Time Delay Stability Analysis of Pairwise Interactions Amongst Ensemble-Listener RR Intervals and Expressive Music Features

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The collaborative performance of scripted music live generates a network of mutual interactions between musicians and listeners and individual physiological responses moderated by instructions in the score.

The individual responses, including changes in the Autonomic Nervous System (ANS), were the object of the prior studies considering either the listeners and the players. However, there is a lack of studies about **mutual changes** and the **network of interactions** between musicians, listeners, and music features.

In this study, we applied the time delay stability (TDS) method, based on the framework developed in [1], for monitoring physiological couplings, measured by RR interval series, in a musical setting.

Study design

RR interval series and music features (loudness and tempo) were collected during nine performances of Schubert's Trio No. 2, Op. 100, Andante con moto on five days between December 2022 and March 2023 from the trio of professional musicians (violinist, cellist, and pianist), one listener and recorded audio signals (see Figure 1).

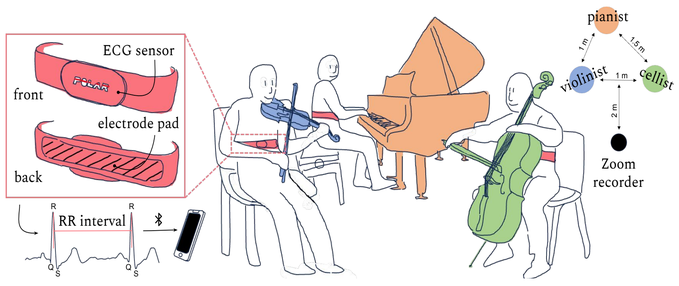
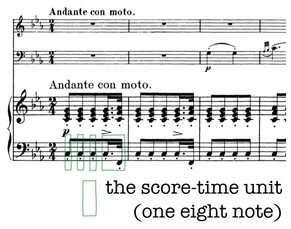


Figure 1: Study setting.

Score-time domain: to align all musical features and the corresponding RR interval time series across the nine performances for analysis, we convert all signals from (real) time to the score-time domain [2]. For this, we aligned the timestamps in the original signals to the timestamps of the musical beats (eighth notes).

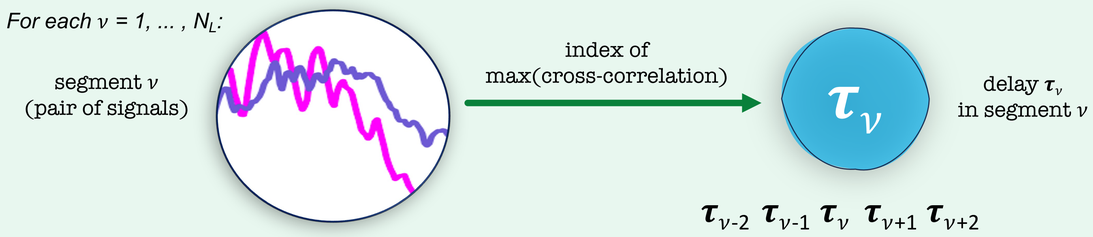


Study outcomes: We compared the average **probability of TDS** for **all signal pairs** (violinist, cellist, pianist, and listener RR and music loudness and tempo) between **music and baseline** and with two types of **surrogate data**: 1) all samples in the signals were shuffled, and 2) signals from different performances (randomly selected).

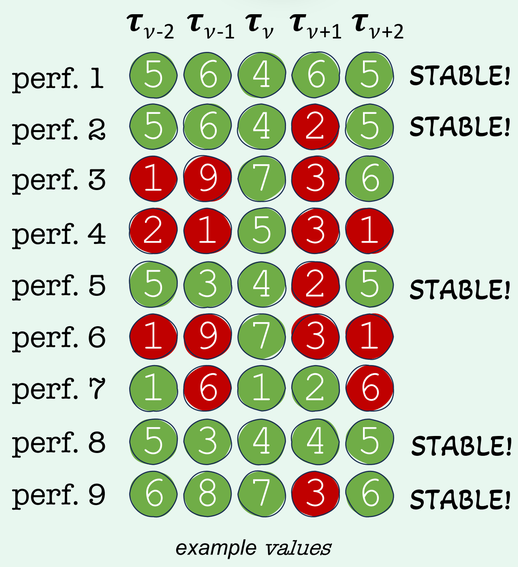
Method

Time delay stability (TDS) framework

1. Divide signals into N_L overlapping segments $\nu = 1, \dots, N_L$, where: N – signal length, 848 eight notes (the score-time unit), L - segment length, 30 eight notes, overlapping with hop size 10 eighth notes.
2. Normalise signal values in each segment by the mean and standard deviation.
3. Calculate cross-correlation for all possible pairs of signal `correlate` function from the Python `scipy` library and determine a score-time delay τ_ν that maximises the absolute value of the cross-correlation function for segment ν.



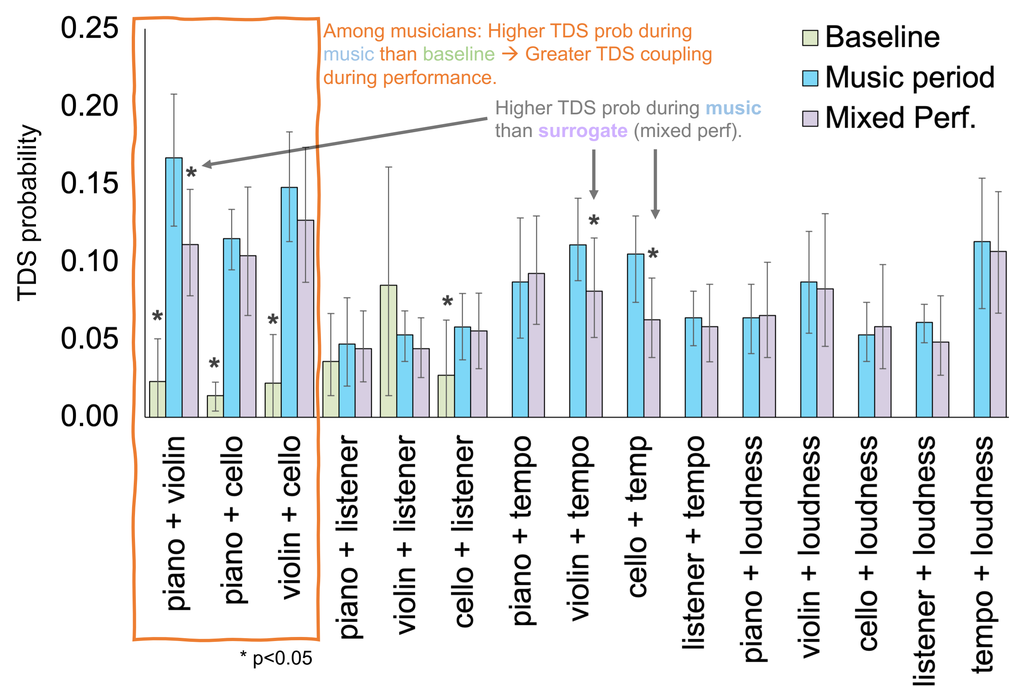
4. Determine stability for each segment for each pair in each performance. We consider two signals in segment ν linked if the value τ_ν is approximately constant in time. Following Bashan et al. [1], segment ν is labelled as stable when τ_ν changes no more than ±1, in at least four out of five consecutive segments (see example on the right).
5. Calculate TDS probability p_ν in each segment ν which is the number of performances when stability criterion (point 4) was met divided by total number of performances.



example values

In this example, segment ν provides τ_ν stability in 5/9 performances, thus the **TDS probability p_ν** for that segment is 0.56.

Results



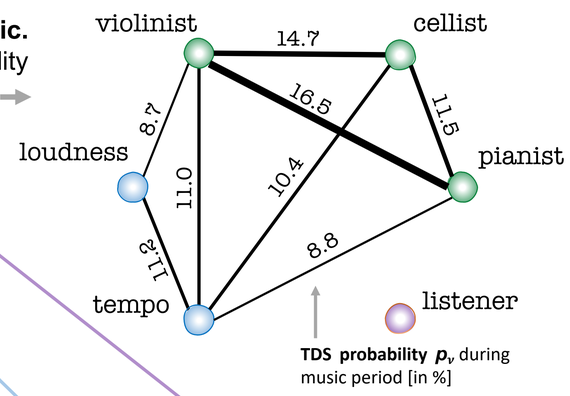
* p<0.05

Baseline vs. music period: larger mean TDS probability for music compared to the baseline among musician pairs ($p < .001$) and listener + cello ($p = .025$).

Shuffled data: mean TDS probability approx. constant at 0.038 − 0.041 (lower and upper bounds of 95% CI: 0.0185 − 0.0214 and 0.0627 − 0.0684). Baseline and pairs with listener (except violin+listener) mostly below threshold of 0.07, upper bound for shuffled data.

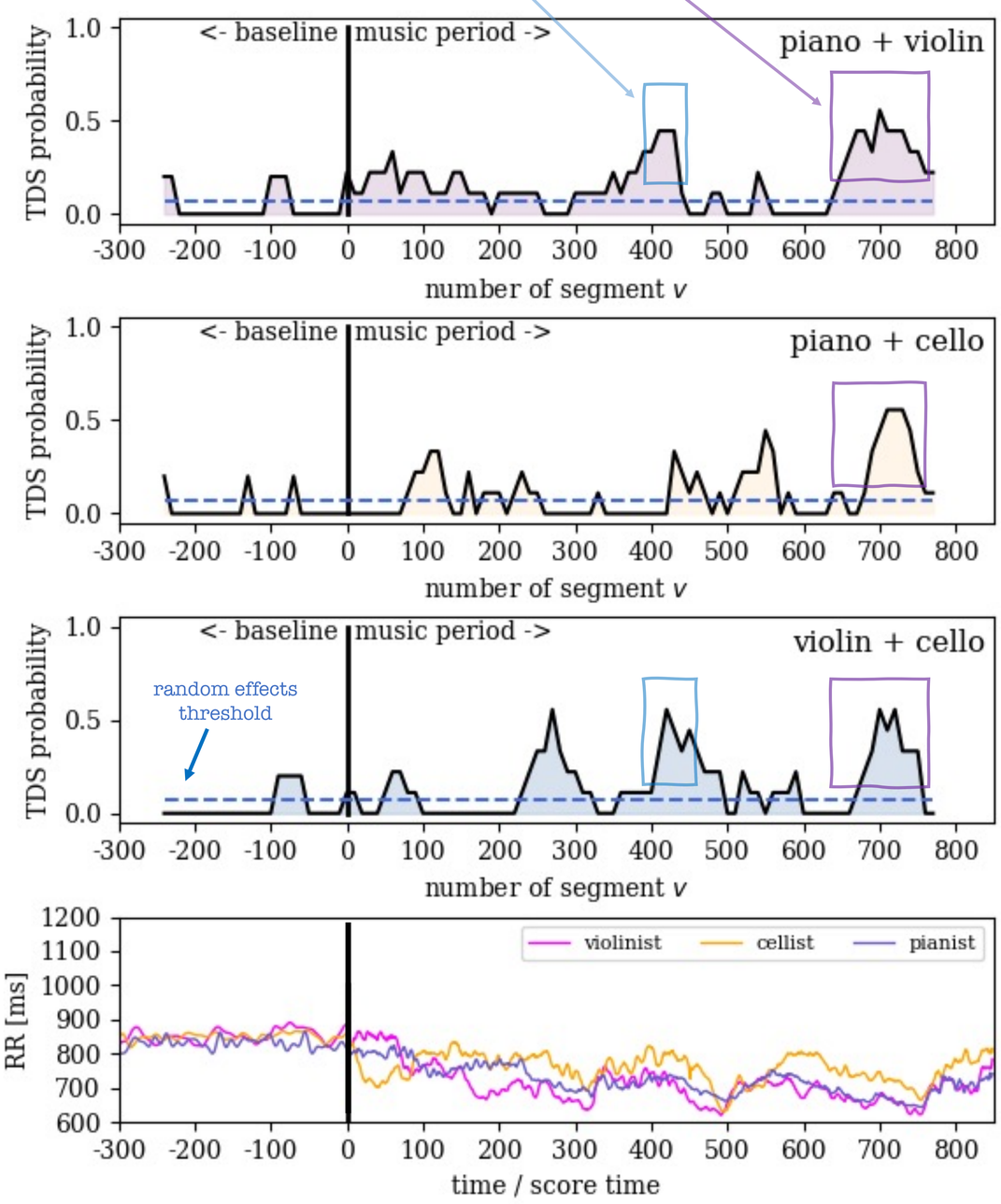
Pairs with signals from mixed performances vs. the same performance: larger mean TDS probability is observed for piano+violin ($p<0.001$), violin+tempo ($p = .045$), and cello+tempo ($p<0.001$).

Network connectivity during music. Connections signify mean TDS probability above 7% (upper bound of shuffled data).



Final intense climactic section, musicians' RR intervals decrease, music then dies down for the end.

Tense section where instruments **jointly but quietly crescendo then die down to transition to a new key**.



Conclusions

To our knowledge, this is the first use of TDS across people and music, and in a musical environment.

Some structures of the music **might increase mutual coupling** between musicians and between each musician and musical tempo.

Future extensions include using TDS to analyse signals from musicians with cardiovascular diseases in comparison to healthy individuals.

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References:
[1] Bashan A, Bartsch RP, Kantelhardt JW, Havlin S, Ivanov PC. Network physiology reveals relations between network topology and physiological function. Nature Communications 2012;3(1).
[2] Chew E, Callender C. Conceptual and Experiential Representations of Tempo: Effects on Expressive Performance Comparisons. In Mathematics and Computation in Music. MCM 2013, volume 7937 of Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2013; 76–87.

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