Using Granger Causality to quantify information flow between the sounds of ensemble musicians		
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INTRODUCTION	METHODS	DISCUSSION
 Background To play synchronously with each other, musicians musilisten to and watch each other closely in order to ant each others' playing. 	 Participants • 7 professional violinists with an average of 37 years of experience 	 Information flow in sound The results confirm the efficacy of Granger causality to quantify causal relationships between amplitude envelopes of musical performances.
• Changet al (2017) used Granger causality (GC) anal		The experimental design allowed for only one direction of

Chang et al., (2017) used Granger causality (GC) analysis with motion to show that body sway time series of leaders influenced those of followers in a string quartet, even without any visual cues.

Stimuli

- An expressive recording of Danny Boy, as a 16-bit WAV file at 44.1 kHz sampling rate
- The experimental design allowed for only one direction of information flow: from the recording to the performance. This type of control is not possible in a fully live setting, and it allowed us to constrain potential information flow to only one direction, effectively making the recording a "leader" and the violinist a "follower".

• GC has been used to investigate communication among musicians (D'Ausilio et al., 2012) and acoustical influences on perception (Dean & Bailes, 2010), but to our knowledge has not yet been applied to sound in a performance setting.

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Granger Causality

• Granger causality (or Granger coupling) is a measure of directed functional connectivity that quantifies how well information contained in the past of one variable helps predict the future of another based on vector autoregressive (VAR) modelling (Granger, 1969)

Hypothesis

• Musicians playing together use information in the sound of fellow musicians, such as expressive features, to anticipate how each other will play in order to be

• Transcribed sheet music of the piece without bowing or dynamics markings



- Violinists concurrently listened to and played along with a recording, while attempting to match all expressive features (dynamics, vibrato, slurs, timing, attack/decay, etc.)
- Violinists had not heard the recording before, and the sheet music conveyed only which notes to play, not how to play them.
- Each musician performed 8 consecutive trials.

By nature, two identical time series cannot contain predictive value over one another. To the extent that musicians got closer to the recording over trials, the less information could flow from one time series to the other. This explains the decrease in Granger causality over successive trials.

Cross-Correlation

- Average cross-correlation values decreased over successive trials. We expect this is because both time series become more similar as the musicians become more familiar with the recording
- This aligns with our results regarding Granger Causality.

FUTURE DIRECTIONS

Visual Component

• Could the availability of visual information increase the

together.

Predictions

- When a musician plays with a recording, GC values between the amplitude envelope time series of the recording to that of the performance will be larger than vice versa.
- GC values will **decrease** over successive performances, and cross-correlation values will increase
- Amplitude envelopes were extracted using a Butterworth filter and downsampled to a range of frequencies.



- Two granger causality values were calculated for each trial: **Recording to Performance and Performance to Recording**
- The MVGC Toolbox (Barnett & Seth, 2014) calculates a suggested model order (the number of lagged observations included in the model) for each trial

1. GC values depend on down-sampling rate



RESULTS

2. GC is larger from recording to

over successive trials

performance, and decreases

3. Cross-correlation increases over successive trials, and does not depend on down-sampling rate



accuracy and/or speed at which musicians can learn to emulate expressive features in music?

Live performances

- Given the results, we believe this technique has potential \bullet for analyzing groups of performing musicians.
- We plan to apply Granger causal analysis to recordings of a string quartet to look for causal relationships among musicians' sounds.

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ACKNOWLEDGMENTS





