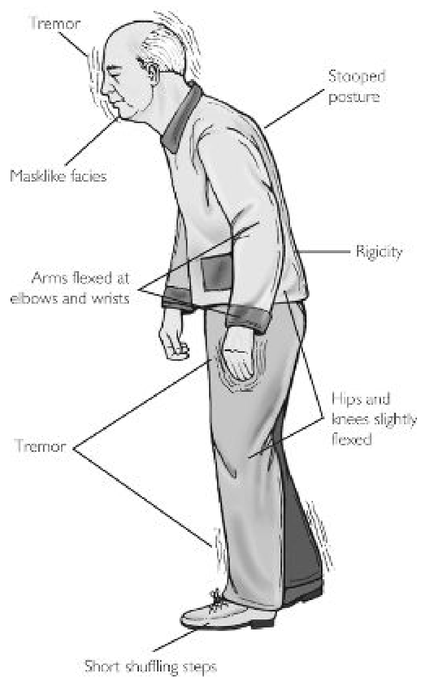
Applied Machine Learning

Real-world applications: eLearning and eHealth

P& T
On 1 July 2011

Parkinson's disease (PD): motor symptoms

- Four major motor impairments -> unstable gait and falls



  - **Tremor:** Involuntary trembling of the limbs
  - **Rigidity:** Stiffness of the muscles
  - **Akinesia:** Lack/slowness of initiating and maintaining movement
  - **Postural instability:** Stooped posture and difficulty maintaining balance

There is no cure for PD until now. Rhythmic Auditory Stimulation (RAS) is a clinically proven neurologic music therapy for motor rehab (but: manpower intensive).

How can SMC help make RAS intervention accessible & affordable?

Outline

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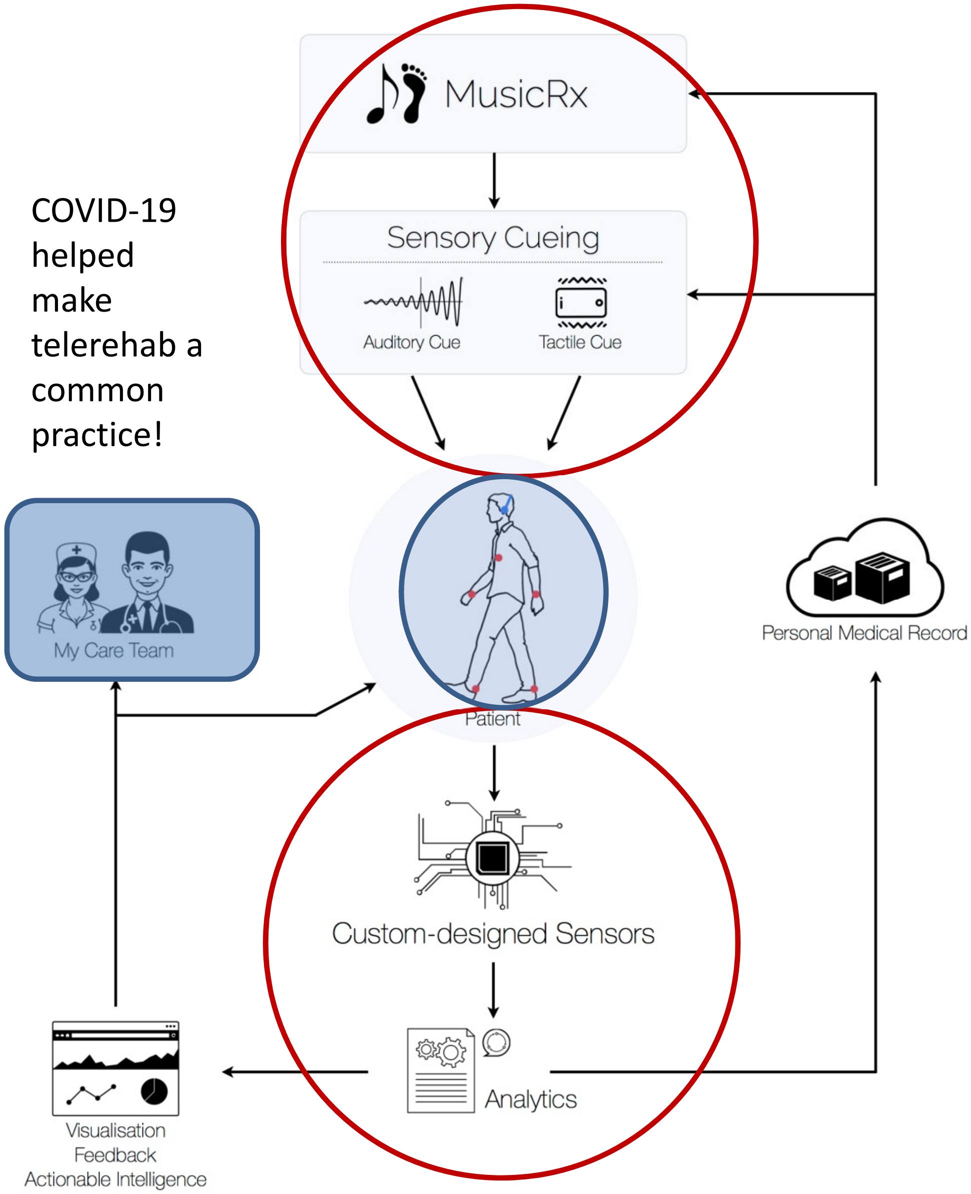
Accessible & affordable Music and wearable computing for Parkinson's disease patients (e-Health framework)

COVID-19 helped make telerehab a common practice!



Computerized music intervention to improve patient's gait
(e.g., **MusicRx-C, MIMES**)

How do we know the intervention is effective? We need evidence!

Wearable sensors based **Gait assessment** to quantify outcome measures: **a closed loop solution**
(e.g., **iRACE, MANA**)

Affordable music & wearable technology for health/rehab (RAS)

Research Problems

(2 clusters):

Sound and Music computing

- A Music Search Engine for Therapeutic Gait Training (ACM MM2010)
- Auditory Tempo Stability (ISMIR2013, PloS One2014)
- Music recommendation for health and learning (ACM MM2012/2014, ISMIR2014)
- **MIMES:** Real-time gesture recognition and sonification (IEEE ICOT2017)
- **MusicRx-C:** Algorithmic music composition for rehabilitation

Mobile/Wearable computing

- **iRACE:** gait measurement and RAC (ACM MM2014, PloS One2015)
- **MANA1.0:** IMU sensor based gait measurement (ACM ASSETS2016/2018)
- **MANA2.0:** UWB+IMU sensor based gait measurement (ACM UbiComp2019)

We have explored several research communities for this line of research and I have got to know a number of world-class clinicians☺

2014 ISMIR Taipei, Taiwan Oct 27-31, 2014 The 15th International Society for Music Information Retrieval Conference

ISMIR 2017, SUZHOU, CHINA

International Society for Music Information Retrieval (ISMIR)

Keynote: Sound and Music Computing for Exercise and (Re-)habilitation

Ye Wang

Enhancing Collaborative Filtering Music Recommendation by Balancing Exploration and Exploitation (ISMIR2014 best paper)

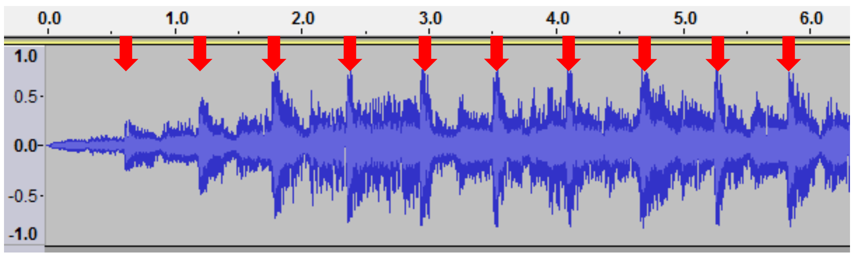
Zhe Xing, Xinxi Wang, Ye Wang

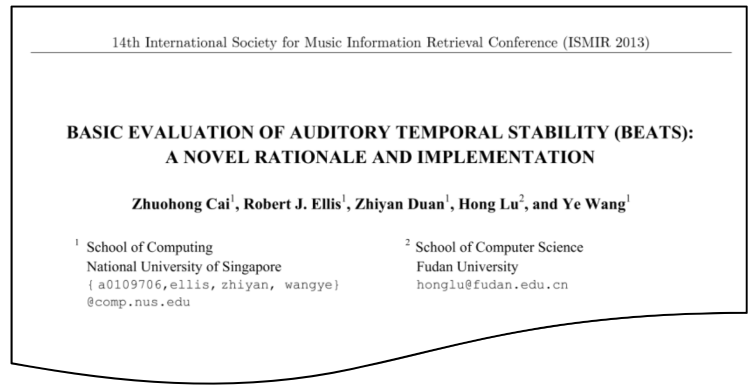
Nominated for Microsoft Research PhD Fellowship

Since then, **music and health, well-being and therapy** have become a topic of interest in the ISMIR research community. I have then organized ISMIR2017 at NUSRI Suzhou (thanks to Prof. Tan Tiow Seng) to make this line of research a prominent feature in the community.

Stanford/CCRMA 2016/SMS   Lorentz Center 2019   WearSys2020

Stability of musical tempo and gait
(Million song dataset)




14th International Society for Music Information Retrieval Conference (ISMIR 2013)

BASIC EVALUATION OF AUDITORY TEMPORAL STABILITY (BEATS): A NOVEL RATIONALE AND IMPLEMENTATION

Zhuohong Cai[1], Robert J. Ellis[1], Zhiyan Duan[1], Hong Lu[2], and Ye Wang[1]

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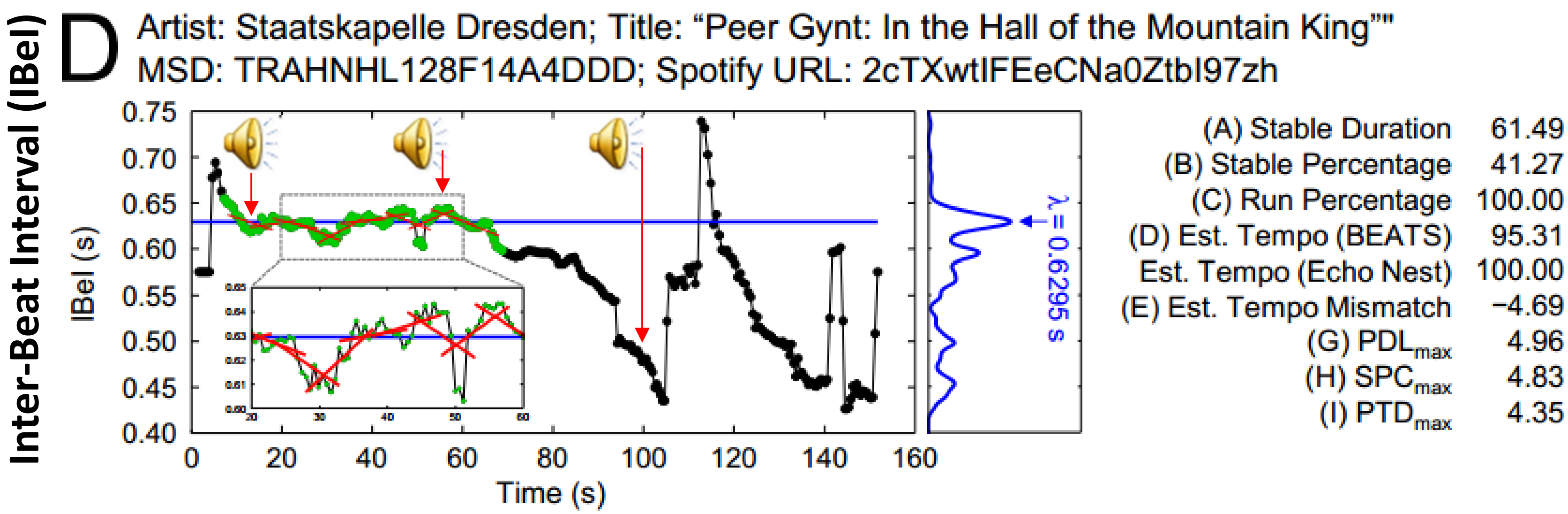
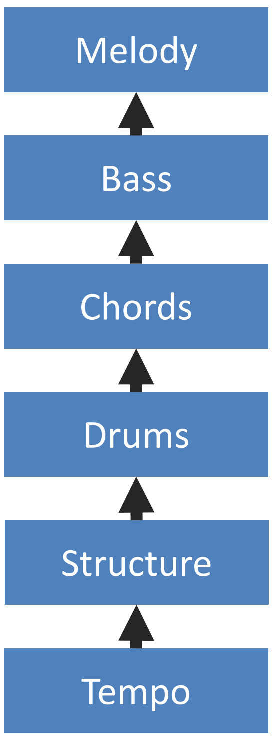
Only 20% of the MSD has stable tempo from the beginning to the end!

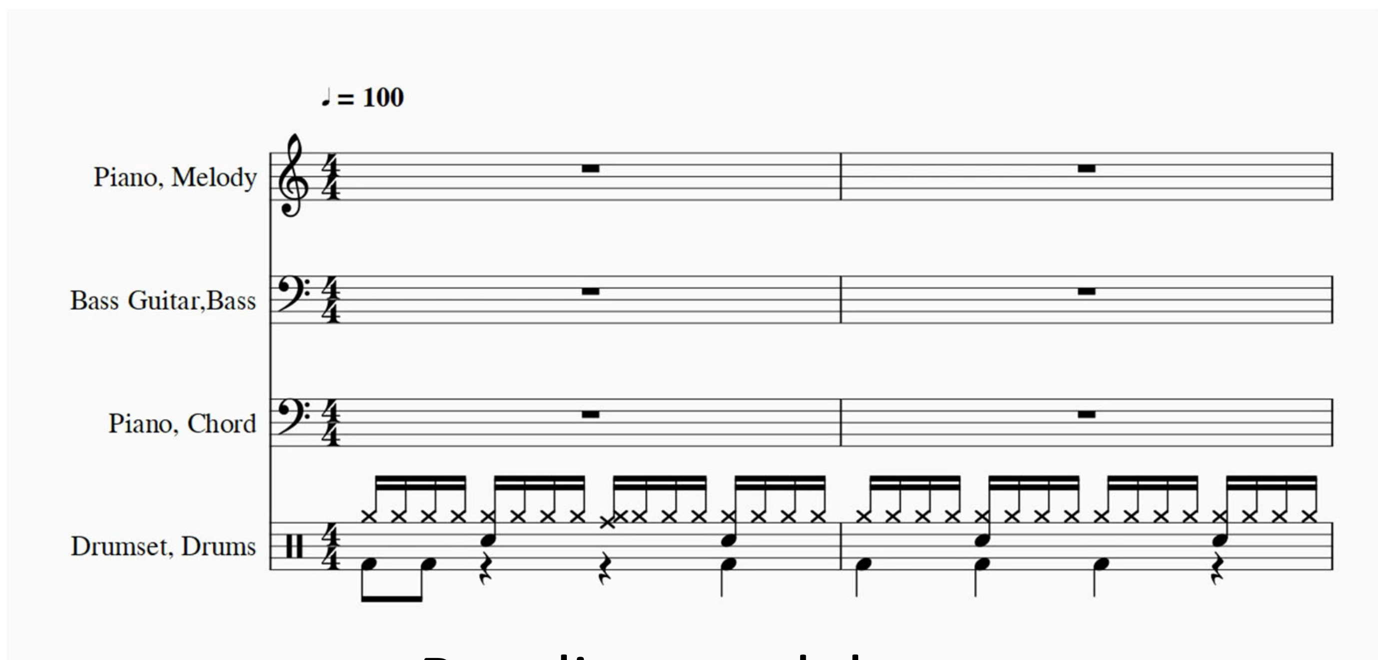


It is difficult to find music which satisfies both user preference and clinical requirements. Do we have a better solution?

MusicRx-C: **Automatic music composition** which has several advantages for clinical applications.

AI-generated royalty free music for healthcare!





Baseline model

Affordable music & wearable technology for health/rehab (RAS)

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Sound and Music computing

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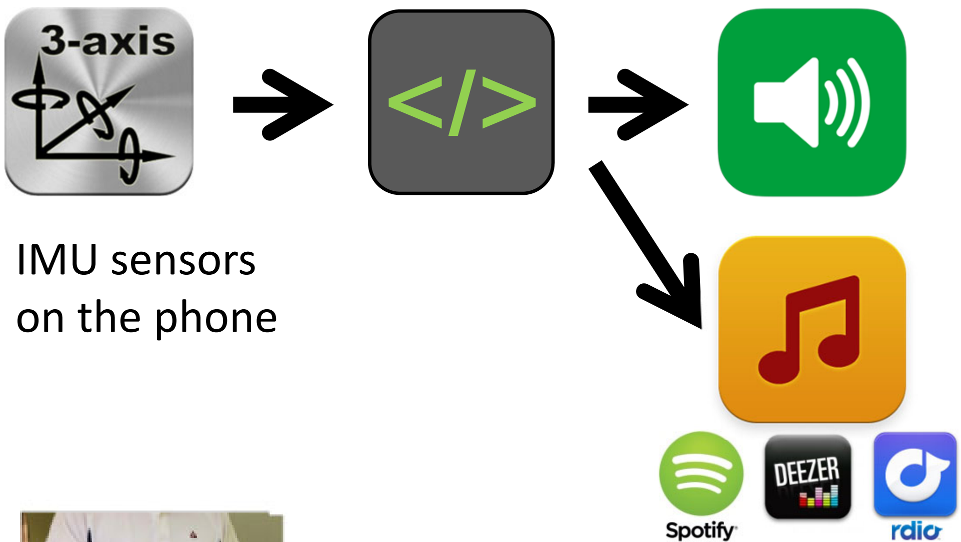
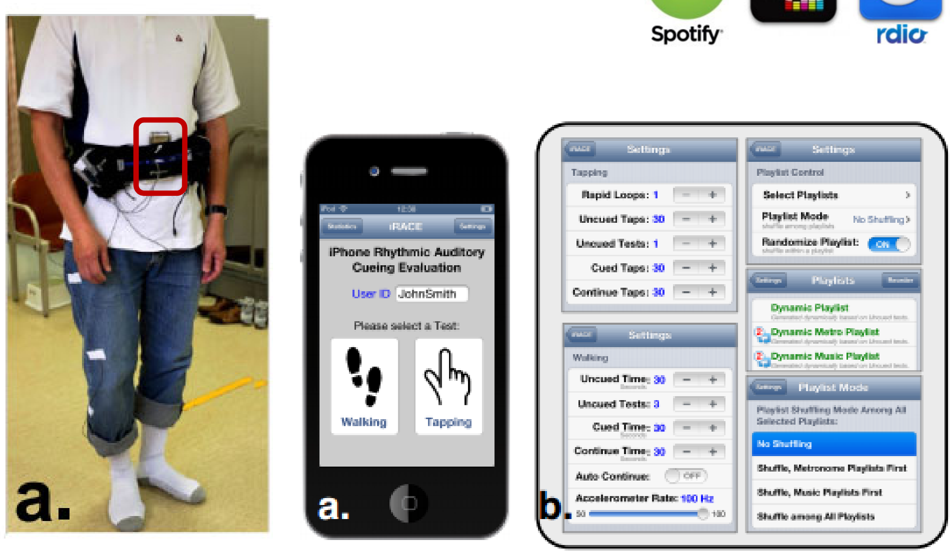
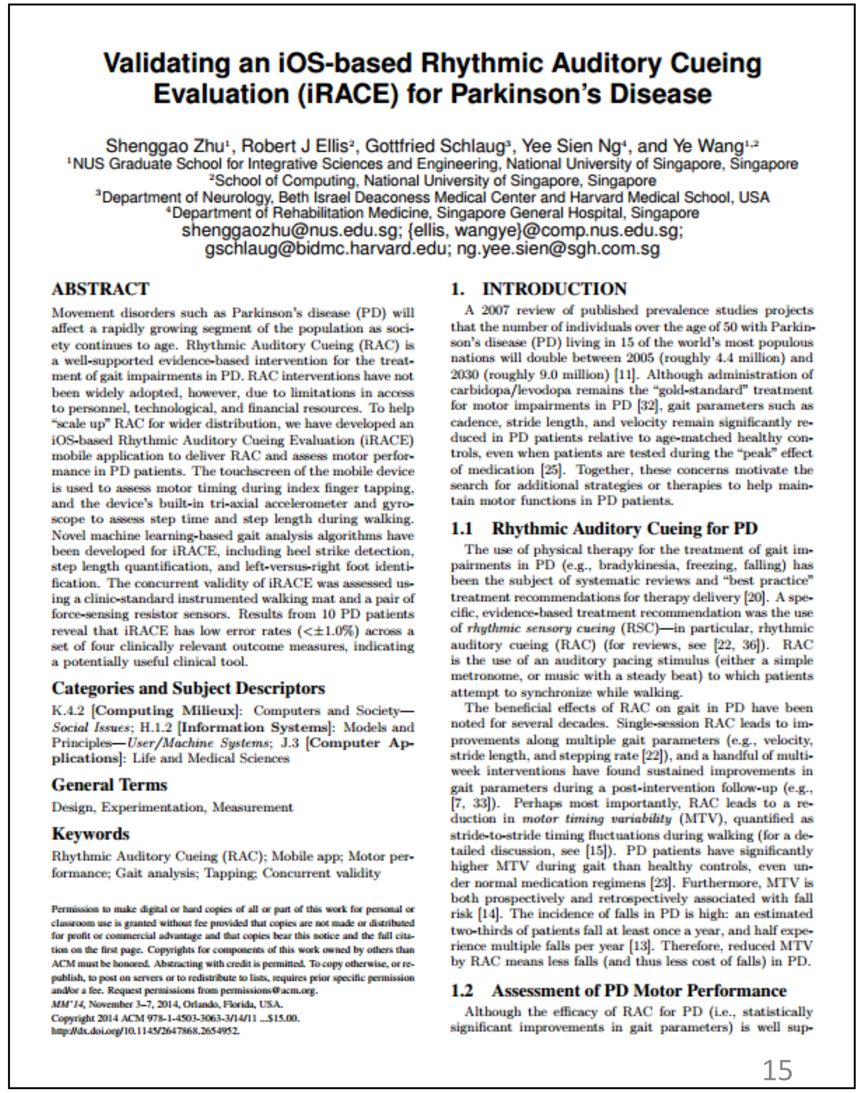
iRACE: Music-enhanced exercise and motor rehabilitation







Validating an iOS-based Rhythmic Auditory Cueing Evaluation (iRACE) for Parkinson's Disease

Shenggao Zhu[1], Robert J Ellis[2], Gottfried Schlaug[3], Yee Sien Ng[4], and Ye Wang[1,2]
[1]NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore
[2]School of Computing, National University of Singapore, Singapore
[3]Department of Neurology, Beth Israel Deaconess Medical Center and Harvard Medical School, USA
[4]Department of Rehabilitation Medicine, Singapore General Hospital, Singapore
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ABSTRACT

Movement disorders such as Parkinson's disease (PD) will affect a rapidly growing segment of the population as society continues to age. Rhythmic Auditory Cueing (RAC) is a well-supported evidence-based intervention for the treatment of gait impairments in PD. RAC interventions have not been widely adopted, however, due to limitations in access to personnel, technological, and financial resources. To help "scale up" RAC for wider distribution, we have developed an iOS-based Rhythmic Auditory Cueing Evaluation (iRACE) mobile application to deliver RAC and assess motor performance in PD patients. The touchscreen of the mobile device is used to assess motor timing during index finger tapping, and the device's built-in tri-axial accelerometer and gyroscope to assess step time and step length during walking. Novel machine learning-based gait analysis algorithms have been developed for iRACE, including heel strike detection, step length quantification, and left-versus-right foot identification. The concurrent validity of iRACE was assessed using a clinic-standard instrumented walking mat and a pair of force-sensing resistor sensors. Results from 10 PD patients reveal that iRACE has low error rates (<±1.0%) across a set of four clinically relevant outcome measures, indicating a potentially useful clinical tool.

Categories and Subject Descriptors

K.4.2 [**Computing Milieux**]: Computers and Society—*Social Issues*; H.1.2 [**Information Systems**]: Models and Principles—*User/Machine Systems*; J.3 [**Computer Applications**]: Life and Medical Sciences

General Terms

Design, Experimentation, Measurement

Keywords

Rhythmic Auditory Cueing (RAC); Mobile app; Motor performance; Gait analysis; Tapping; Concurrent validity

MM'14, November 3–7, 2014, Orlando, Florida, USA.
Copyright 2014 ACM 978-1-4503-3063-3/14/11 ...$15.00.
http://dx.doi.org/10.1145/2647868.2654952.

1. INTRODUCTION

A 2007 review of published prevalence studies projects that the number of individuals over the age of 50 with Parkinson's disease (PD) living in 15 of the world's most populous nations will double between 2005 (roughly 4.4 million) and 2030 (roughly 9.0 million) [11]. Although administration of carbidopa/levodopa remains the "gold-standard" treatment for motor impairments in PD [32], gait parameters such as cadence, stride length, and velocity remain significantly reduced in PD patients relative to age-matched healthy controls, even when patients are tested during the "peak" effect of medication [25]. Together, these concerns motivate the search for additional strategies or therapies to help maintain motor functions in PD patients.

1.1 Rhythmic Auditory Cueing for PD

The use of physical therapy for the treatment of gait impairments in PD (e.g., bradykinesia, freezing, falling) has been the subject of systematic reviews and "best practice" treatment recommendations for therapy delivery [20]. A specific, evidence-based treatment recommendation was the use of *rhythmic sensory cueing* (RSC)—in particular, rhythmic auditory cueing (RAC) (for reviews, see [22, 36]). RAC is the use of an auditory pacing stimulus (either a simple metronome, or music with a steady beat) to which patients attempt to synchronize while walking.

The beneficial effects of RAC on gait in PD have been noted for several decades. Single-session RAC leads to improvements along multiple gait parameters (e.g., velocity, stride length, and stepping rate [22]), and a handful of multi-week interventions have found sustained improvements in gait parameters during a post-intervention follow-up (e.g., [7, 33]). Perhaps most importantly, RAC leads to a reduction in *motor timing variability* (MTV), quantified as stride-to-stride timing fluctuations during walking (for a detailed discussion, see [15]). PD patients have significantly higher MTV during gait than healthy controls, even under normal medication regimens [23]. Furthermore, MTV is both prospectively and retrospectively associated with fall risk [14]. The incidence of falls in PD is high: an estimated two-thirds of patients fall at least once a year, and half experience multiple falls per year [13]. Therefore, reduced MTV by RAC means less falls (and thus less cost of falls) in PD.

1.2 Assessment of PD Motor Performance

Although the efficacy of RAC for PD (i.e., statistically significant improvements in gait parameters) is well sup-

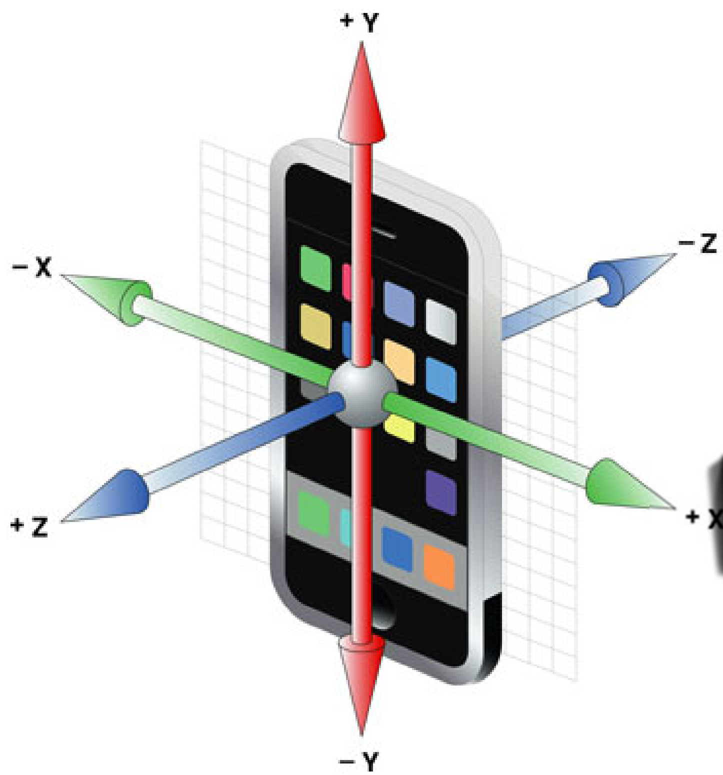
iRACE

An iOS-based Rhythmic Auditory Cueing Evaluation (iRACE) for Parkinson's Disease

Pros and cons of a smartphone based solution

Cons

- Limitations on **placement**
- Accuracy in measurement
- Redundancy and inefficiency



Pros

- Of the shelf hardware
- Mature development environment (API)
- Both sound and IMU processing on the same device

Small form factor

Identify the gap: accessible & affordable MANA sensors for gait analysis

Activity/fitness trackers (e.g, Fitbit)

Clinical gait devices

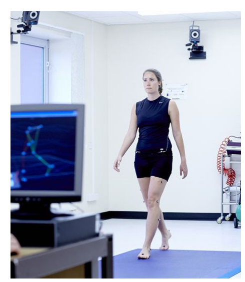
Portability

Cost

Accuracy

>$60k

Gaitrite



Ground truth

Developing MANA IMU sensors as part of training 2 PhD students (Shenggao and Boyd)

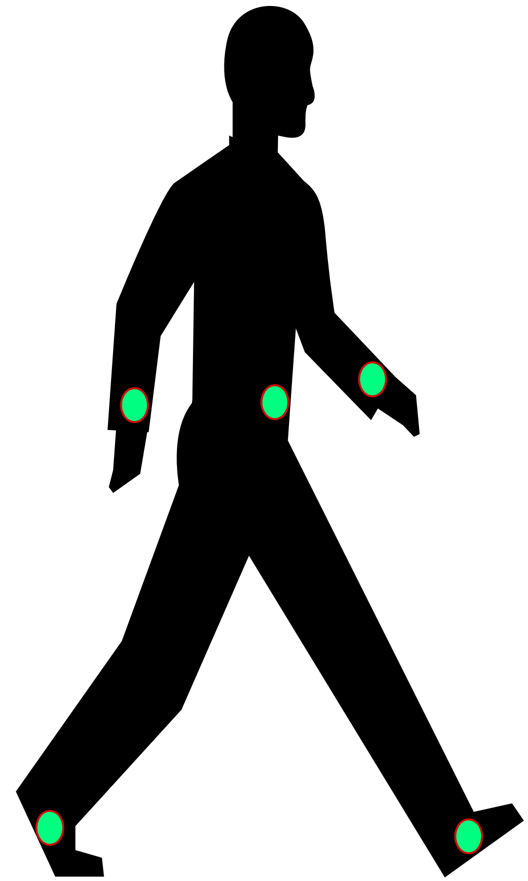
- Ultra-low power event-driven sensing
- Wireless charging
- On-board signal processing
- Low-power communication

Shenggao: MANA1.0

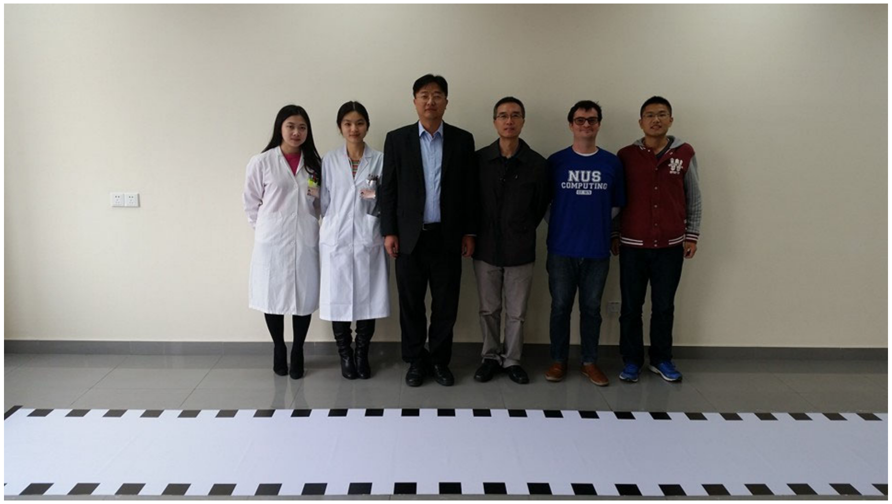
Boyd: MANA2.0

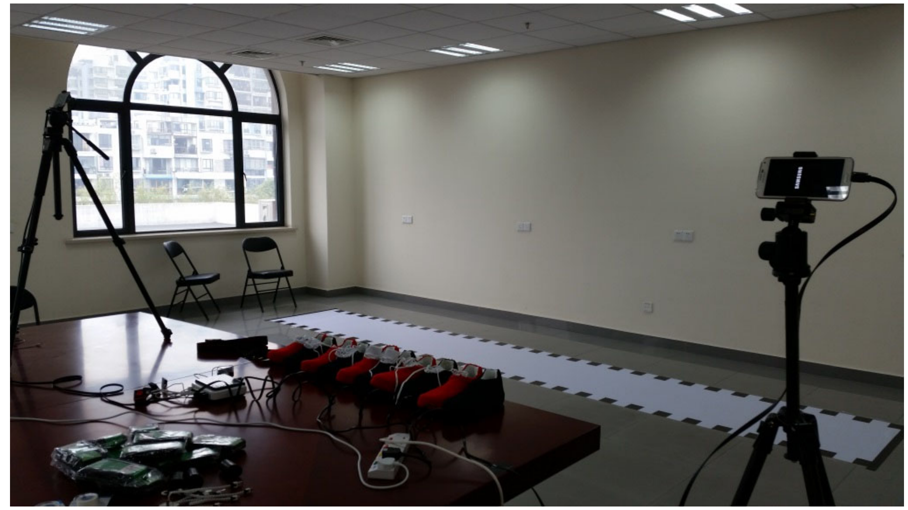
I must have completely underestimated the challenges along the journey of building hardware sensors in the CS department!

Flexible placements of wearable sensors for data collection

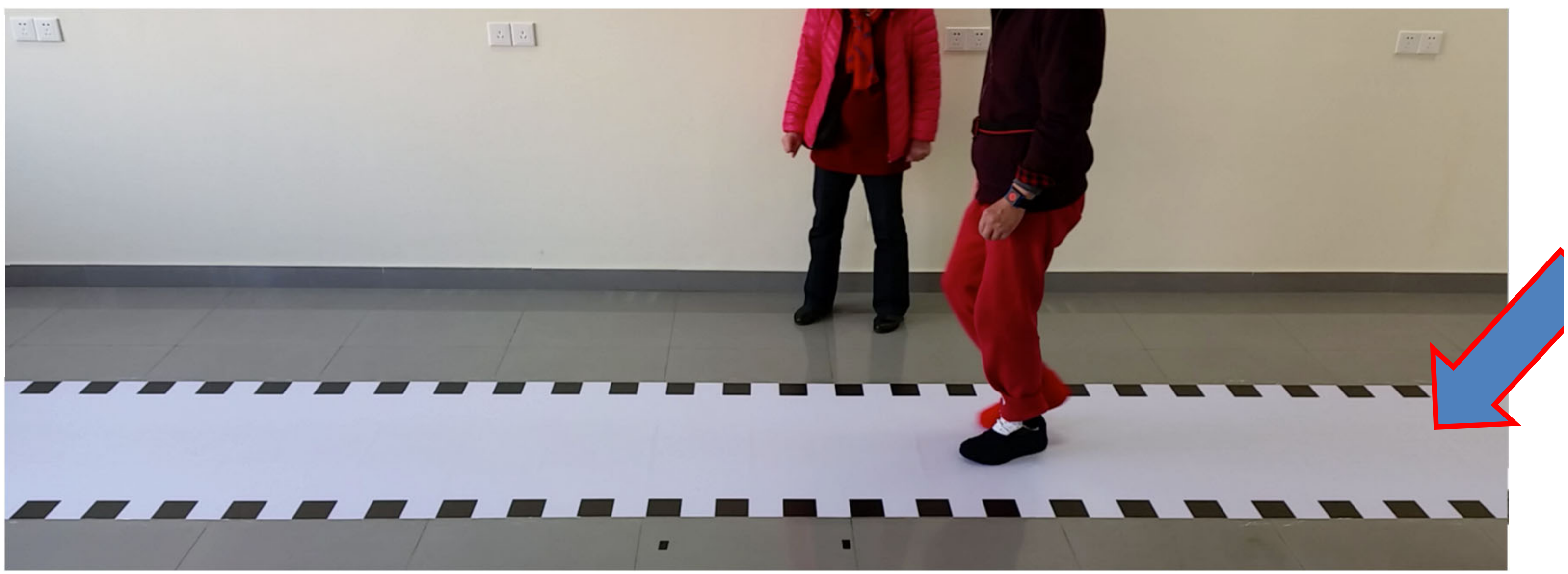


MANA1.0 system: clinical experiments

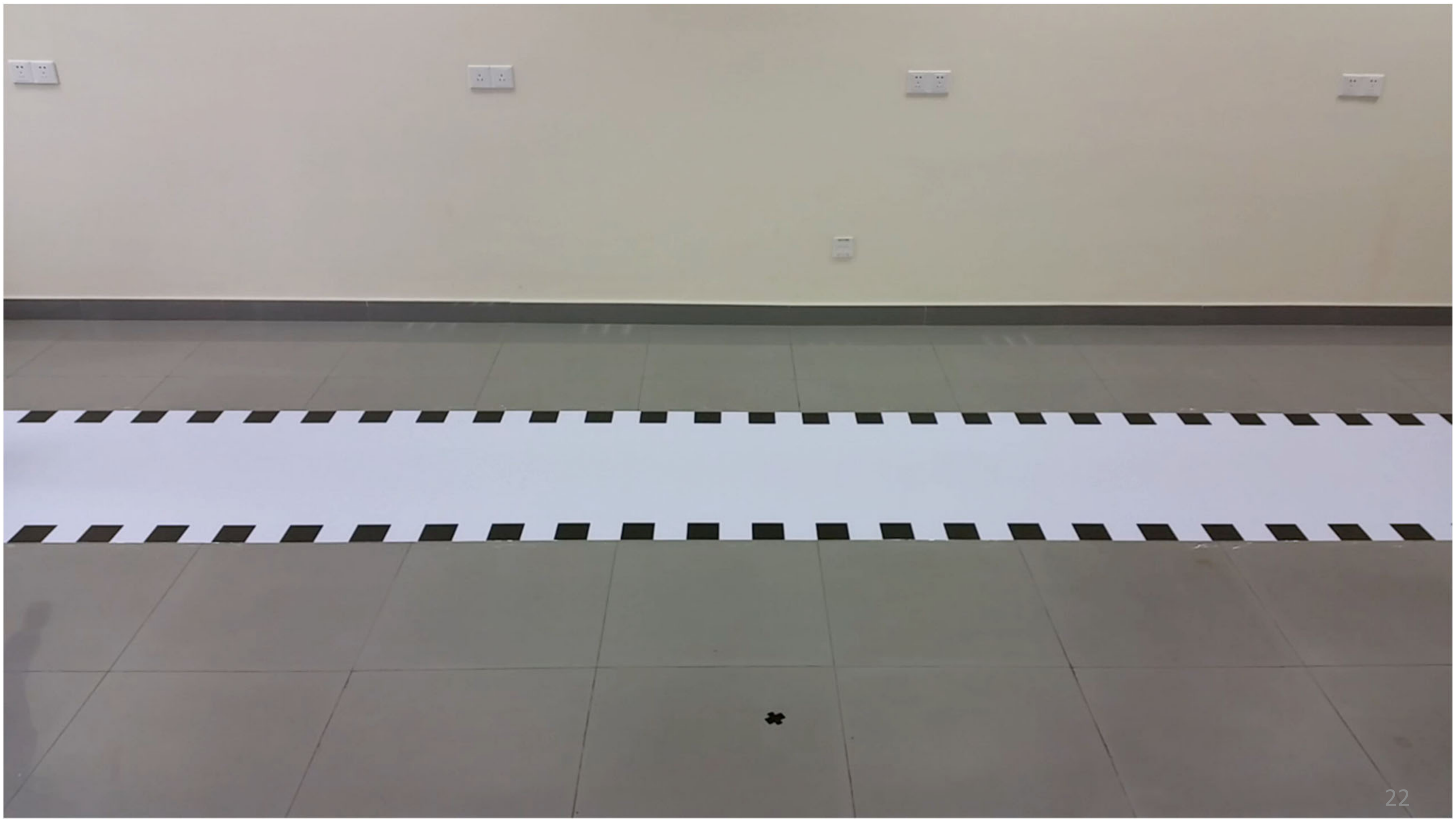




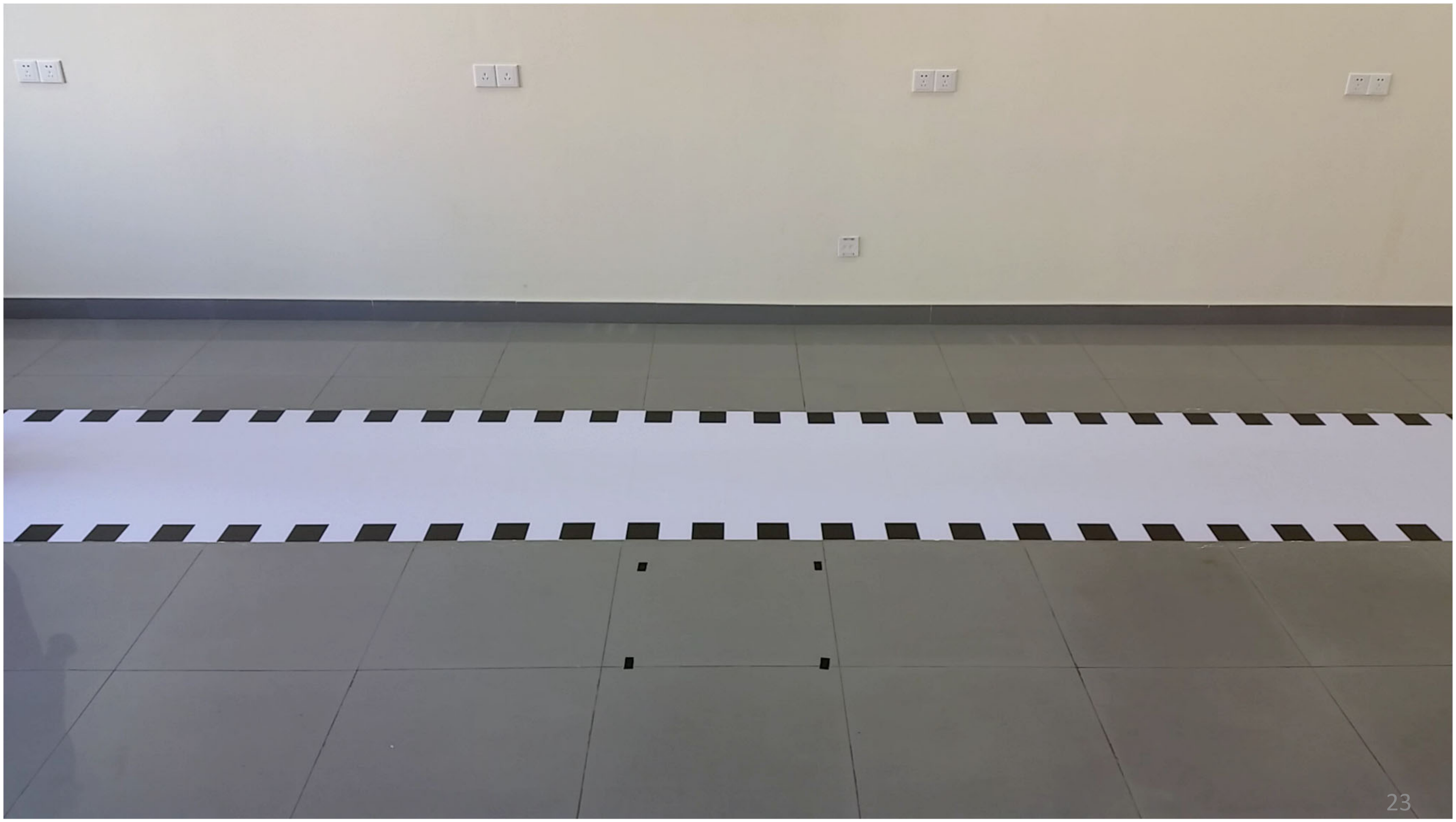
GaitRite



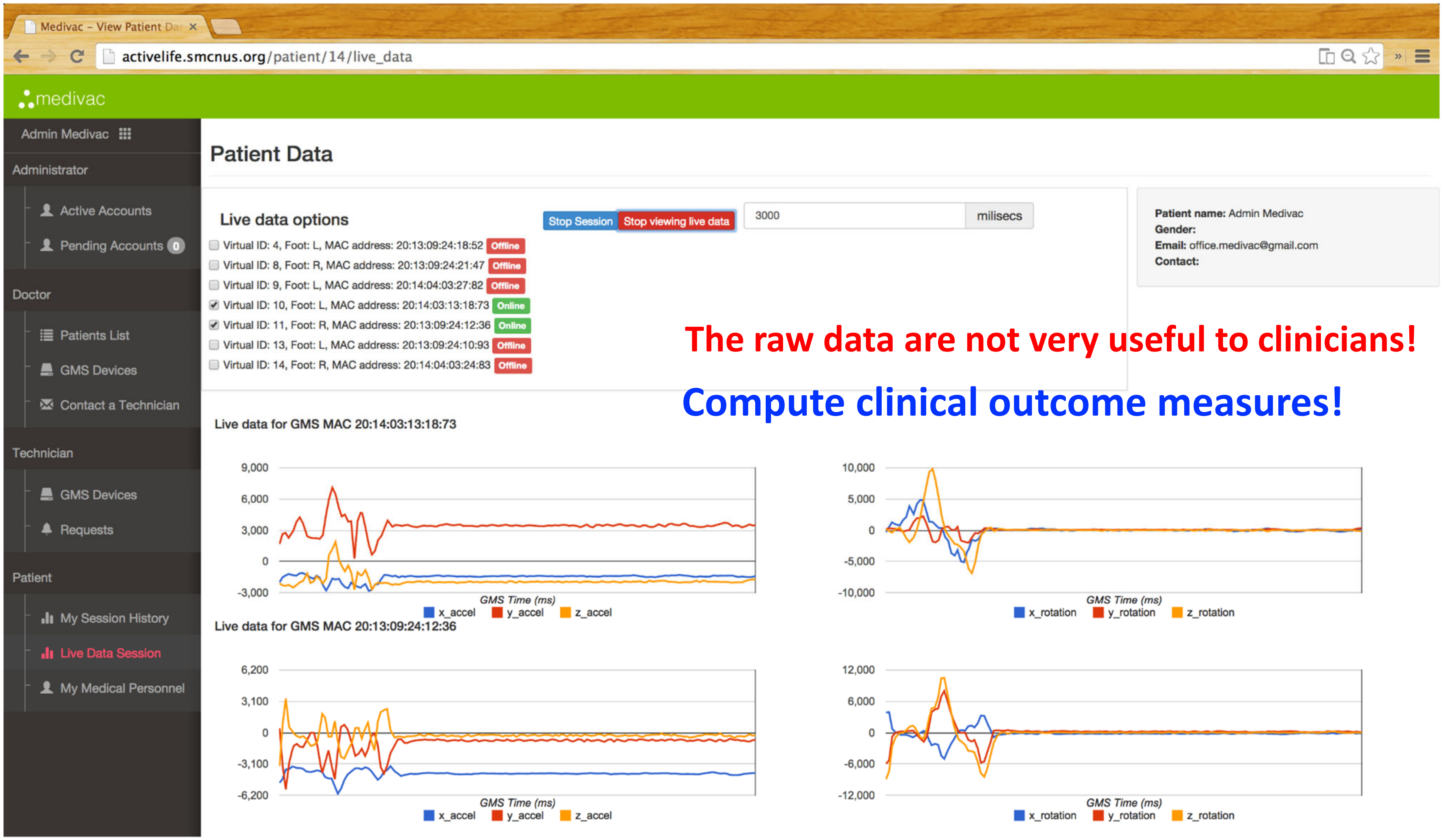
Healthy adults



Parkinson’s disease patients



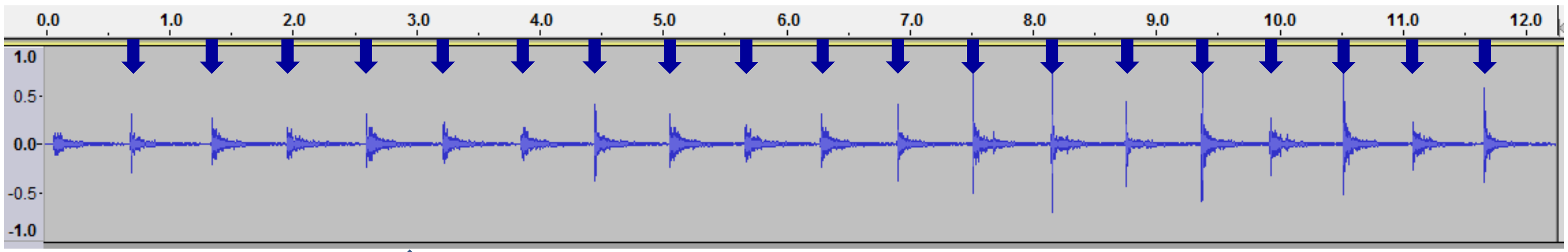
Data collection, analysis and visualization

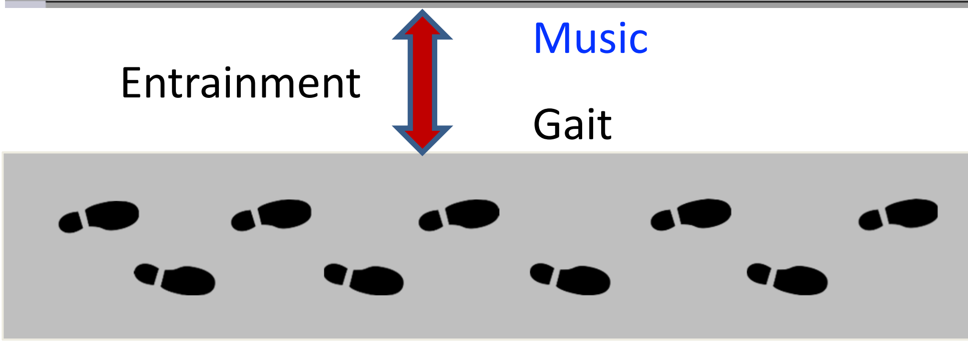


The raw data are not very useful to clinicians!

Compute clinical outcome measures!

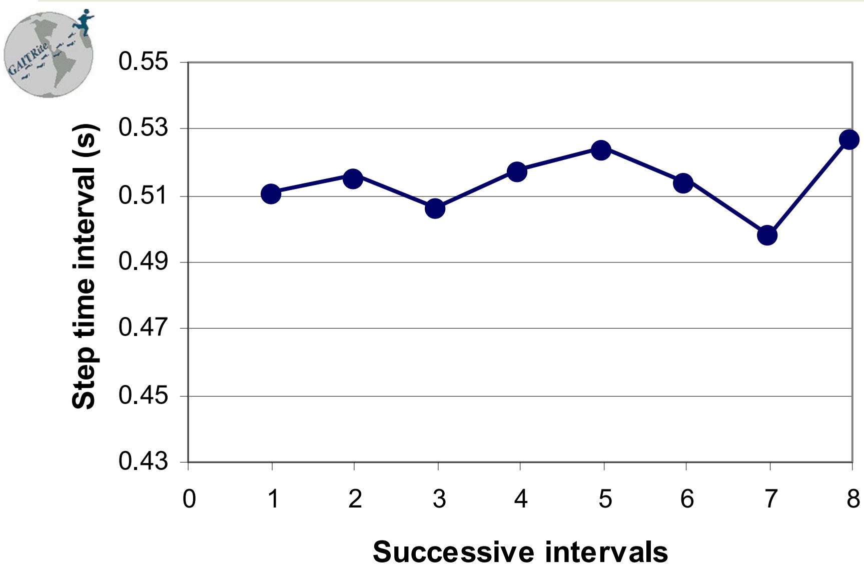
Synchronize your gait to musical beats

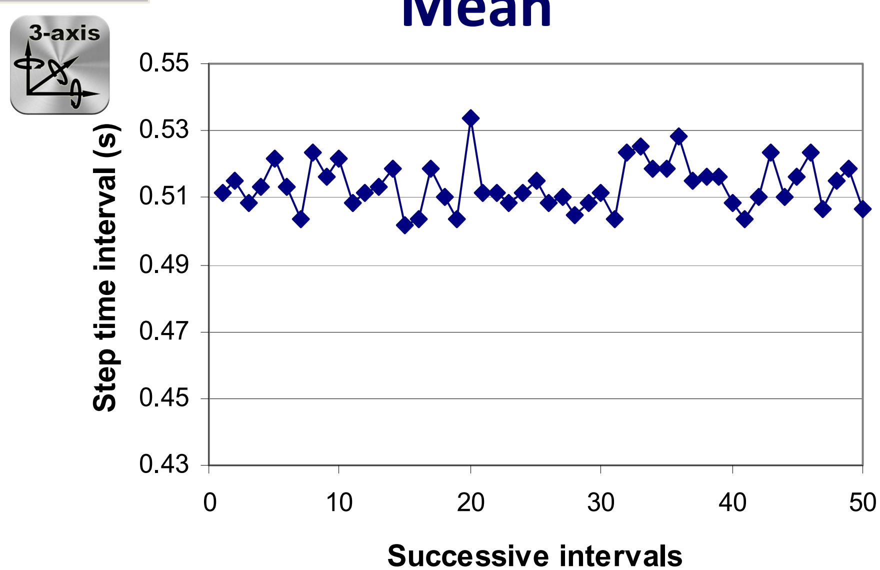




Clinical outcome measure
Coefficient of Variation (CV):

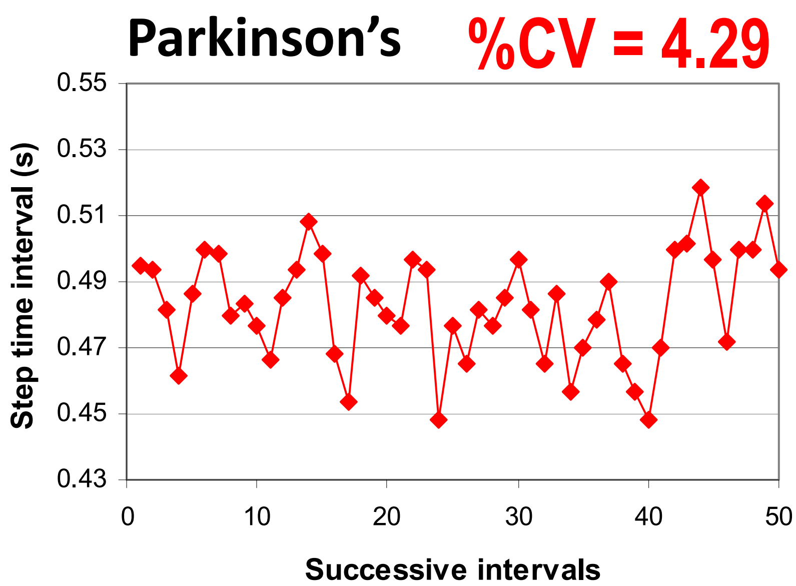
$$CV = \frac{StdDev}{Mean} \times 100 = 1.57\%$$

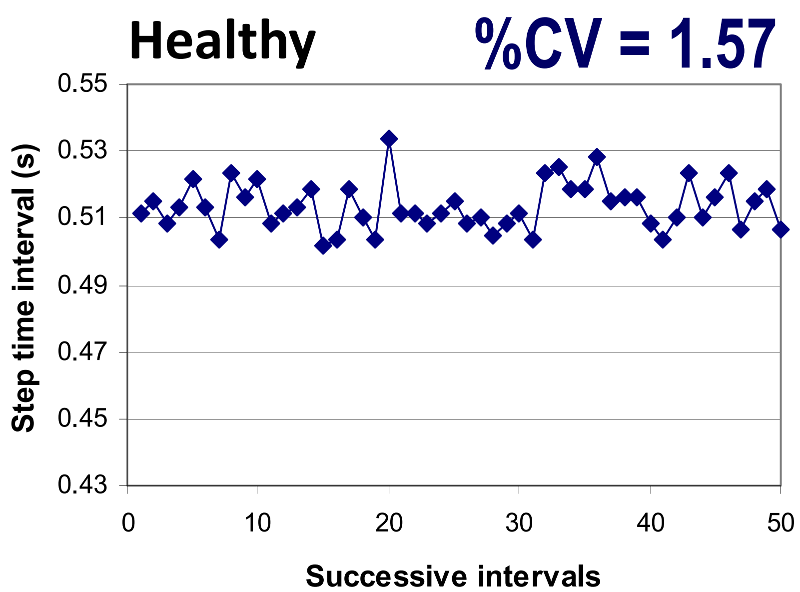




Temporal dynamics of gait in PD

- Compared with healthy individuals, patients with Parkinson's disease (PD) and Huntington's disease (HD) show <u>significantly increased</u> gait variability.





Other important outcome measures: step length and width.
It is challenging to compute them with our MANA1.0 sensors!
This motivated us to develop MANA2.0.

MANA1.0 IMU sensors: clinical trial with PD patients

RENO, NEVADA 2016

A computer vision-based system for stride length estimation using a mobile phone camera

Wei Zhu, ***Boyd Anderson, Shenggao Zhu*** & Ye Wang

The 18th International ACM SIGACCESS Conference on Computers and Accessibility

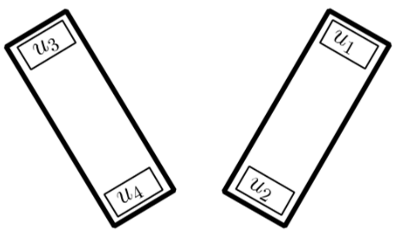
ASSETS GALWAY, IRELAND 2018

MANA: Designing And Validating A User-Centered Mobility Analysis System

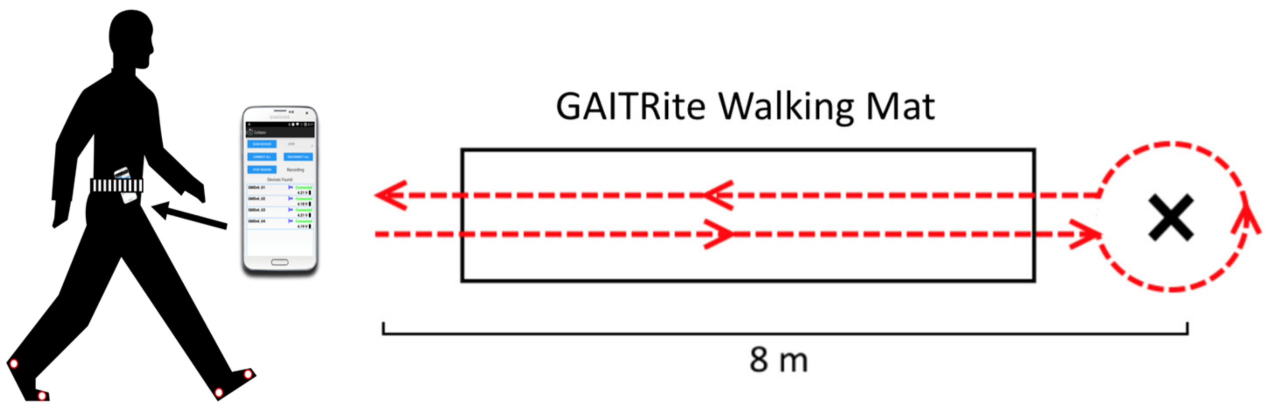
Boyd Anderson, Shenggao Zhu, Ke Yang, Jian Wang, Hugh Anderson, Chao Xu Tay, Vincent Y. F. Tan, Ye Wang

Developing MANA2.0 : Ultra-Wideband (UWB) sensors

a)



b)



MANA2.0 UWB sensors: data collection with NUS students

UBICOMP 2019

Mobile Gait Analysis Using Foot-Mounted UWB Sensors

Boyd Anderson, Mingqian Shi, Vincent Y. F. Tan, Ye Wang

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- **Reflections, key insights and future directions**
- Advice based on a neuroscience-inspired & DL-based educational model

What have we learnt from this exploration?

- **The bar for such interdisciplinary research is very high (clinical collaborators, students with the right mindset and skills, as well as grants - all must be in place: passion alone is insufficient)**

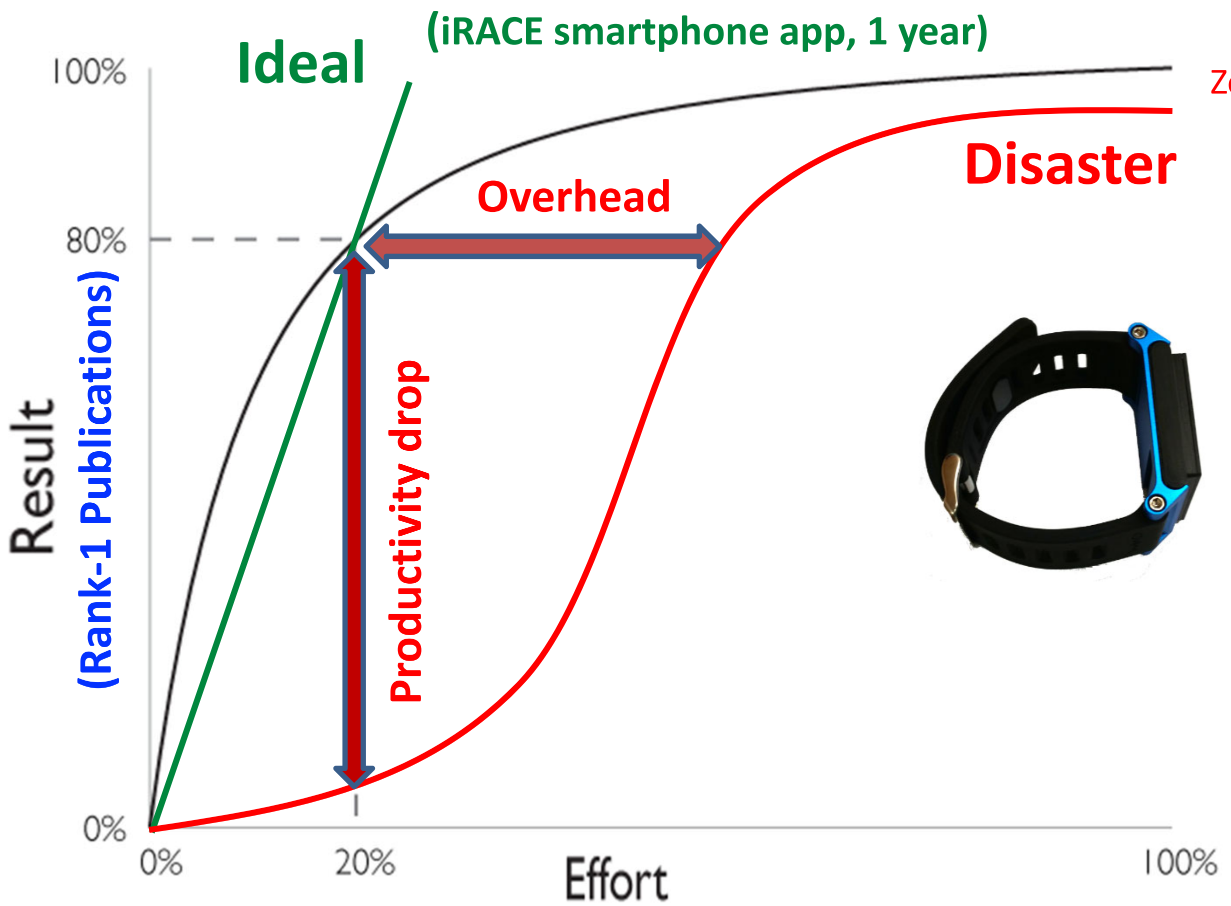
- **A lot of overhead will incur for such research projects (IRB applications, subject recruitment, etc. can be overwhelming and even scary to many CS students)**

- **I am not sure whether my decision to develop our own hardware sensors (MANA sensors) was a wise decision – let's evaluate it**

Are our iRACE/MANA projects a success or failure?

Pareto principle (80/20 principle)

MM2014, PLoS one2015, Asian Pacific Assistive Rehabilitative & Therapeutic Technologies Challenge2015



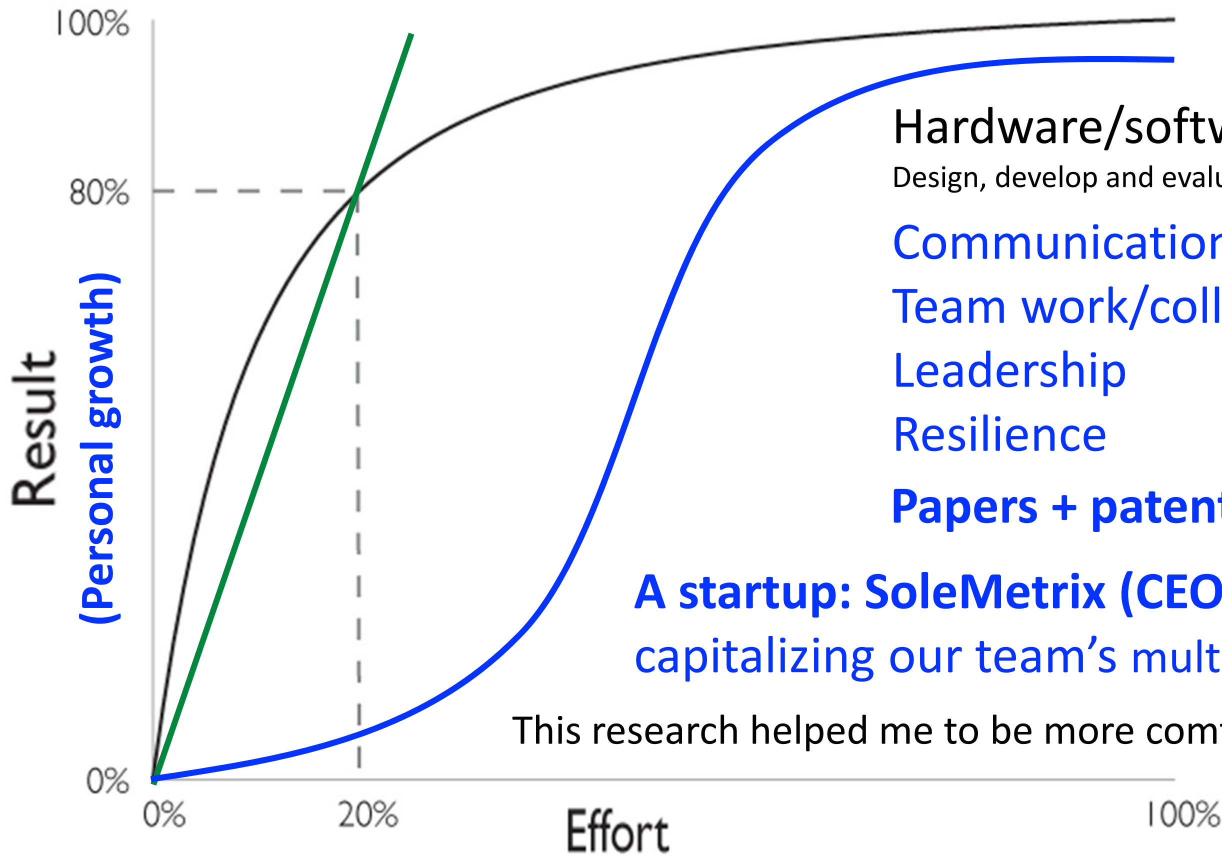
Zero rank-1 publication!

This might not be the best use of my time.

Is our MANA sensor project a success or failure?

A less glooming assessment/perspective

Growth mindset



2 PhDs + 5 FYPs

Hardware/software/algorithm

Design, develop and evaluate a prototype

Communication skills

Team work/collaboration

Leadership

Resilience

Papers + patent + MVP

A startup: SoleMetrix (CEO: Dr. Boyd Anderson):
capitalizing our team's multi-years research effort

This research helped me to be more comfortable to teach CG4002

Co-chair of CEG JAC☺

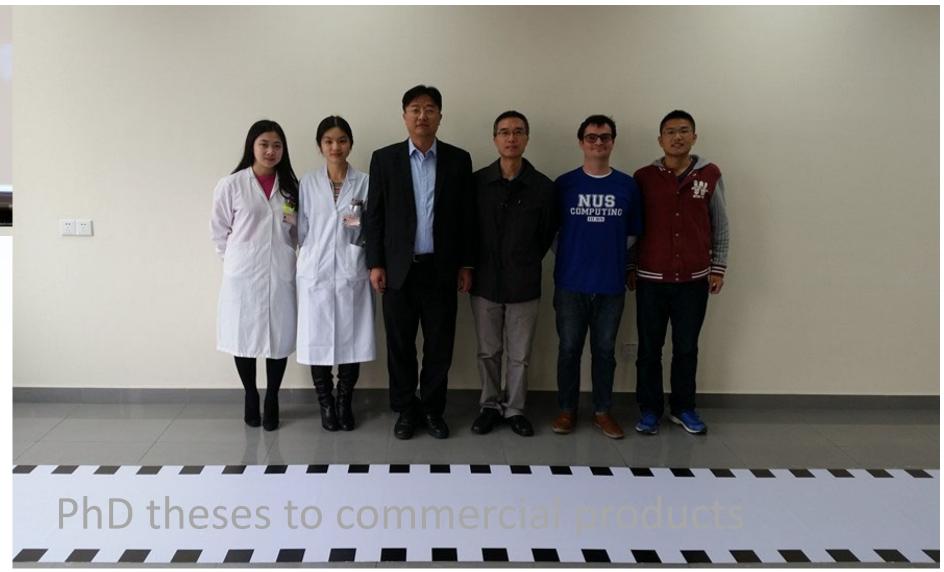
In short, this unique journey has significantly broadened our horizon, and allowed us to experience pain but to see **bigger pictures and connections!**

Thanks to my students, collaborators, and funders who enabled this exploration

Zhonghua Li
Shenggao Zhu
Chitralekha Gupta
Boyd Anderson
Mingqian Shi
Xichu Ma
Rob Ellis

Gottfried Schlaug (HMS)
Jian Wang (Huashan)
Yee Sien Ng (SGH)
Patsy Tan (SGH)
Hugh Anderson

Nokia (FI), **Smule** (US), **MOE** (SG), **A*Star** (SG), **NRF** (SG)
No fund - no fun:-)



The COVID-19 pandemic in 2020 gave me a natural break point to reflect☺

Challenges in this direction

1) Technology: assessment of mobility and speech

Data collection and annotation are challenging!

2) Clinical: collaborators who must have both passion & time

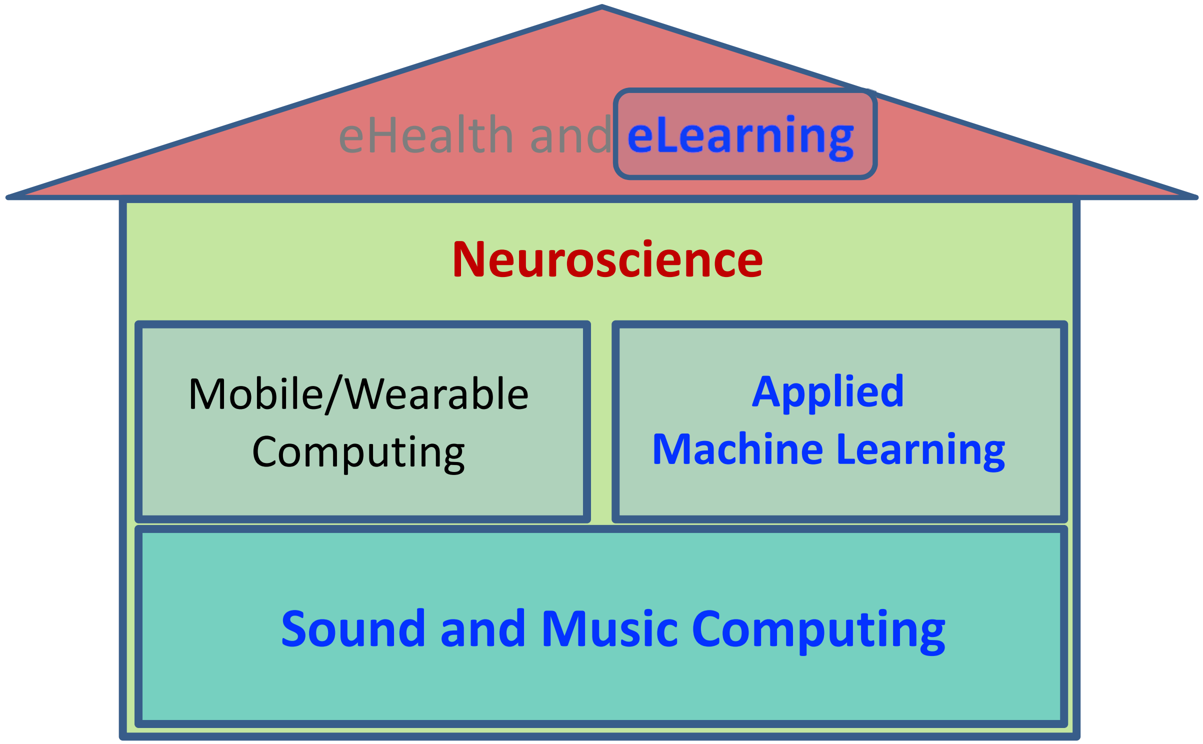
Passion is a necessary but insufficient condition!

IRB and recruiting patients!

COVID-19 brought our clinical experiments to a standstill!

What are our next research frontiers?

Neuroscience-inspired and application-driven research program: a multidisciplinary approach



In our second application scenario, instead of helping PD patients, we develop SMC technologies to help people like myself! Here is a true story which motivated me to start a brand new research theme in the lab!

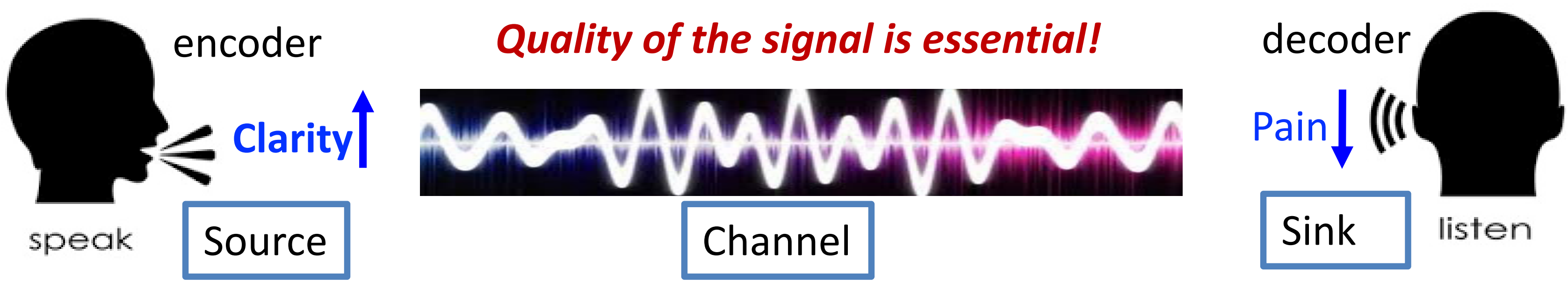
An anonymous student feedback before my P&T: “I had difficulties to understand Prof. Wang’s bizarre English during his lectures. He should take an oral English lesson to make his lectures less painful to understand.”

Good pronunciation is crucial for effective communications

I took this comment as an insult initially. But later I realized that the comment was sensible – it helped me identify not only my own weakness in English but also an immensely important societal need - a pain that billions of language learners suffer! They all desire a good solution which is a great opportunity for my lab!

In the past 3 days, you have listened to so many research talks. Are you tired? If yes, why?

Let me analyze this phenomenon from the Shannon information theoretical point of view.



The speaker should keep the ***entropy (~uncertainty)*** as low as possible to ensure accurate decoding of your message. Conversely, bad pronunciation makes it a mentally taxing task.

I assume that you will be much less tired if every presenter spoke crystal clear English like a TV broadcaster/Rob Ellis – making the listening a more pleasant experience! This expectation might be a bit too high from the listeners. Nevertheless, it is worth for the speakers to be considerate from the listener's standpoint and to make the effort!

Thanks to the student's feedback, I made some serious effort to improve my own English while launching a number of research projects to address this important problem!

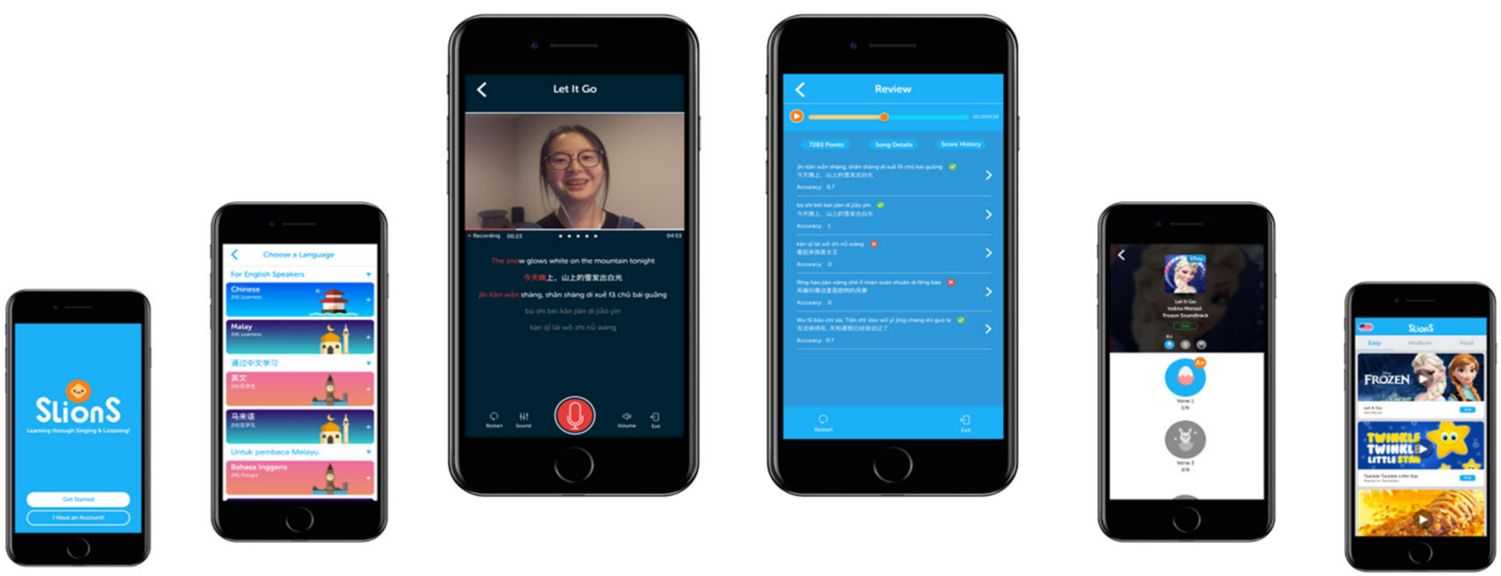
SMC to Transform Language Learning
From rote learning to engaging , joyful & effective learning

We have developed the world's first Karaoke app – SLIONS (Singing and Listening to Improve Our Natural Speaking) for language learning! But I must stress that our SLIONS Karaoke app is free from transmitting COVID-19 virus and is safer to use as compared to the ones in KTVs☺

Research Problems:

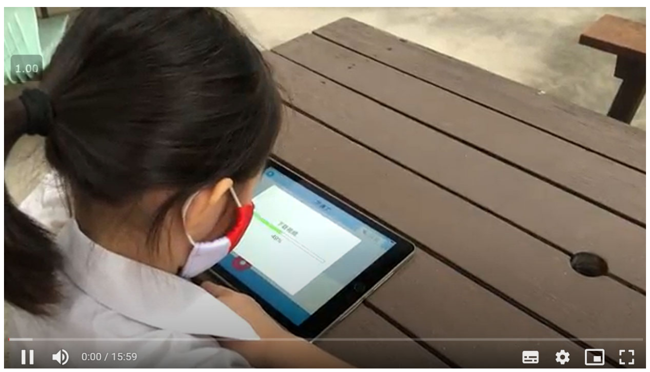
1) lyric complexity (ISMIR 2015)
2) Singing voice intelligibility (ISMIR 2017, IEEE/ACM TASLP2020)
3) Singing-to-text transcription (ISMIR2017/2018, Interspeech2018, ICASSP2019, IEEE/ACM TASLP2020)
4) SLIONS Karaoke app for language learning (ACM Multimedia2018)

Wang Riwu: NUS Outstanding Undergraduate Researcher Prize (OURP) AY 2018/2019



SLIONS-Kids: an AI-enabled Smartphone App for P1/P2 Kids to learn Mandarin, developed during the COVID-19 pandemic

SLIONS Kids



Ng Xin Ler: SoC Outstanding Computing Project Prize for the AY 2019/2020

Ronald Santoso: SoC Outstanding Computing Project Prize for the AY 2020/2021

Based on my experience so far, our undergraduate students are entirely capable of doing quality research as long as they are inspired to do it!

SLIONS-Kids

SLIONS-Kids

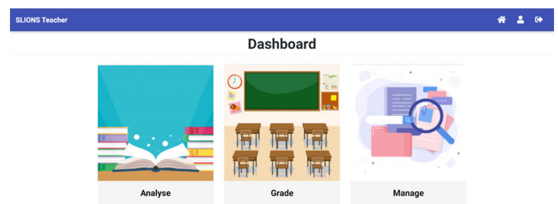
Mobile App

For students

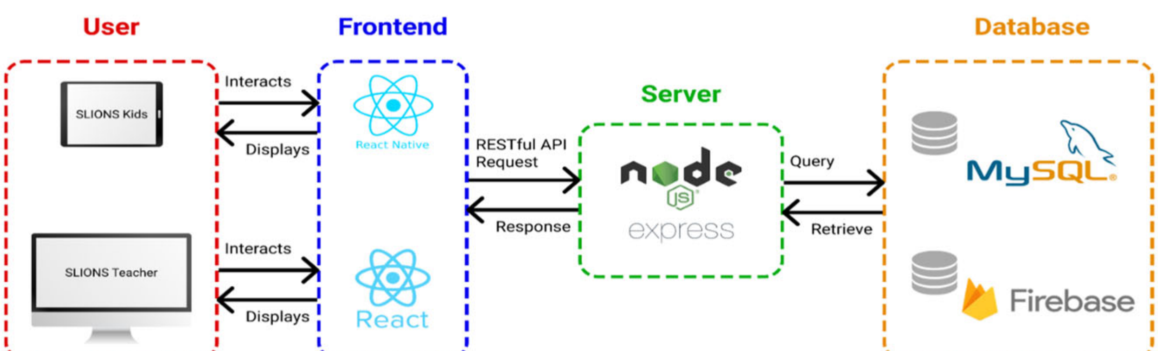
Sing and read to learn a language

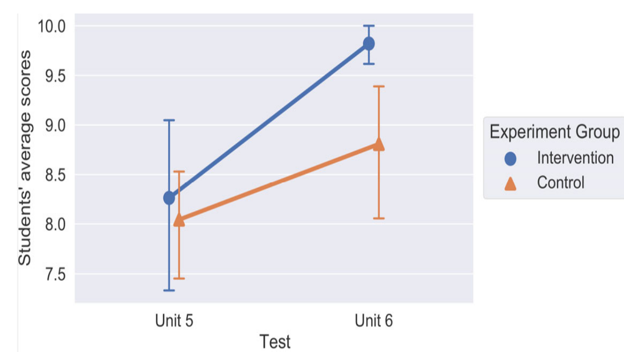
Web app

For teachers



Rate, give comments and see statistics

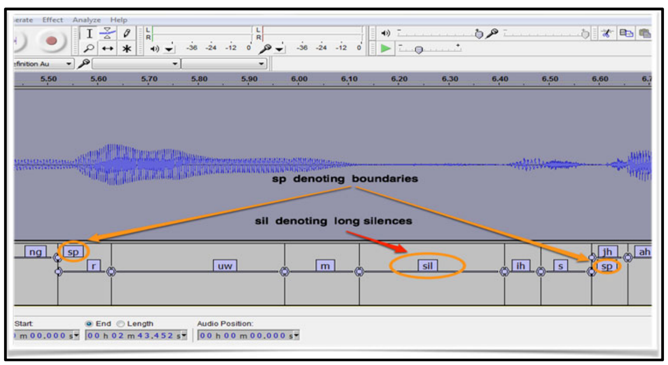




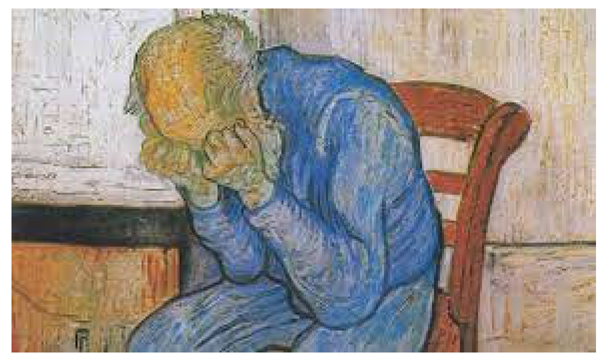
The NUS Sung and Spoken Lyrics Corpus (NUS-48E): A Quantitative Comparison of Singing and Speech

Zhiyan Duan, Sam Fang, Bo Li, Khe Chai Sim and Ye Wang

This line of research on speech/singing voice eventually qualified me to become a APSIPA Distinguished Lecturer (2021-2022).



Data collection & **annotation = pain!**



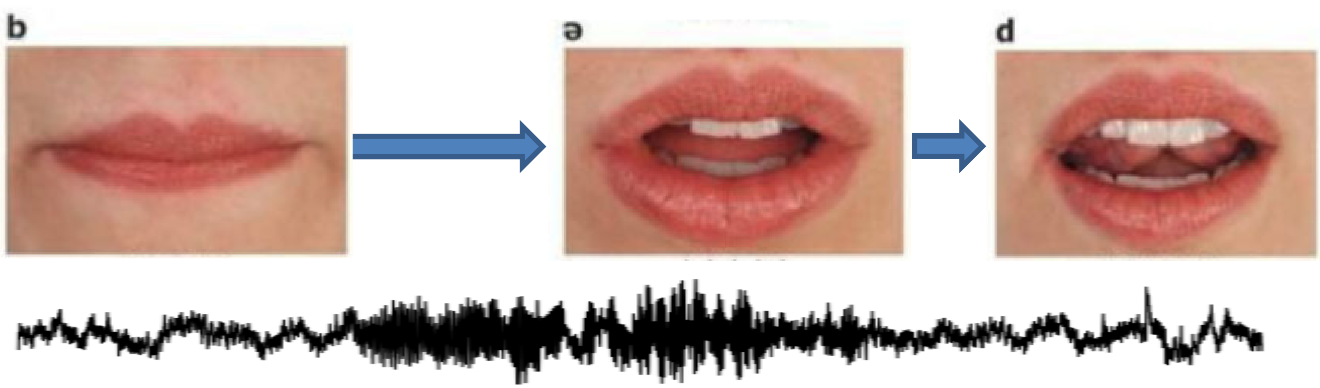
We created the first phonetically annotated, paired sung-spoken lyrics dataset which is widely used in both *speech* and *music* research communities for various ML tasks!

APSIPA ASC is unranked conference here locally. But this paper has much higher citations than most of my rank-1 papers☺

STRODE: Stochastic Boundary Ordinary Differential Equation

This year my very considerate PhD student Huang Hengguan wanted to reduce my pain of data annotation by proposing a generalized unsupervised learning approach to estimate the timing of an event such as a phoneme!

Presented at ICML2021 less than 2 weeks ago



Mispronunciation detection in speech and singing
For Computer Assisted Language Learning (CALL)

If our projects are successful

Misunderstanding ↓ Understanding ↑ World peace ↑

Current multidisciplinary research project

AI-Lyricist:

Generating Music and Vocabulary Constrained Lyrics

To be presented at ACM Multimedia 2021

RS+RF available!

Xichu (Stan) Ma(CS), Min Yen Kan (NLP), Wee Sun Lee (ML), Rebecca Starr (linguistics), Ye Wang (SMC)

Outline

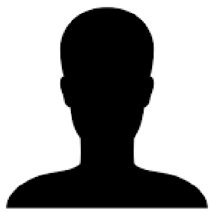
- Motivation
- Music and wearable computing for motor functions
- Reflections, key insights and future directions
- **Advice based on a neuroscience-inspired & DL-based educational model**

A Neuroscience-inspired & DL-based Educational Model

Ye WANG's formula with input from Abhik ROYCHOUDHURY

3I * 3HS = NP

The DL-based model makes me a more qualified educator now☺



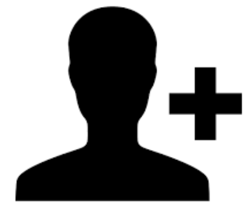
Intellect
Imagination
Initiative

Curiosity & Desire to learn

Transfer Function (coach)

Healthy
Happy
Hardworking (24h limit)
Smartworking ***(neuroscience)***

Right environment to learn



Person

*Papers
*Patents
*Products
*PhD

Happy and successful Habit of life time learning

Experimental Results:

Ph.D: Faculty member/posdoc (2)
R&D leaders in industry (5)
Entrepreneurs (2+2)

Arun Shenoy
Singapore's first Grammy-nominated music producer!

M.Sc & B.Sc: Many award-winning and successful MSc and BSc graduates

NUS GRIP is the flagship innovation programme to cultivate deep tech entrepreneurs, and to transform the university's world-class research into their own **deep tech start-ups**.

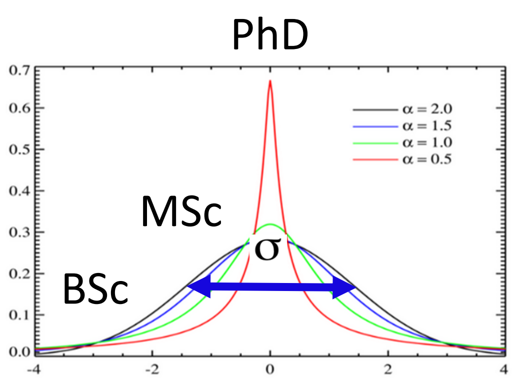
Some advices

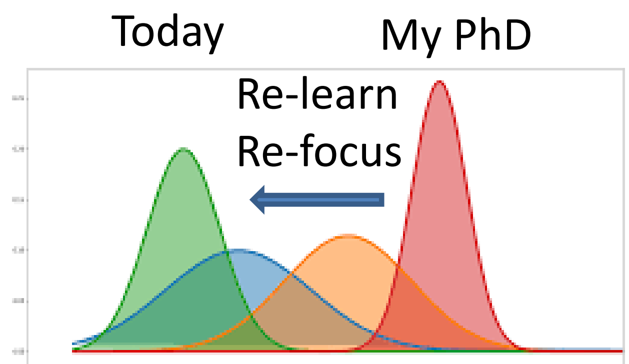
Many of our NUS students tend to be too hardworking to the level that a special job was created for me in 2013. According to my educational model, you should focus more on smartworking than hardworking! Take good care of your brain which is a delicate organ – don't abuse it! If the BNN is broken, you have little chance to repair it!
I consider a research journey such as PhD program a marathon rather than 100 m. How can you make your research career sustainable while maintaining a healthy and happy life? Here are 4 key ingredients from the neuroscience perspective:

Diet	*Sleep*	*Exercise*	*Social interaction*
e.g., background music	*e.g., lullaby for kids*	*e.g., energetic music*	*e.g., party, karaoke*

Speech and Music can play a key role here - thus SMC is important!

Breadth or depth





My academic journey after PhD

Broaden your horizon (undergrats + masters)!

Apply Dijkstra's algorithm (PhD students and a/P)

A journey of life time learning towards interdisciplinary research:
A geographic signature

读千卷书	**Read 1000 books**
行万里路	**Travel 10000 miles**
交八方友	**Make friends in many countries/disciplines**
成大气候	**Succeed in having a positive impact on mankind**

In conclusion, I have produced less rank-1 papers in the past 10 years than the previous 9 years before P&T at NUS. But I believe that I have done research which is much more meaningful to myself, my students and the society!

With the lessons learnt in the past decade, I am confident that we can do better in our future research with more scientific and societal impacts.

Thank you

Q& A