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Multidimensional analysis of interdependence in a string quartet

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In a musical ensemble such as a string quartet, the performers can influence each other's actions in several aspects of the performance simultaneously. Based on a set of recorded string quartet exercises, we carried out a quantitative analysis of ensemble interdependence in four distinct dimensions of the performance: dynamics, intonation, tempo, and timbre. We investigated the fluctuations of interdependence across these four dimensions, and in relation to the exercise being performed. Our findings suggest that, although certain differences can be observed between the four dimensions, the most influential factor on ensemble interdependence is the musical task, shaped by the underlying score.

Keywords: interdependence; string quartet; ensemble performance; signal processing; motion capture

Studying the inner workings of joint music performance is a complex task. Previous research (Keller 2008) points out some important characteristics of ensemble performance: the sharing of a common goal among performers, the implicit (i.e. non-verbal) communication between performers, and specific "ensemble skills" which are required for ensemble cohesion to be achieved.

Previous research on musical collaboration has been carried out for tapping tasks (Repp 2005) and piano duets (Goebl and Palmer 2009), among others. On the subject of interdependence (as opposed to synchronization), different computational approaches for intonation and dynamics have been evaluated (Papiotis *et al.* 2012).

In this study, we analyzed several recordings of a professional string quartet in terms of ensemble interdependence: the degree to which the musicians are influencing each other's performance. We extracted numerical features that characterized the produced sound in terms of four performance dimensions (*dynamics*, *intonation*, *tempo*, and *timbre*), and quantified the amount of interdependence between these features for each pair of musicians. Finally, we aggregated the obtained results to investigate relationships between dimensions, and the effect of the underlying musical score on the overall amount of interdependence.

METHOD

Experimental material

The experimental recordings are based on an exercise handbook for string quartets (Heimann 1958) specifically designed to assist in improving the ensemble's capabilities for collaborative expression. This material is divided into six categories: dynamics, intonation, phrasing, rhythm, unity of execution, and timbre. We analyzed nine of the recorded exercises; a brief description of each exercise is provided in Table 1.

Each exercise was recorded in two experimental conditions: *solo* and *ensemble*. In the first condition (*solo*), each musician performed their part alone without having access to the full ensemble score. In the second condition (*ensemble*), the quartet performed the exercise together following a brief rehearsal period (~10 minutes).

Data acquisition and processing

All exercises were recorded by the same group of professional musicians. Individual audio for each musician was acquired through the use of piezoelectric pickups attached to the bridge of the instrument while motion capture data were acquired through the use of a wired MOCAP system that tracked the movement of the bow in relation to the instrument strings. Instrumental (sound-producing) gestures were computed from the raw motion capture data as described in Maestre (2009). For every recording, a semi-automatic alignment between the performance and the music score was performed using a dynamic programming routine that combined audio and instrumental gesture features to detect note change events.

Interdependence estimation

The general framework for estimating interdependence in a single performance dimension was the following: first, four continuous features (one time series for each musician) were extracted from the recorded performances. Then, using a sliding window analysis, we sequentially calculated the Mutual Information between each pair of features for every window. Finally, a single

Table 1. Description of the recorded exercises per category and exercise focus. (U of E=unity of execution.)

ID	*Category*	*Exercise focus*	*Duration*
D1	Dynamics	*Vertical listening*: the ability to adjust one's intonation according to the intonation of the rest of the ensemble.	2:00
D2	Dynamics	Immediate (*subito*) changes in dynamics.	2:00
I1	Intonation	Gradual (*crescendo/diminuendo*) changes in dynamics.	5:00
P1	Phrasing	Synchronous bow strokes of slurred notes (*legato*).	3:00
R1	Rhythm	Small changes in tempo (*poco piu/meno mosso*).	3:00
R2	Rhythm	Different degrees of rhythmic syncopation.	3:00
U1	U of E	Sound as one instrument (chords).	2:00
U2	U of E	Sound as one instrument (ascending/descending scales).	2:00
T1	Timbre	Similar tone quality for different bow/string contact points (*sul tasto/sul ponticello*) and different dynamics levels.	2:00

overall interdependence value was obtained by averaging across all musician pairs and analysis windows (Papiotis *et al.* 2012).

For the *Dynamics* dimension, we extracted the Root Mean Square (RMS) energy of each musician's individual pickup signal, mapped to a logarithmic scale. For exercises with score-imposed changes in dynamics (D1, D2, and T2), we applied a note-by-note detrending to the logRMS feature in order to remove any bias introduced by dynamics-related indications appearing in the score. For the *Intonation* dimension, we extracted the so-called "Intonation deviations"—the difference between the estimated pitch from the recordings and the "reference pitch" that is obtained by the aligned score (according to equal temperament). For the *Tempo* dimension, we computed a tempo curve for each musician using the note onset times provided by the score-performance alignment. Given the relatively short duration of the exercises, Mutual Information was applied to the entire tempo curves instead of windowing them. For the *Timbre* dimension, we used two separate features—the *bow-bridge* distance, the distance (in cm) of the point of contact between bow and string from the instrument's bridge, and the *Spectral Crest*, a descriptor of spectral "peakiness" that has low values for noisy signals (and therefore "flat" spectrums) and high values for tonal signals; after computing the amount of interdependence for both features, we averaged the two results to obtain a single value.

The above procedure was carried out in each recorded exercise, both for the *ensemble* as well as the (artificially synchronized) *solo* recordings; in this way, "*solo* interdependence" was used as a baseline that was subtracted from the "*ensemble* interdependence," removing any bias introduced by the score. As a final post-processing step, we normalized the obtained Mutual Information values per dimension, according to the Euclidean norm, across all exercise categories.

RESULTS

Figure 1 shows the mean normalized values for Mutual Information per exercise and performance dimension.

One can first observe that the estimated Mutual Information values for each exercise type varied according to the exercise goal: the *Dynamics* exercises demonstrated highest interdependence for the Dynamics dimension, the *Intonation* exercise for the Intonation dimension, the *Rhythm* exercises for the Tempo dimension, and the *Timbre* exercise for the Timbre dimension; moreover, the *Unity of execution* exercises demonstrated highest interdependence for the Dynamics and Tempo dimensions. The sole exception is the *Phrasing* exercise, which demonstrated highest amounts of interdependence for the Intonation and Timbre dimensions but notably lacked interdependence in the Dynamics dimension. Mean interdependence per dimension across all exercises was as follows (from highest to lowest): Tempo (0.385), Dynamics (0.349), Timbre (0.340), and Intonation (0.306). The small differences across dimensions suggest that each dimension was of equal importance to the overall ensemble interdependence.

In addition to interdependence, we calculated two statistics for each exercise: the *Mean Absolute Asynchrony* between each pair of simultaneous notes in the score, and the *Mean Note Duration*. The obtained values for each exercise can be seen in Table 2.

It can be seen that across all exercises, the asynchrony between musicians varied from small values (~20 milliseconds, U2) to quite large values (~120 milliseconds, T1). The fact that the *Dynamics, Intonation,* and *Timbre* exercises sustained high amounts of interdependence despite the large asynchronies supports the notion that synchronization and interdependence are two separate qualities, each describing a different aspect of ensemble performance. A correlation analysis between Mean Note Duration and each performance dimension revealed a positive correlation for the Dynamics (0.86, $p<0.05$) and Intonation (0.79, $p<0.05$) dimensions.

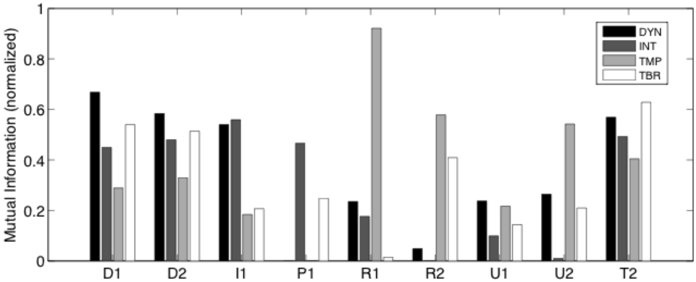

Figure 1. Normalized values of Mutual Information per exercise and performance dimension (DYN=Dynamics, INT = Intonation, TMP = Tempo, and TBR = Timbre).

Table 2. Mean Absolute Asynchrony and Mean Note Duration for each exercise.

	D1	*D2*	*I1*	*P1*	*R1*	*R2*	*U1*	*U2*	*T1*
MAA (seconds)	0.100	0.091	0.114	0.036	0.042	0.037	0.054	0.022	0.118
MND (seconds)	4.535	4.419	6.555	0.972	0.939	0.572	1.485	0.309	4.624

Finally, Figure 2 shows the overall amount of interdependence per exercise, averaged across all four dimensions.

One can see that the highest interdependence values occurred for the exercises that were based on simpler concepts (*Dynamics, Intonation, Rhythm,* and *Timbre*), while the *Phrasing* and *Unity of Execution* exercises, which require coordination in multiple aspects simultaneously, sustained lower amounts of interdependence. From the above figure, it can be observed that ensemble interdependence was not an ever-present quality, but rather a varying quantity that was strongly influenced by the underlying musical score.

DISCUSSION

We directed our focus on a little-researched topic in ensemble music performance: the concept of interdependence between musicians. While some dimensions appeared to sustain higher levels of interdependence more commonly than others, it was seen that the underlying musical task is ultimately the most influential factor, as a common goal shared by the musicians. We believe that through the analysis of more recordings, the inclusion of musical pieces besides exercises, and a more sophisticated analysis of the musical score, such a methodology can yield important conclusions on the complex subject of joint musical performance.

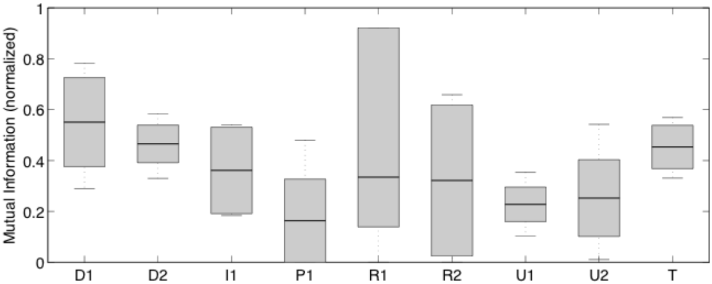

Figure 2. Mutual Information values averaged across performance dimensions for each exercise.

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