DOI: 10.1111/nyas.14858

CONCISE REPORT

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Creating a shared musical interpretation: Changes in coordination dynamics while learning unfamiliar music together

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Funding information
Canadian Institute for Advanced Research; Natural Sciences and Engineering Research Council of Canada, Grant/Award Number: Discovery Gran RGPIN-2019-05416; Canadian Institutes of Health Research, Grant/Award Number: Project Grant MOP 153130; Social Sciences and Humanities Research Council of Canada, Grant/Award Number: Insight Grant 435-2020-0442

Abstract
The ability to coordinate with others is fundamental for humans to achieve shared goals. Often, harmonious interpersonal coordination requires learning, such as ensemble musicians rehearing together to synchronize their low-level timing and high-level aesthetic musical expressions. We investigated how the coordination dynamics of a professional string quartet changed as they learned unfamiliar pieces together across eight trials. During all trials, we recorded each musician's body sway motion data, and quantified the group's body sway similarity (cross-correlation) and information flow (Granger causality) on each trial. In line with our hypothesis, group similarity increased, while group information flow decreased significantly across trials. In addition, there was a trend such that group similarity, but not information flow, was related to the quality of the performances. As the ensemble converged on a joint interpretation through rehearsing, their body sways reflected the change from interpersonal information flow for coordinative mutual adaptations and corrections, to synchronous musical coordination made possible by the musicians learning a common internally based expressive interpretation.

KEYWORDS
body sway, interpersonal coordination, joint action, music performance, nonverbal communication

INTRODUCTION

Humans are highly social and our ability to engage in joint actions to achieve collective goals may be one of the critical ingredients that enabled our species to develop sophisticated cultures and technologies.[1–3] Joint music-making is a prime example of a human activity that places high demands on our ability for coordinated action. In the Western classical tradition, music is generally executed in real time following an underlying beat, leaving little room for pausing to reflect or correct as can be done in verbal interactions. Further, whether playing the same or different notes or rhythmic patterns, musicians' parts in ensembles often fit together temporally to be coordinated with each other, unlike in conversations which typically involve turn taking. Because the sounds of each musician fit together to create joint structures, performance as a whole exhibits collective features, such as harmonies and rhythms, that are not present in the individual parts. Even when people simply listen to music with others, their shared attention may facilitate shared joint action, such as

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increases in the energy of their movements to the music.[4–6] Engaging in synchronous movements with others in response to music has social consequences, increasing affiliation, trust, and cooperation between those engaging in the synchronous movement,[7,8] even in infancy.[9–11] Thus, understanding musicians' coordination is important for understanding the dynamics of human joint action in the service of collective goals as well as for understanding why music-making is a powerful social activity. In the present study, we focused on how coordination dynamics change as a musical ensemble from the Western classical tradition learns to play an unfamiliar piece of music based on a score.

Musical scores outline the musical notes and their relative durations, yet many aspects of performance are not precisely defined in a score, including the tempo, expressive timing variations, phrasing, intensity dynamics, and variations in timbre. As such, ensembles not only have to perform their respective parts in a technically competent and synchronous manner, but they must also arrive at a shared understanding about how the piece is meant to be played—for instance, what expressive variations of tempo to introduce and where. This also means they must be able to anticipate each other; the compound delay from sensory processing and motor planning makes it impossible to rely only on a reactive or feedback strategy to produce synchronized variations.[12] If a musician waits to hear how fellow musicians will slow down at a phrase ending, for example, it will be too late to slow down precisely with them.

Coperformers can anticipate each other by attending to the joint musical output, but also by attending to sensorimotor signals in body sway movements.[13–16] Indeed, during performance, musicians sway their bodies expressively in ways that are not necessary to play an instrument. These movements likely support planning processes in musical production,[17–19] similar to how hand gestures support planning process in speech production.[20,21] Because body sway reflects how musicians plan to play their upcoming notes, ensemble musicians can capitalize on their coperformers' body movements to predict what and how each other will play next and plan their own movements accordingly.

Past studies have investigated communicative body sway by manipulating performance conditions and examining their influence on body sway coordination between performers. One aspect of body coordination is how similar, or synchronous, the body sway time series of interacting musicians are. Techniques like cross-correlation (CC) can be used to describe the synchrony between musicians' body sway times-series with zero lag or various phase delays.[22] In this paper, we refer to *similarity* as the maximum CC value within a window of phase delays. Musicians appear to synchronize their body sways as a cue to help them coordinate in difficult playing conditions, such as when auditory feedback is perturbed[23] or when there is no musical pulse.[16,24,25] However, synchrony may also reflect alignment in the performers' internal representation of how to play the music. For instance, body sway synchrony between musical duos is related to acoustic synchrony at the note level.[26] Further, studies tracking duos as they rehearsed pieces together found their body sways became more similar with increased rehearsal,[24,27] suggesting that the synchrony of their movements reflects their convergence on a joint interpretation of a score.

Another aspect of body sway coordination relates to prediction; in situations of delayed sensory feedback and multiple possible expressive variations of the musical score, musicians can use body sway to predict how the other ensemble members will play the upcoming notes. Previous studies have shown that the body sway movements of one musician can mathematically predict the subsequent movements of another musicians using Granger causality (GC)—a technique that determines the extent to which the history of one time series can predict the current status another time series, over and above prediction within one time series. When applied to the body sway time series of musicians, larger values of GC indicate better prediction, with more *information flow* from the time series of one musician to that of another. We have previously used GC in small ensembles to show that the body sway of leaders predicts that of followers more than vice versa,[28] and that there is more group information flow when musicians play with emotional expression than without.[29] Higher overall group information flow between all pairs in the ensemble is also related to higher ratings of performance quality in these studies, indicating that this measure relates to the success of the performance.

In the current study, we examined how body sway coordination, including measures of similarity (CC) and information flow (GC), changes in a small ensemble that learns to play an unfamiliar musical score together. Specifically, we used motion capture to measure the body sway of a professional string quartet while they played two unfamiliar pieces over eight successive trials each. The full score of each piece of music and how their fellow musicians intended to play their parts was completely unfamiliar on trial 1 and became more familiar as they repeated the piece together over the eight trials. Importantly, we asked the string quartet to not communicate with each other verbally to encourage the use of nonverbal communication while playing.

If body sway is related to how musicians plan to play their next notes then, theoretically, musicians' body sway movements should be more similar when they have more similar interpretations of how to play a piece of music. In other words, alignment in musicians' body sway may reflect alignment in their internal representations of how to play a piece. As such, we predicted that body sway similarity (CC) would be the lowest when the pieces were most unfamiliar (i.e., trial 1) and would increase over trials as the musicians became more familiar with the pieces and converged on joint interpretations.

In terms of information flow (GC), one might initially expect an increasing level of information flow in the group as they learn the piece over the trials, indicating that musicians interact more competently with learning. However, once the quartet has learned a common interpretation of a piece, they should have a common internal model of how the piece is to be played in the group, and they should, therefore, rely less on signals from each other's movements. In other words, when pieces are most unfamiliar in the early trials, musicians may rely more strongly on using feedback from body sway than that on an internally generated feedforward strategy to help them predict how their fellow musicians intend to play their upcoming notes. Thus, we predicted that information flow would be highest when the pieces were most unfamiliar (i.e., trial 1) and that these values would decrease over trials as

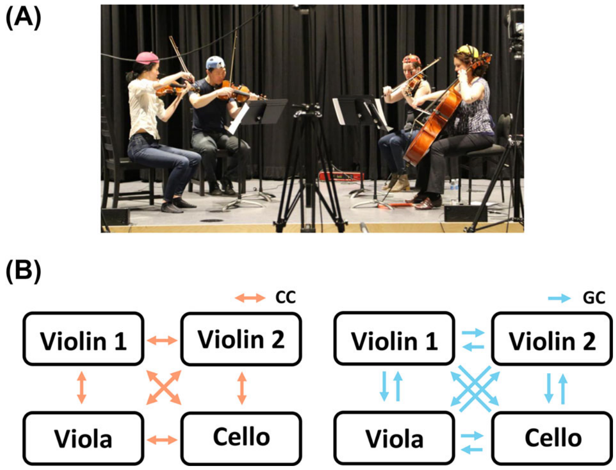

FIGURE 1 (A) Motion capture recording setup on the LIVELab stage. Each musician is wearing retroreflective markers on their heads. Microphones were attached to each instrument. (B) (Left) Illustration of the six CC coefficients across all musician pairings. We took their average to represent the overall amount of group synchrony on each trial. (Right) Illustration of the 12 GC values across all musician pairings. Their average represents the overall amount of information flow across all possible musician pairings on each trial.

the group learned and came to a common interpretation of how to play each piece.

EXPERIMENTAL METHODS

The participants were members of the Madawaska String Quartet, an internationally recognized Canadian string quartet based in Ontario, consisting of one first violinist (F), one second violinist (M), one violist (F), and one cellist (F). The quartet performed two pieces chosen from the Romantic era: String Quartet No. 1 in G minor by Franz Berwald (bars 1–135, piece 1) and String Quartet No. 1 in D Major, Op. 63 by Niels Gade (bars 1–220, piece 2). These pieces were selected because they were emotionally expressive, which requires stylistic interpretation beyond the notes indicated in the score, and they were not known by any of the performers. Each piece was between 5 and 6 min long. Musicians were given their own parts ahead of time so they could obtain basic familiarity with their respective individual parts without hearing or seeing the other instruments' parts.

The data were collected in the McMaster University's Large Interactive Virtual Environment laboratory (LIVELab, https://livelab.mcmaster.ca) using an infrared optical motion capture system (see Supplementary Materials for details). To record head movements, each performer wore a felt cap with four retroreflective markers attached, one each at the front- and center-midline areas and one above each ear. Performers were seated on the stage in a semicircle configuration (Figure 1A). They performed each piece together for eight successive trials without verbally interacting with each other. Piece 1 was performed in the morning and piece 2 was performed in the afternoon after a lunch break. To examine a secondary question, musicians were instructed to play alternating trials in a mechanical or an expressive fashion. Results of this secondary manipulation can be found in the Supplementary Materials.

After each trial, performers rated three aspects of the performance using a 9-point Likert scale ranging from low (1) to high (9): overall quality ("How would you rate the overall quality of the current performance?"), expressivity ("How would you rate the current performance in terms of expressivity?"), and technical synchrony ("How technically synchronized were the musicians in the current performance?").

The time series of anterior-posterior body sway was obtained from the position of each musician's head movements for each trial of each piece, following Chang *et al.*[28] To determine the similarity between the musicians' time series, we calculated windowed CCs between each pair of musicians on each trial for windows of approximately two bars, moving in steps of one bar, and allowing for lags up to plus or minus one beat. Similar to the procedure used by Keller and Appel,[26] we took the average of the maximum unsigned CC coefficient across all windows between each pair of musicians. Unsigned CC coefficients, which encompass both in-phase and anti-phase similarities, were taken because we were interested in both in-phase and phase-lagged patterns based on visual inspection of performances. We then took the average of the CC coefficients across all six musician pairings as a measure of group similarity for each trial (see Figure 1B, left).

To determine group information flow, we used the Multivariate Granger Causality toolbox[30] for MATLAB to estimate the strength and direction of GC between the body sway of each pair of musicians. Twelve unique GC values were calculated for each trial, corresponding to the degree to which the body sway of one performer predicted that of the other performer (note that because GC is a directed measure, there are twice as many GC values as CC values). The average of these 12 values was taken as a measure of the overall amount of information flow in the group for each trial (see Figure 1B, right). See Supplementary Materials for more details.

RESULTS

Body sway

Figure 2 shows how similarity (CC) and information flow (GC) change across trials for both pieces. We used linear mixed effects (LME) modeling with the *lme4* package[31] in R to test the effects of trial on the outcome variables group similarity (CC) and information flow (GC). We modeled both CC and GC as fixed effects of trial (eight trials), and random effects of pair (six unidirectional pairs for CC and 12 directional pairs for GC) and piece (two pieces). Standardized *b* coefficients are reported as the estimates.

We found that CC significantly increased across trials ($b = 0.0021$, $p = 0.011$, semipartial $R^2 = 0.071$), indicating that the musicians' body sway became more similar as familiarity with the pieces increased (Figure 2A). On the other hand, GC significantly decreased across trials ($b = -0.0005$, $p < 0.001$, semipartial $R^2 = 0.066$), indicating that the musicians' body sways predicted each other to a higher degree as familiarity with the pieces increased (Figure 2B). Although these GC values

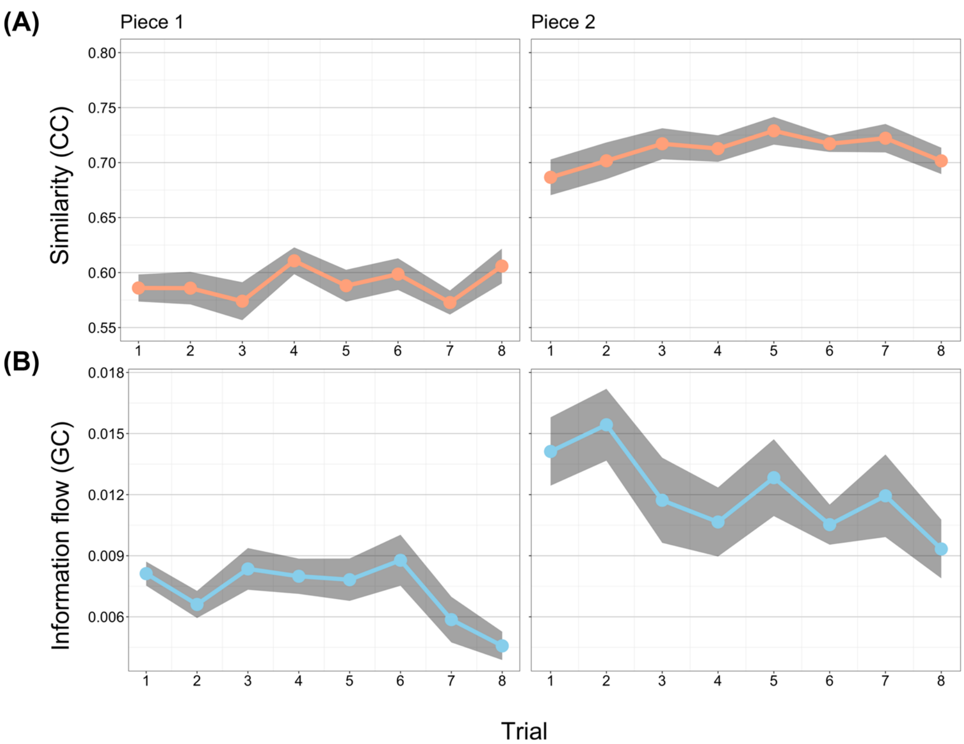

FIGURE 2 CC and GC of group body sway across trials. Left column is piece 1 and right column is piece 2. For piece 1, odd trials are mechanical and even trials are expressive. For piece 2, even trials are mechanical and odd trials are expressive. (A) For each piece, CC increased across trials. (B) For each piece, GC decreased across trials. Shaded areas represent standard error of the mean.

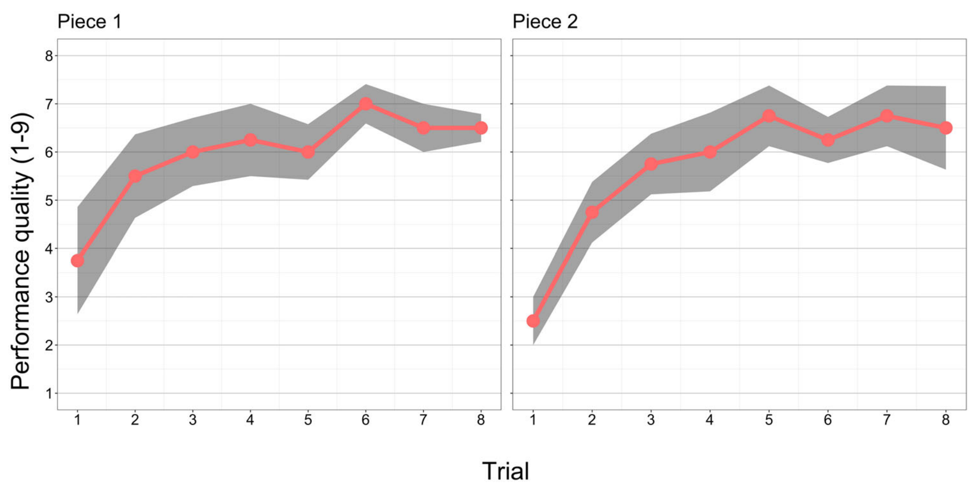

FIGURE 3 Ratings of performance quality over trial for piece 1 and piece 2. Shaded areas represent standard error of the mean.

are small, they are in line with values found in previous studies.[15,28,29] There were no other significant effects in the models.

Ratings of performance quality

Figure 3 shows the average performance quality ratings from the performers for each trial and piece. We ran an LME model to predict performance quality ratings from fixed effects of trial and the quadratic trend of trial, as well as random effects of participant. There were both significant linear ($b = 0.748$, $p < 0.001$, semipartial $R^2 = 0.248$) and quadratic ($b = -0.049$, $p = 0.014$, semipartial $R^2 = 0.088$) trends in our model. We tried adding piece as a random effect in the model, but it did not improve the fit ($p > 0.05$). The highest rated trial for piece 1 was trial 6 and for piece 2 was trial 5.

We conducted exploratory analyses of how CC and GC related to the various ratings by the performers on each trial (Figure 4). Three separate LME models were fitted to predict each body sway measure (CC and GC), with each model testing fixed effects of one of our three performance rating measures: (1) performance quality,

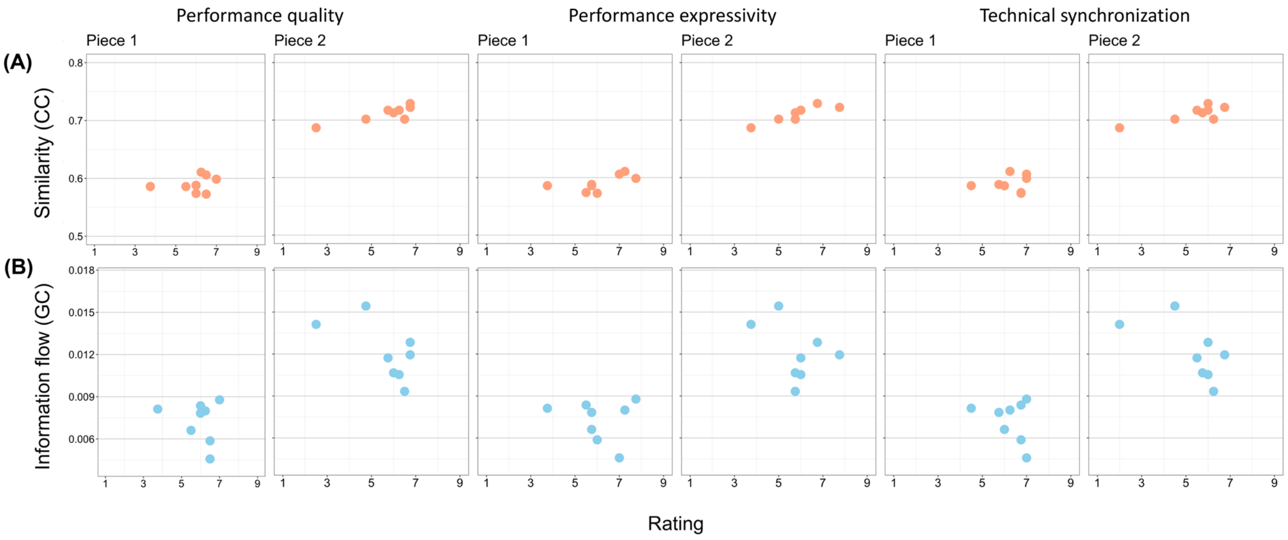

FIGURE 4 Relations between body sway measures and performance ratings given by the performers. The left two columns are performance quality, the middle two columns are performance expressivity, and the right two columns are technical synchronization. (A) Relation between CC and performance ratings. (B) Relation between GC and performance ratings.

(2) performance expressivity, and (3) technical synchronization. We ran these models independently because we were interested in the independent effect of each rating on our outcome measures. In each model, we also included random effects of piece and fixed effects of trial; we decided to include trial as a fixed factor in all models as a control, since both CC and GC as well as performance quality ratings were related to trial sequence. For our CC performance quality model, we found that there was a marginal effect of quality when controlling for trial ($b = 0.009$, $p = 0.06$, semipartial $R^2 = 0.265$). In the CC expressivity model, there was a significant effect of expressivity when controlling for trial ($b = 0.011$, $p = 0.003$, semipartial $R^2 = 0.538$). There were no other significant effects of performance ratings in any of the other models (p's > 0.05).

DISCUSSION

We found that body sway similarity (CC) increased but information flow (GC) decreased as a small ensemble learned to play musical pieces together across eight trials. Furthermore, there was a trend such that group similarity, but not information flow, was positively related to the group's performance quality and expressivity ratings.

We suggest that the increasing similarity in body sway as the pieces became more familiar may indicate a gradual alignment of the musicians' intentions of how to play the scores. Musicians' body sway reflects the expressive intentions with which they plan to play their upcoming notes,[17] and is likely involved in the internal planning processes associated with musical production. On trial 1, each musician was only completely familiar with their individual part but did not know how their part fit into the musical piece at large; therefore, the similarity between the musicians' body sways was relatively lower. As they came to a joint interpretation of the score, their body sway movements became more similar. These results are similar to Williamon and Davidson, who qualitatively reported that the body sway movements of a piano duo became more similar as they rehearsed new music together,[32] Bishop *et al.*, who showed that the body sway of piano and clarinet duos became more similar after they rehearsed a piece,[24] as well as Ragert *et al.*, who showed that body sway similarity of duos rehearsing unfamiliar music increased with learning and coincided with increased note onset synchronies.[27] Altogether, the trend of increasing similarity across studies supports the idea that the similarity of musicians' body sway was related to their learning of a common internally based interpretation of the music (though see Ref. 33 for cautions with CC analyses).

While group similarity increased, group information flow decreased as the group learned the pieces. This decreasing trend indicates that the musicians at first may have relied more on feedback from cues reflected in body sway when the pieces were most unfamiliar (i.e., trial 1), but as they gained a more coherent joint conception of how to play the pieces over repetitions, they came to rely more heavily on an internal feedforward strategy based on accrued knowledge through repeatedly playing the pieces. While this might seem at odds with previous studies that found that musicians tend to watch each other more after rehearsing a new piece,[14,34] this increased looking may reflect the fact that musicians need to look at the score less as a piece becomes familiar, rather than direct increased benefit from looking at each other.

Taken together, we suggest that these results are consistent with the active inference perspective, which sees interpersonal interactions as generalized synchronization driven by mutual predictions.[35,36] As the musicians learned the unfamiliar pieces together, they updated their initial internal models of how to play the pieces to form a shared model. This joint model became more coherent as they became more familiar with playing the pieces together (over eight trials), reflected by the increased similarity in their body sways and trend for increased performance quality over trials. As the shared models became more precise with practice, there were fewer errors to correct, and musicians needed to rely less on direct information from body sway. This perspective is also in line with our mechanistic understanding of CC and GC calculations. If two time series are completely synchronous (i.e., CC values are equal to 1), GC values must converge to null since one time series cannot help to predict the other over and above predictions within a time series.

One interesting question for future work is to investigate whether the CC and GC trends reflect the performers' direct observation and influence of body movements (i.e., visual interaction) or whether the performers' body movements associate with their sound production and, therefore, the direct interpersonal influences are largely through hearing each other's sounds. Based on the past work, these measures likely reflect both to a degree. In terms of CC, Bishop *et al.* showed that, after rehearsing a piece for up to 40 min, performers' head motions were more coordinated when they could see each other compared to when they could not, indicating that their synchrony depended to some extent on visual information.[24] However, the performers appeared to be more synchronized in their head motions under this rehearsed-but-no-visual-contact condition than the first time they played the piece together under an unrehearsed-with-visual-contact condition, indicating that familiarity with a shared interpretation was more important to synchrony than visual contact. In terms of GC, our previous work found that predictive relationships between the body sway of string quartet members were still present, although not as strong, when performers could not see one another compared to when they could see each other.[28] Another study by Hilt and colleagues found that perturbing visual information in an orchestra disrupted information flow in the predicted direction; turning a first violin section away from the conductor toward the second violin section resulted in greater influence of the second violin section's body sway on the first and reduced influence of the first on the second compared to baseline, indicating a role of visual observation of body movements.[15]

We also found that similarity (CC) was related to the musicians' goal of successfully creating a joint performance. Group synchrony, but not information flow, was marginally related to enhanced ratings of performance quality. As the musicians became more similar in their body sways, they tended to increase their ratings of performance quality. In other words, the more aligned the musicians' body sways, the more aligned their joint interpretations of the piece, and the more successful their joint performance. Although this trend did not reach significance ($p = 0.06$), ratings were only collected from four musicians and, as such, were likely underpowered. We also found a significant relation between group similarity and performance expressivity, such that the musicians rated pieces as more expressive, the more synchronized they were in their body sway. We suggest that, when the performers' expressive intentions are aligned, their body sway is also more aligned.

In our past studies, we found that group information flow (GC) was related to performance quality, but we did not find a similar relation in the current study. This may be because the performances analyzed in our past studies were comprised only of initial performances of each piece. In these past studies, it is likely that the best initial performances were achieved with the use of predictive processes measured with information flow. In the current study, where internal models of the joint group performance were becoming more accurate with repeated trials, predictive processes relying on body sway were likely less necessary and, therefore, did not relate significantly to performance success.

The quartet members in the current study were highly familiar with each other and were already familiar with idiosyncrasies of each other's playing styles, which may have facilitated their learning of the unfamiliar pieces. In other words, the performers may have already developed expectations of each other's performance style, which helped them to predict how everyone in the ensemble would likely play the unfamiliar pieces and which, in turn, helped them learn to play the pieces together quickly. Indeed, the musicians improved quickly as shown by the performance quality ratings over time (Figure 3). In the future, it would be interesting to compare ensembles consisting of musicians highly familiar with one another to those who are unfamiliar with each other to see how this affects body sway interactions while learning new music together.

Given that we focused on a highly constrained musical task (i.e., reading from a score) from the Western classical music tradition, future studies are needed to determine the generalizability of the findings. It would be interesting to know whether body sway interactions function similarly in different musical traditions, scenarios, and interactional structures, such as improvisation or call-and-response. Further, asking musicians to not communicate verbally during rehearsal is somewhat unnaturalistic, and might have increased their reliance on nonverbal cues. Future studies might profitably also explore learning over longer time-scales (e.g., months), as well as different performance conditions, such as during live concert performances (e.g., see Refs. 37 and 38).

There are competing perspectives to the learning of a shared joint mental model among interacting musicians. For example, Linson and Clarke's ecological and distributed theory proposes that open-ended collaborative improvisation can result from the individual musicians' detection of different affordances for coordination patterns that are created on the fly by the group.[39] Individuals do not necessarily need to converge on the same premeditated plan of action and, instead, they can rely on interpersonal interactions with a limited prediction horizon. This is consistent with the enactive approach to social interaction. It shows how participatory sense-making can lead to the discovery not only of novel patterns of coordination but also their significance to the individuals who may not have intended them initially.[40,41] Conducting future studies that leave more space for flexibility, improvisation, and mutual adaptation may shed light on evidence for these different perspectives.[37]

Given that joint action is crucial for human cultural and technological advancement and has profound effects on social interactions, it is important to understand how humans can coordinate their actions together. The current study showed how nonverbal body sway behavior changed in a classical musical ensemble as they learned to coordinate unfamiliar pieces together. Over the course of learning the unfamiliar pieces, the group's body sways became more similar, while the predictive relationship between the sways decreased. This suggests that body sway reflects the musicians' internal planning processes involved in music performance when learning unfamiliar pieces of music based on a score. Future work can investigate whether and how these relations are affected by visual contact, performer familiarity, rehearsal conditions, performance conditions, and musical genre.

ACKNOWLEDGMENTS

This research was supported by grants to L.J.T. from Social Science and Humanities Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the Canadian Institutes of Health Research, and the Canadian Institute for Advanced Research, and by a Alexander Graham Bell Canada Graduate Scholarship to E.A.W. and a Vanier Canada Graduate Scholarship to A.C. We would like to thank the Madawaska Quartet for participating in the study, Sarah Fraser Raff, Jeewon Kim, Anna Redekop, and Amber Ghent. We would also like to thank Alyssa Murdoch for assistance in creating figures, as well as Dave Thompson, Susan Marsh-Rollo, and the LIVELab staff for technical assistance. E.A.W. and D.D. accept responsibility for the integrity of the data analyzed.

AUTHOR CONTRIBUTIONS

Conception and design: A.C., D.B., D.D., E.B., and L.J.T.; acquisition of data: A.C., D.B., D.D., and E.B.; data analysis: E.A.W. and D.D.; interpretation of data: E.A.W., L.K., D.D., and L.J.T.; drafting manuscript: E.A.W., L.J.T., and D.D.; revising and approval of manuscript: all authors.

COMPETING INTERESTS

The authors declare no competing interests.

PEER REVIEW

The peer review history for this article is available at: https://publons.com/publon/10.1111/nyas.14858.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Wood, E. A., Chang, A., Bosnyak, D., Klein, L., Baraku, E., Dotov, D., & Trainor, L. J. (2022). Creating a shared musical interpretation: Changes in coordination dynamics while learning unfamiliar music together. *Ann NY Acad Sci.*, *1516*, 106–113. https://doi.org/10.1111/nyas.14858