Violinists Employ More Expressive Gesture and Timing Around Global Musical Resolutions: A Motion Capture Study

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Performers express musical structure using variations in dynamics, timbre, timing, and physical gesture. Previous research on instrumental performance of Western classical music has identified increased nontechnical motion (movement considered supplementary to producing sound) and ritardando at cadences. Cadences typically provide resolution to built-up tension at differing levels of importance according to the hierarchical structure of music. Thus, we hypothesized that performers would embody these differences by employing nontechnical motion and rubato, even when not explicitly asked to express them. Expert violinists performed the Allemande from Bach's Flute Partita for motion capture and audio recordings in a standing position, then we examined nontechnical motion and rubato in four cadential excerpts (two locally important, two globally important) and four noncadential excerpts. Each excerpt was segmented into the buildup to and departure from the dominant-tonic progression. Increased ritardando as well as nontechnical motion such as side-to-side whole-body swaying and torso rotation in cadential excerpts were found compared to noncadential excerpts. Moreover, violinists used more nontechnical motion and ritardando in the departure segments of the global cadences, while the buildups also showed the global-local contrast. Our results extend previous findings on the expression of cadences by highlighting the hierarchical nature of embodied musical resolution.

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Playing music expressively is one of the hallmarks of expert performance. While a musician's expression ultimately targets audible features, such as fluctuations in volume, texture, vibrato, or timing, it may also involve physical, bodily gestures that supplement the technique required to play an instrument or sing. These expressive devices are employed by performers to articulate different aspects of the music. In the domain of Western classical tonal music, cadences carry a particular importance in musical structure, as moments of musical closure defined by patterns of harmony, melody, and meter (Neuwirth & Bergé, 2015). The present study examines how highly trained violinists express cadences at different levels of structural salience through their timing fluctuations and physical motion.

Western classical tonal music of the eighteenth and nineteenth century is strongly characterized by cadences. They punctuate musical structure and define phrase boundaries, creating chunks that exhibit predictable patterns, thereby facilitating the perception of the music (Huron, 2006; Meyer, 1956). Music theorists have identified many cadence types (Caplin, 1998), with three of the most common categories being the authentic cadence (a movement from the dominant chord to the tonic), half cadence (a movement from any chord to the dominant), and deceptive cadence (a movement from the dominant chord to any nontonic chord). Authentic cadences in particular are associated with perceived finality and resolution (Margulis, 2005; Sears, 2015), and aid in the establishment or reaffirmation of the *tonality* (or key) of the music, which is usually not constant throughout a piece. Other cadence types tend not to offer the same level of conclusion as authentic cadences. For instance, half cadences and deceptive cadences in Mozart sonatas are rated as less conclusive than authentic cadences by young adults trained in Western music, as well as by those without formal training but with exposure to Western music in their culture (Sears et al., 2014). In addition, cadences of the same category may be perceived as more or less conclusive depending on their context (Kramer, 1982). Sears et al. (2014) found that musicians and nonmusicians reliably rated authentic cadences from secondary, subordinate

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themes in Mozart piano sonatas as more conclusive than those in main themes. Theoretical models of phrase hierarchy and tonal tension predict an increase in tension up until the moment of cadential resolution, especially for authentic cadences that provide a sense of global structural resolution to the preceding music (Lerdahl & Jackendoff, 1983a; Lerdahl & Krumhansl, 2007). These predictions have been confirmed empirically in listeners' perception of tension in a Mozart piano sonata (Krumhansl, 1996) and a Chopin Prelude (Bigand & Parncutt 1999).

Music theorists have further suggested that phrase hierarchies in tonal music are defined by how the tonal center of the piece changes over time. Typically, an authentic cadence in the initial key of a piece toward the music's end is deemed to be its ultimate goal, hence carrying the most global weight (Meyer, 1956; Schenker, 1935/1979). Before that cadence occurs, modulations bring the piece to several subordinate keys that reach local conclusions before a return to the initial key. These additional keys lead to nested, recursive musical structures with local conclusions; as such, long-range nonadjacent dependencies theoretically underpin the final tonal resolution in the home key (Lerdahl & Jackendoff, 1983b; Schenker, 1935/1979). Further, such nested structures may coincide with thematic parallelisms and formal plans (e.g., ritornello form, binary form, sonata form), imparting the associated cadences different levels of structural salience when considering the piece as a whole. For instance, even if the music at the concluding cadence in each half of a binary-form piece is virtually identical after transposition, the closing cadence in the home key at the end of the second half is typically deemed to be more structurally salient than the closing cadence in the dominant key at the end of the first half. Schenker's background-level analysis of the first movement of Mozart's Piano Sonata No. 11 in C major, K. 545 offers a good example of this concept. The movement's structure is in dialogue with sonata and binary form principles. While the final cadential pattern is very similar in each half of the piece, the first half's authentic cadence in the dominant key is not assigned as much structural weight as the second half's corresponding cadence in the tonic key (Schenker, 1935/1979). Still, the cadence at the end of the first half is structurally salient in some way; it is in fact one of only a small handful of the authentic cadences appearing at the background level. The question thus arises of how performers, who have full access to the tonal structure in the score, express nonadjacent hierarchical relationships between cadences.

Performers are uniquely tasked with using the structure of a composition as the basis of musical expression. One such form of expression is expressive timing or *rubato*, which is characterized by the lengthening and shortening of notes relative to their notated durations. In particular, *ritardando* (slowing down), has been observed at phrase endings in Western classical music performance (Davidson, 2012; Palmer, 1989, 1996; Palmer & Krumhansl, 1987; Timmers et al., 2006). Performers also employ rubato to show patterns of melodic and harmonic tension within phrases (Palmer, 1996) and to emphasize metrical structure (Clarke, 1993). Theoretical models of rubato in performance tend to predict more extreme ritardando at globally important phrase endings than locally important endings and rely on music-theoretic hierarchies of phrase structure (Todd, 1985, 1989). Rubato patterns at phrase endings are also more consistent across different players than in the middle of phrases, where there is more individual variation (Repp, 1992).

In addition to rubato, performers can use expressive body motion to reflect an embodied sensitivity to phrase architecture. When they are not part of the technique of playing an instrument, these expressive movements are frequently termed *ancillary* (Nusseck & Wanderley, 2009; Seger et al., 2014; Wanderley et al., 2005) or *nontechnical* motion (Buck et al., 2013; Huberth & Fujioka, 2018; MacRitchie et al., 2013). Performers employ increased amounts of nontechnical motion around phrase endings much like they do with ritardando; this has been found consistently both within and across studies of multiple instruments, including solo piano (Buck et al., 2013; Juchniewicz, 2008; MacRitchie et al., 2013), solo clarinet (Vines et al., 2006; Wanderley et al., 2005), and ensemble performance (Davidson, 2012; Davidson & Coulam, 2006; King & Ginsborg, 2011). It has also been identified in dance choreography to music (Krumhansl & Schenck, 1997). Once again, the individuality of musical interpretation is observable in the variability of motion profiles between performers mid-phrase. This variability may reflect local rhythmic or melodic grouping (Huberth et al., 2019; Wanderley et al., 2005), as well as individual differences between performers' interpretations of the phrase structure of a piece (Buck et al., 2013; Desmet et al., 2012). Even if performers mostly share a conception of the phrase structure of a piece, they may have idiosyncratic motion styles. For instance, MacRitchie et al. (2013) found that nine pianists all exhibited periodic nontechnical motion that corresponded to the same phrase boundaries in two Chopin preludes, but the motion between these boundaries exhibited a degree of individual variation.

Notwithstanding their individuality, there appears to be common ground between the types of nontechnical motions that performers use in expressing musical phrases. In one of our previous studies (Huberth et al., 2019), all six violinists exhibited side-to-side whole-body swaying as one of the primary nontechnical components of motion in their performance of an unaccompanied violin sonata by Heinrich Biber. An increase in velocity in this nontechnical component of motion was found at phrase boundaries in the piece. Moreover, nontechnical motion changes when different phrasings are expressed intentionally. For instance, Huberth and Fujioka (2018) asked cellists to play an excerpt from an unaccompanied Ricercar by Domenico Gabrieli and examined the head motion by video-image analysis. The cellists' head movements were significantly more frequent after being instructed to bring out short prescribed melodic groupings than when asked to express those notes as integrated into a longer musical phrase. Pianists also generally agree in the usage of the torso and head in expressing musical intent (Massie-Laberge et al., 2019). That upper body motion is an important component of performance-related expression in pianists was also found by Thompson and Luck (2012): pianists moved their upper body significantly less compared to the "normal" and hyper-expressive ("exaggerated") performance conditions when asked to play without expression ("deadpan") as well as when asked to suppress their motion ("immobile"). Interestingly, the most discrepancies between pianists' motions in the nonexpressive (immobile, deadpan) and expressive (normal, exaggerated) conditions occurred around cadences.

Altogether, these findings suggest that musical expression and nontechnical motion are intimately linked in a manner shared extensively between individual players and guided by the internal structure of the music. These gestural cues are effective ways for performers to express the structure of musical phrases (Vines et al., 2006), as well as melodic discontinuities and pitch interval sizes (Huberth et al., 2019; Thompson et al., 2005). The present study extends this research by exploring how violinists embody the structural salience of cadences in their expressive timing and motion in a binary-form movement from a Bach Partita.

Our motion analysis was conducted using principal component analysis (PCA) on a performance averaged across multiple violinists using whole-body movement. This dimensionality reduction technique identifies the directions of motion that account for the most variance in our data. Visualizing the motion profiles of the principal components (PCs) of interest allowed us to interpret whether they primarily represented technical or nontechnical motion. PCs based on whole-body motion capture the co-movement of all body parts rather than isolating biomechanical movements of particular body parts. Thus, the level of technicality of a PC is a point on a spectrum, rather than a binary decision. Defining technical movement as essential to producing sound, body movements largely in synchrony with notes is a strong indicator of that PC representing primarily technical motion. To examine nontechnical motion, researchers have examined motion from subsets of body parts (Buck et al., 2013; Huberth & Fujioka 2018; MacRitchie et al., 2013; Massie-Laberge et al., 2019). Here we performed PCA on *all* body parts, following the procedure of Toiviainen et al. (2010), who analyzed whole-body motion to explore how music-induced movement was synchronized with different metrical levels. Including the whole body allows for a richer understanding of the spatiotemporal dynamics of how different body parts move together: violinists' whole-body motion is relatively unrestricted, therefore offering many potential motion types for the expression of cadences. Furthermore, instead of performing PCA on individual performances (Huberth et al., 2019), we were interested in seeing how motion common to *all* performers was modulated by cadence saliency, motivating our use of PCA on the *averaged* performance as opposed to the data from individual players or isolated excerpts of the music.

We recorded audio and motion data from highly skilled violinists and analyzed timing and motion in eight excerpts of the movement. Four of these excerpts featured an authentic cadence, while the other four served as controls, as they contained a dominant-tonic (V-I) chord progression but had no cadential function with respect to the musical structure. To examine the relevance to the musical form, two of the four cadential excerpts were chosen from each half of the piece, with the one excerpt from each half containing a locally salient cadence and the other containing a globally salient cadence. Of the four noncadential excerpts, two came from each half of the piece. Three hypotheses were tested. First, violinists would play the cadential excerpts differently from the noncadential excerpts. Thus, we expect that increased amounts of nontechnical motion and ritardando would feature in the cadential excerpts, particularly at the moment of resolution and departure from the V-I chord progression. Second, more importantly, we hypothesized that violinists would use increased amounts of nontechnical motion and ritardando to highlight resolutions in globally salient cadences, compared to locally salient cadences. In particular, the majority of such emphases would be focused on the moment of resolution of the cadence, involving more nontechnical motion compared to technical motion. Lastly, we hypothesized that violinists would differentiate the structural importance of cadences according to the binary form. Thus, we expected to see increased nontechnical motion and ritardando in the globally salient cadence in the second half of the piece compared to the first half, while such difference may be absent in the locally salient cadences between the halves. Practice logs and post-recording questionnaire were collected from violinists, in order to see whether they consciously paid attention to cadences in terms of the musical form and nonadjacent tonality and phrase relationships. However, they were not explicitly asked to highlight the cadences or form in their performance, nor asked about their evaluation of the importance of excerpts or structural features in question, so that we could observe measures extracted from a naturalistic performance.

Method

PARTICIPANTS

Nine highly trained violinists participated in this study. Three violinists' data were collected alongside the Biber sonata performance in our previous study (Huberth et al., 2019). The additional six violinists were newly recruited. Participants had an average age of 30 years ($SD = 4.0$ years) and had played violin for an average of 23.4 years ($SD = 4.2$ years). All participants were professionals or advanced performers studying at Stanford University; they maintained an active performance schedule and received regular private lessons. Because our motion recording was set up in a sound booth with a low ceiling, we specifically recruited participants who fit comfortably and were able to stand and play without disruption to their natural movements (especially the whole bow on the E string). Their heights were approximated by computing the vertical distance between the midpoint of the two ankle joints and the head joint as they stood in the reference pose (see Motion Capture Data Analysis for more details). The mean head height of the players was 167.0 cm ($SD = 6.2$ cm). All violinists received an honorarium for their participation. Performance data from two of the six newly recruited violinists were excluded on account of irreparable missing marker data from the motion capture, giving a total of seven violinists in our final analysis. All participants signed an informed consent form prior to their participation in the experiment. The study protocol was approved by the Stanford Institutional Review Board.

MUSICAL MATERIAL

Violinists performed the Allemande from Johann Sebastian Bach's Partita for Solo Flute, BWV 1013, transposed from A minor to G minor in order to accommodate technical aspects of violin playing relative to the four open strings. This binary-form movement is composed almost entirely of isochronous sixteenth notes and traverses a number of key areas that are closely related to the home key. As such, the movement contains several cadences of varying degrees of structural importance.

Eight excerpts were selected for both motion and timing analysis, four with an authentic cadence and four with a noncadential V-I chord progression. Each excerpt had a duration equivalent to three measures (12 quarter-note beats). Of the four cadential excerpts (labeled C1, C2, C3, and C4) displayed in Figure 1B, Excerpts C1 and C2 appear in the first half of the binary form, with Excerpts C3 and C4 appearing in the second half. Each cadential excerpt contains an authentic cadence that ends one musical phrase and transitions to the beginning of the following phrase. The cadences in Excerpts C1 and C3 were deemed to be locally conclusive without providing large-scale structural closure, as they transition immediately back to the main motive from the opening of the movement (see Figure 1A). In contrast, the cadences in Excerpts C2 and C4 are globally conclusive and provide large-scale structural closure, since neither cadence transitions immediately back to the main motive and both appear near the close of each half of the binary-form movement. One of the two cadences at each level of salience appears in the first half of the piece, with the other appearing in the second half. The four noncadential excerpts (labeled N1, N2, N3, and N4), displayed in Figure 1C, feature the V-I progression at the same position as the authentic cadence in the cadential excerpts. These V-I progressions appear in the middle of musical phrases, rather than at their conclusion. Excerpts N1 and N2 appear in the first half of the binary form, with Excerpts N3 and N4 appearing in the second half.

The eight excerpts were further divided into buildup and departure segments, whereby the buildup segment of six beats (equivalent to 1.5 bars) does not contain the V-I chord progression, while the departure contains the V-I progression. The musical excerpts were chosen based on previous music-theoretic analyses of the piece (Ford, 2014; LaBerge, 1995; Nakajima, 2013), as well as the first, second, and third authors' musical analysis. A timeline representing the position of these excerpts within the whole piece is shown in Figure 1D.

FIGURE 1. (A) The first two bars (bars 1.1–2.4) of the Allemande from Johann Sebastian Bach's Flute Partita in A minor, BWV 1013 (transposed to G minor), with the main motive (bars 1.1–1.2) boxed off. (B) The four cadential excerpts chosen for timing and motion capture analysis. Each excerpt is 12 beats long and is split up into two segments of six beats, called "buildup" and "departure" respectively. Excerpts C1 (bars 7.1–9.4) and C3 (bars 23.1–25.4) contain authentic cadences that are locally salient for musical resolution and are segmented with dashed boxes. Excerpts C2 (bars 17.3–20.2) and C4 (41.3–44.2) contain authentic cadences that are globally salient and are segmented with solid boxes. The small diagonal boxes in the departure segments indicate the two sixteenth notes where the harmony switches from chord V to chord I. The arrows show the first note of the main motive as it appears after the cadence: in Excerpts C1 and C3, this note is immediately after the cadence; in Excerpt C2, this note does not occur immediately after the cadence, instead happening two beats later; in Excerpt C4, it is not heard. (C) The four noncadential excerpts divided into buildup and departure segments. Excerpts N1 (bars 4.1–6.4), N2 (bars 12.1–14.4), N3 (bars 30.1–32.4), and N4 (bars 33.1–35.4) all contain a noncadential V-I progression at the same point as the authentic cadence in the corresponding cadential excerpts. The main motive does not appear after these cadences. (D) Timeline showing the position of each excerpt in the whole movement. The tightly dashed line partway through Excerpt C2 represents the sectional divide between the two parts of the binary form.

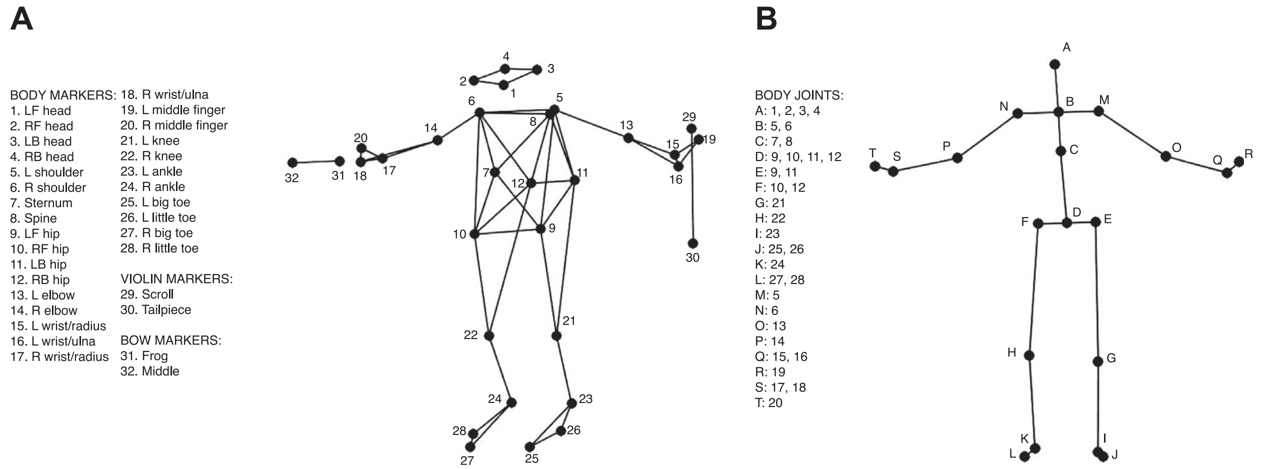

FIGURE 2. (A) Anterior view and legend of the location of the markers attached to the participants' bodies (L = left, R = right, F = front, B = back) as well as the violin and bow markers; (B) Anterior view of the locations of the secondary body joints used in the subsequent analysis. Legend reflects the marker numbers from which the joints were derived. Participants held this "standard" posture shown in this figure for a few seconds when their markers were calibrated before the performance.

Since there are no rests in this movement and the rhythm proceeds almost entirely in sixteenth notes, it is difficult to determine the location of cadential departures unambiguously. On the other hand, the fact that the opening motive appears at most of the selected cadences helps to define them more clearly as phrase boundaries. In the case of Excerpt C4, although the opening motive does not follow, the cadence marks the beginning of the coda passage and the resolution is to the home key of G minor. The chosen cadential excerpts clearly establish new tonal centers. In contrast, with the noncadential excerpts, either the existing tonality is reinforced or there is a quick modulation away from the briefly established tonal center without a return.

PROCEDURE

All violinists received the music at least two weeks before their scheduled session. They were instructed to use the printed fingerings and bowings to ensure consistency between performances for motion capture analysis and to observe the provided metronome marking of 65 quarter notes per minute. Observing this tempo throughout the piece would result in a sixteenth-note duration of 0.23 s. They were allowed to consult a metronome before their performance to double-check their tempo, but to keep the procedure as naturalistic as possible they were not given a metronome count-in immediately before their performance. No markings regarding the segments of analytical interest were specified on the score. Participants were asked to prepare the piece, without repeats, as if they were performing it in the context of a solo recital. Memorization of the music was not required and the music was attached at a fixed point on the wall of the recording booth. All players were instructed to wear dark, close-fitting clothing to minimize interference with the motion capture apparatus. On arrival to their experimental session, participants received information about the nature of the procedure and signed the informed consent form. After this, reflective markers were affixed to their bodies and instruments, as shown in Figure 2A. The violinists stood on a reference spot at a fixed distance from the cameras and their markers were calibrated while they held the static standard pose (stand straight while stretching open arms) displayed in Figure 2B. Most of the violinists recorded the Bach until two satisfactory performances were obtained. Two participants whose data were collected in a previous experiment only provided a single take each.

PRACTICE LOG AND POST-PERFORMANCE QUESTIONNAIRE

The six violinists who were newly recruited were instructed to keep a practice log for the two weeks prior to their data collection. The template for this practice log is included as Table A1 in the Appendix. In this log, they recorded the time spent practicing the piece and added specific comments about what their practice sessions entailed. In addition to ensuring that participants practiced sufficiently for their performances, the practice log allowed us to gain insights into the role of musical analysis in the performance preparation process, with attention given to whether or not that analysis revealed any expressive intentions relative to the hierarchical structure of the piece. We also administered a post-performance questionnaire for the newly recruited violinists, designed to gauge which parts of the piece were most important in each performer's interpretation. The questions we asked are included as Table A2 in the Appendix. They were also given an unmarked score of the piece to annotate to supplement their responses to the questionnaire. Note that the pre-performance practice log and post-performance questionnaire did not contain specific inquiries about the cadences, because our interest was to observe naturalistic performances without drawing attention to these excerpts.

The four newly recruited violinists whose performance data were included in the motion and timing analysis supplied practice logs and questionnaires. An additional fifth violinist, whose performance data were rejected in the motion and timing analysis, provided answers for the questionnaire. These data were also included for the questionnaire analysis.

APPARATUS

The violinists' motion was recorded with a 12-infrared camera optical motion capture system (Osprey Digital RealTime System, Motion Analysis Corporation, Santa Rosa, CA) using a sampling rate of 60 Hz. Recording was administered using the Cortex software (ver. 7, Motion Analysis Corporation). Three-dimensional positions of 32 reflective markers were recorded: two on a violin bow provided for the players (CodaBow Diamond NX Violin Bow) at the frog and the midpoint; two on the violin held in place with rubber bands at the scroll and the tailpiece, and 28 on the violinists' body in a configuration used in previous music-related movement research (Burger et al., 2018; Burger et al., 2013; Toiviainen et al., 2010).

Audio was recorded using a clip-on microphone (Audio-Technica PRO 35 Cardioid Condenser Clip-on Instrument Microphone), attached to the instrument on the edge of the chin rest. This ensured minimal dampening of the tone of the instrument. The microphone was angled towards the left f-hole. Audio recordings used a 44.1 kHz sampling rate and 16-bit depth via AD converter (MOTU Thunderbolt 828x) and stored with motion recording, in a time-synchronized manner.

IOI ANALYSIS FOR AUDIO DATA

To investigate rubato, we analyzed the internote onset intervals (IOIs) from the audio recording data with the Sonic Visualizer software (release 2.5, Queen Mary, University of London). After cropping the audio files to start at the first note (thereby excluding any noise from the calibration period), note onsets ($N = 727$ for each performance) were semi-automatically extracted using the spectral flux note onset detection plugin, a tool developed for Sonic Visualizer (Sapp, 2006). This algorithm detects a note onset when the change of magnitude of a spectrogram exceeds the local mean. We employed a window size of 1,024 samples to calculate the spectrogram and a 441 sample (10 ms) hop size. Note onsets were thereafter inspected visually for accuracy and corrected if necessary. The IOIs were subsequently log-transformed and mean-centered within each participant.

Means of the log-transformed, mean-centered IOIs were calculated in each segment of each excerpt. Two repeated measures analyses of variance (rmANOVAs) were subsequently performed on these values. The first was a two-way rmANOVA on all eight excerpts, with factors of *type* (cadential, noncadential) and *segment* (buildup, departure). The second was a three-way rmANOVA on just the four cadential excerpts (Excerpts C1–C4), with factors of *segment* (buildup, departure), *salience* (local, global) and *half* (first, second). In advance of running the rmANOVAs, we conducted a Shapiro-Wilk test to examine the normality assumption; this test was successful ($p = .41$). The sphericity assumption was met by default since there are only two levels per factor. Post hoc paired t-tests were then conducted, using Bonferroni corrections where appropriate and a significance level of $\alpha = .05$.

Certain notes in the score were not sixteenth notes, but these were adjusted as follows:

- Notes 289 and 290 were thirty-second notes, so they were combined as if they were one note (they were performed under a single bow).
- Note 291 was a dotted eighth note, so this was split into three equal-duration sixteenth notes.
- Note 727 was a half note, but since this note did not coincide with an excerpt of interest, it was ignored.

MOTION CAPTURE DATA ANALYSIS

Marker data were initially post-processed manually in the motion capture software by correctly labeling any misidentified markers and interpolating missing marker trajectories when markers went out of view of the cameras. Following the manual marker fixes, the marker trajectories were smoothed using a Savitzky-Golay FIR filter (Savitzky & Golay, 1964). This filter was implemented in the Motion Capture (MoCap) Toolbox (Burger & Toiviainen, 2013) using the MATLAB programming language (The MathWorks, Inc., Natick, MA). A window length of nine samples and a polynomial order of two was used on a set of 20 secondary markers derived from the original 28 body markers; this procedure is similar to those used in previous motion capture studies (Burger et al., 2018; Burger et al., 2014; Toiviainen et al., 2010). Several joints reflect the same position as an original marker, while some were calculated by averaging the positions of several markers at once. The original marker set and the secondary joints are displayed in Figure 2A and B, respectively.

The secondary joints were also used to estimate each violinist's height as they held the reference pose in Figure 2. First, we measured the distance from each ankle joint (joints I and K in Figure 2B) to the head joint (joint A in Figure 2B). We treated each of these ankle-head distances as the hypotenuse of a right-angle triangle and the midpoint of the ankles as the base. For each hypotenuse-base pair, we calculated the triangle height by using Pythagoras's theorem: specifically, we subtracted the squared base of the triangle from the squared hypotenuse, then took the square root. The two triangle heights were subsequently averaged to obtain an estimate of each violinist's height.

For the performance part of the joint data, we performed PCA to reduce the data into a small number of orthogonal components of motion time series. The majority of the variance observed in the joint data is encapsulated in these PCs. The PCA was performed with built-in functions in the MoCap Toolbox. Since we wished to observe the level of nontechnical motion shared by all players, a "grand average" performance was generated by aligning all the performances to one common time scale. Specifically, the grand average was obtained by time-warping every good take of the motion data such that each sixteenth note was set to a duration of 0.2 s (12 frames at the 60 Hz sampling rate), then averaging all the position data across each take in every player. The time-warping procedure has precedents in previous musical motion capture studies (Thompson & Luck, 2012; Wanderley et al., 2005). The motion capture from participants who only provided a single take were weighted such that each participant contributed equally to the grand average. The PCA was subsequently applied to this grand average performance, and the projection of each individual separate take on each PC was calculated to extract the portion of the movement that contains this component around the appropriate musical segments. Note that we did not normalize our motion data by body size. While normalization would be useful for biomechanical modelling, we were interested in tracking shared movement in a common, already centered PC space. Since our participants were all similar in height, we made no further normalizations to avoid inadvertent distortions or artifacts in the data.

PCs were classified as being primarily technical or nontechnical by visual inspection of the motion capture animations produced by the MoCap Toolbox. Brief versions of the animation videos are viewable at https://ccrma.stanford.edu/~aditya/violin_bach_pc_videos/. A PC was determined to be primarily technical if the motion was generally synchronous with note onsets and the right arm was seen to be involved in bowing up and down and/or string crossing. On the other hand, a PC that does not exhibit this motion and tends to be out of sync with note onsets would be characterized as primarily nontechnical. This means that nontechnical motion of the right arm would be extracted as part of nontechnical motion PCs, being out of sync with note onsets and moving in conjunction with other body parts without up-down or string crossing tendencies.

Of the first three PCs (hereafter PC1, PC2, PC3) that explained 85% of the whole motion data variance, we identified PC1 and PC3 as primarily representing nontechnical motion and PC2 as primarily representing technical motion (see the Results section for more details of their nature). These classifications were determined by all authors and reflect similar classifications in our previous work (Huberth et al., 2019). We also asked an independent expert, a violin professor at a large public university in the United States with 30 years of teaching experience and approximately 20 students per year, to assess the technicality of the PCs based on the motion capture animations, in order to verify our classifications.

Time courses of the individual performers' time-warped data projected onto these three PCs were obtained for each of the musical excerpts. Each excerpt consisted of 48 sixteenth notes, with one sixteenth note expressed in 12 frames of the time-warped motion data. For all three PCs, the difference in each participant's whole-body position was calculated from frame to frame across all joints and summed in groups of 12 to obtain a value representing the distance traveled in a particular PC during each sixteenth note. Thus, each excerpt resulted in 48 distance measures (one per sixteenth note). For each excerpt, these 48 values were averaged in the first and second half (24 values each), corresponding to the buildup and departure segments. For these measures in each PC, we performed two types of rmANOVAs, similar to those applied to the timing data. The first was a two-way rmANOVA on all eight excerpts with factors of *type* (cadential, noncadential) and *segment* (buildup, departure) to test the first hypothesis about the cadential distinction. The second was a three-way rmANOVA applied to the four cadential excerpts alone, with factors of *segment* (buildup, departure), *salience* (local, global) and *half* (first, second), to test the hypotheses about the embodiment of cadence structure and salience. Note that these two rmANOVAs had to be conducted separately because noncadential excerpts cannot be assigned local/global saliences. In advance of running the rmANOVAs, we conducted Shapiro-Wilk tests to examine the normality assumption.[1] Post hoc paired *t*-tests were then conducted, using Bonferroni corrections where appropriate and a significance level of $\alpha = .05$.

Results

TIMING ANALYSIS: AVERAGE IOIS

Figure 4A shows the mean sixteenth-note IOI for each of the participants in the experiment. The mean of all the individual average IOIs calculated across the whole performance was 0.24 s. This was not significantly different from the prescribed sixteenth-note duration of 0.23 s, $t(6) = 1.21$, $p = .27$, suggesting that participants were largely successful in following the indicated tempo marking.

TIMING ANALYSIS: CADENTIAL VS. NONCADENTIAL EXCERPTS

Next, we examined the log-transformed mean-centered note durations of our excerpts and segments of interest. Considering the two-way rmANOVA with factors of *type* (cadential, noncadential) and *segment* (buildup, departure) performed on all eight excerpts, there was a significant main effect of *type*, $F(1, 6) = 33.29$, $p = .001$, $\eta_p^2 = .90$, where cadential excerpts were performed slower than noncadential excerpts ($M_{\text{cadential}} = 0.03$, $M_{\text{noncadential}} = -0.03$). There was also a significant main effect of *segment*, $F(1, 6) = 56.55$, $p < .001$, $\eta_p^2 = .85$, where departure segments were performed slower than buildups ($M_{\text{departure}} = 0.01$, $M_{\text{buildup}} = -0.01$). There was an interaction between *type* and *segment*, $F(1, 6) = 40.50$, $p = .001$, $\eta_p^2 = .87$: while departure segments were performed significantly slower than buildup segments in cadential excerpts ($p < .001$), there was no significant difference between buildups and departures in noncadential segments ($p = .27$).

TIMING ANALYSIS: GLOBALLY VS. LOCALLY SALIENT EXCERPTS

Individual violinists' log-transformed mean-centered note durations in the four cadential excerpts are shown in Figure 3. These line plots show a relatively consistent pattern from excerpt to excerpt, where the note duration spikes near note 33. This note represents the moment of resolution in each excerpt. Most violinists also show a secondary spike in Excerpt C2 around note 40, where the motive from the opening of the piece begins once more in the dominant key as an extension of the earlier moment of cadence.

We then performed a three-way rmANOVA on the log-transformed mean-centered IOIs from the cadential excerpts alone to examine the factors *half* (first, second), *salience* (local, global), and *segment* (buildup, departure). The results of this rmANOVA are summarized in Table 1, and the means and standard errors of these transformed IOIs are shown in Figure 4B. There was a significant main effect of *segment*, $F(1, 6) = 49.15$, $p < .001$, $\eta_p^2 = .89$, as buildup segments on average were performed faster than departure segments ($M_{\text{buildup}} = -0.05$, $M_{\text{departure}} = 0.08$). The main effect of *salience* was also significant, $F(1, 6) = 27.25$, $p = .002$, $\eta_p^2 = .83$, with locally conclusive cadences being performed faster than globally conclusive cadences ($M_{\text{local}} = -0.01$, $M_{\text{global}} = 0.04$). The main effect of *half* was not significant, $F(1, 6) = 0.25$, $p = .64$, $\eta_p^2 = .04$. The interaction between *segment* and *salience* was significant, $F(1, 6) = 59.28$, $p < .001$, $\eta_p^2 = .91$, whereby the slowing in tempo in the departure segment compared to the buildup was greater in the global condition ($p < .001$) than the local condition ($p = .01$). A second post hoc test revealed that global departure segments were performed significantly slower than local departure segments ($p < .001$), while the opposite was true for the global and local buildups ($p = .005$). Finally, the interaction of *salience* and *half* was significant, $F(1, 6) = 12.85$, $p = .01$, $\eta_p^2 = .68$. The global cadence was played slower in the first half compared to the second, though not quite significantly so ($p = .06$), while the local cadences were not performed at significantly different tempi in either half ($p = .21$).

Overall, these results indicate that violinists were sensitive to the salience of the cadences in Excerpts C1–C4 and differentiated them from the noncadential Excerpts N1–N4. Further, the violinists expressed these saliences differently for locally and globally salient cadences, such that the departure was played slightly slower than the buildup in the local condition but drastically slower in

[1] The PC1 data passed the Shapiro-Wilk test for normality ($p = .13$). PC2 did not ($p < .05$), but our aim in applying the rmANOVA to PC2 motion is to examine whether the patterns observed in the nontechnical motion were also present in the technical motion. PC3 data also did not pass the Shapiro-Wilk test ($p < .05$). However, we identified outlier data in one violinist and the test was passed when this participant's data were removed ($p = .46$).

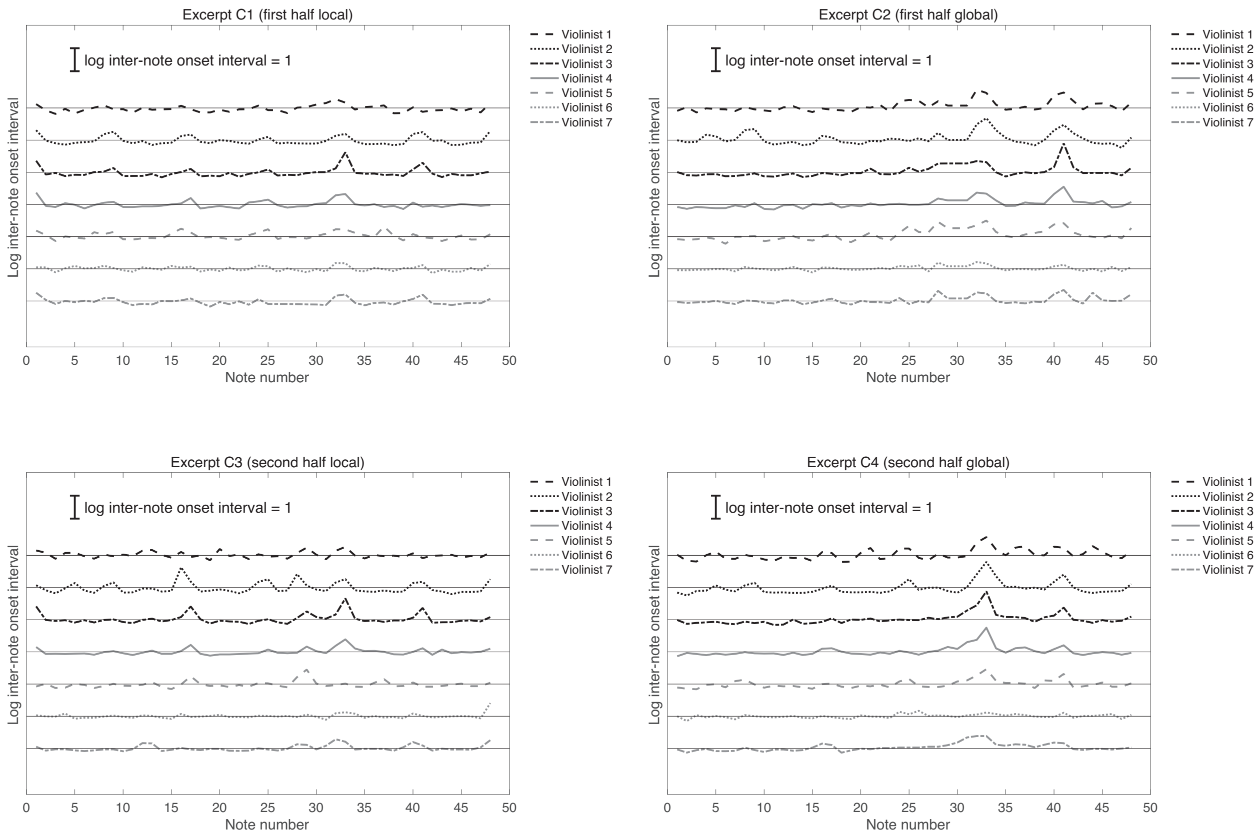

FIGURE 3. Individual violinist log-transformed mean-centered note durations for each 48-note cadential excerpt.

TABLE 1. *Summary of Three-Way rmANOVA on Log-Transformed Mean-Centered Timing Data: Significances and Post Hoc Results*

Predictor	Outcome
Segment	***
	D >>> B
Salience	**
	G >> L
Half	ns
Segment x Salience	***
	G: D >>> B
	L: D > B
Segment x Half	ns
Salience x Half	**
	G: H1 ∼ H2
	L: H1 ∼ H2
Segment x Salience x Half	ns

Note. Significance levels are indicated as ***$p < .001$, **$p < .01$, *$p < .05$, ns = not significant. For post hoc results: D = departure, B = buildup, G = global, L = local, H1 = first half, H2 = second half, >>> = significantly greater ($p < .001$), >> = significantly greater ($p < .01$), > = significantly greater ($p < .05$), ∼ = not significantly different.

the global condition. There was no clear tempo change between excerpts in the two halves.

PRINCIPAL COMPONENT ANALYSIS OF MOTION DATA

The grand average take was decomposed into PCs of motion. The variances of the data explained by the first ten PCs are shown in the graph in Figure 5A, which is analogous to a scree plot. The first PC (PC1) accounted for approximately 45% of the variance in the motion, while the second and third PCs (PC2, PC3) accounted for approximately 25% and 15% of the variance, respectively.

Still-image visuals of the motion profiles of the PCs are displayed in Figure 5B, while short videos of the PC-based whole-body motions may be found at a web page (https://ccrma.stanford.edu/∼aditya/violin_bach_pc_videos/). PC1 is primarily a nontechnical motion, featuring side-to-side swaying that does not involve right-arm bowing motions and is not synchronized with note

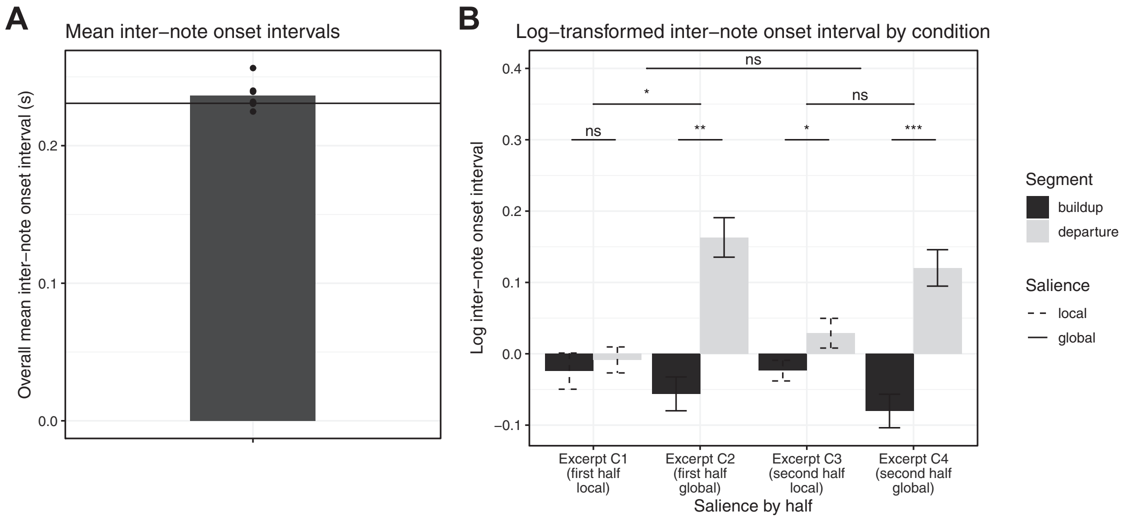

FIGURE 4. (A) Overall average internote onset interval (IOI) in seconds for all performers, together with individual average IOIs (dots) and the IOI that would result from playing at the designated tempo (horizontal line); (B) Mean log-transformed mean-centered note duration for globally and locally salient buildup and departure segments in each half; ***$p < .001$, **$p < .01$, *$p < .05$. The error bars represent the standard error of the mean.

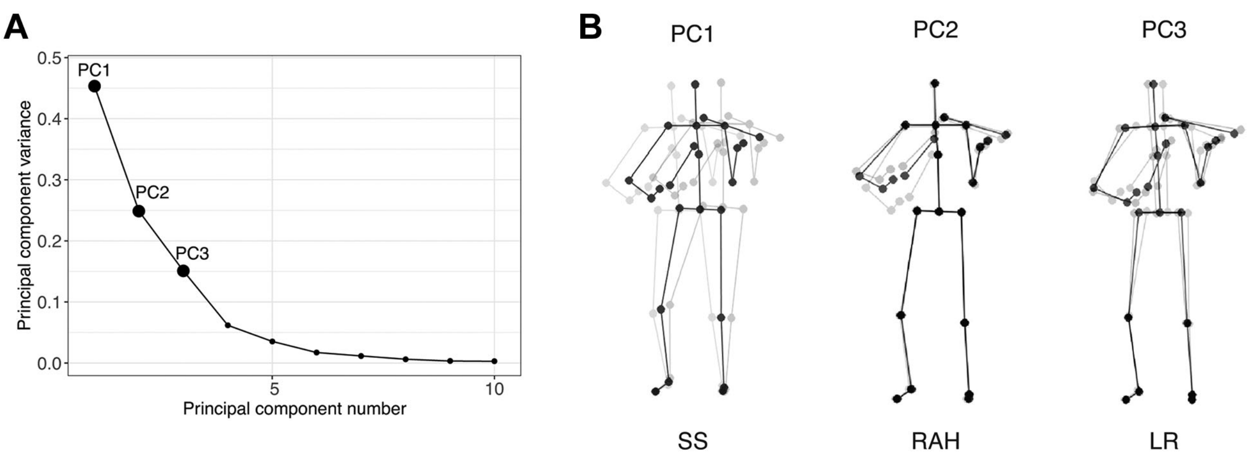

FIGURE 5. (A) Plot showing the proportion of variance in the grand average motion profile accounted for by the first ten principal components of motion; (B) Visualizations of the first three principal components (PCs) of motion. Within a given PC, the posture illustrated in black lines shows the mean position of all the joints, whereas the two postures drawn in grey lines indicates the joint positions with the maximum distance from the mean in both directions. The gloss characterization of each PC is expressed as SS = side-to-side swaying for PC1, RAH = right-arm height for PC2, and LR = left-right rotation for PC3.

onsets. PC2, by contrast, represents bowing and string-crossing motion in the right arm that was synchronized with note onsets, with additional rotation in the left elbow and minimal movement in other body parts; it is thus considered primarily technical. PC3, a left-right body rotation movement, shows some synchronized motion with note onsets; however, we still interpret PC3 as primarily nontechnical because of the heavy involvement of joints other than those in the right arm and the lack of up/down bow and string-crossing motion. Our characterization was confirmed by the independent expert who described PC1 and PC3 as "primarily a form of nontechnical motion that may be related to musical expression," while describing PC2 as "motion that is required in the technique of playing an instrument."

PC MOTION: CADENTIAL VS. NONCADENTIAL EXCERPTS

The total distance traveled in each PC motion was examined to test whether violinists performed cadential and noncadential excerpts differently. We conducted a two-way rmANOVA for each PC using all eight excerpts. In PC1, there was a significant main effect of *segment*, $F(1, 6) = 12.44$, $p = .01$, $\eta_p^2 = .67$, where departure segments featured more PC1 motion than buildup segments ($M_{\text{departure}} = 26{,}600$, $M_{\text{buildup}} = 20{,}400$). Though the main effect of *type* was not quite significant, $F(1, 6) = 5.58$, $p = .06$, $\eta_p^2 = .48$, there was a significant interaction between *type* and *segment*, $F(1, 6) = 26.71$, $p = .002$, $\eta_p^2 = .82$. While there was a significant increase in PC1 motion from buildup to departure segments in cadential excerpts ($p = .002$), no such difference occurred in the noncadential excerpts ($p = .80$). This interaction drove the significant main effect of *segment*, as increased departure motion is dependent on the excerpt being cadential. A second post hoc showed that the noncadential buildups featured more PC1 motion than the cadential buildups ($p < .001$) but the reverse was true for the departures ($p = .02$), indicating that violinists increased the contrast between the buildup and departure for cadences.

In PC2, none of the main effects of *type* and *segment* was significant, nor their interaction.

In PC3, the main effect of *segment* was significant, $F(1, 6) = 14.49$, $p = .009$, $\eta_p^2 = .71$, with departure segments featuring more PC3 motion than buildup segments ($M_{\text{departure}} = 14{,}500$, $M_{\text{buildup}} = 11{,}400$). The main effect of *type* was also significant, $F(1, 6) = 34.29$, $p = .001$, $\eta_p^2 = .85$, with cadential excerpts featuring more PC3 motion than noncadential excerpts ($M_{\text{cadential}} = 14{,}900$, $M_{\text{noncadential}} = 11{,}000$). Finally, there was a significant interaction between *type* and *segment*, $F(1, 6) = 28.90$, $p = .002$, $\eta_p^2 = .83$. There was a significant increase in PC3 motion from buildup to departure segments in the cadential condition ($p = .001$) but not in the noncadential condition ($p = .52$). A second post hoc showed no significant difference between the PC3 motion in the buildup segments ($p = .28$) but significantly more motion in the cadential departure segments compared to the noncadential excerpt ($p < .001$). Once more, the interaction drove the main effects, meaning that increased departure motion is dependent on the excerpt being cadential and the contrast between buildup and departure was greater for cadences.[2]

Altogether, these results are in line with PC1 and PC3's characterization as primarily nontechnical motion, where violinists clearly differentiated cadential excerpts by increasing their motion, and PC2's characterization as primarily technical motion, as this PC was not affected by the musical significance of the cadential excerpts.

PC MOTION: GLOBALLY VS. LOCALLY SALIENT EXCERPTS

Next, we examined in more detail how violinists moved to play cadential excerpts. Figure 6 shows the time courses of the distance traveled in each of the four cadential excerpts for each violinist in the experiment within PC1. There are large fluctuations in the joint distances from note to note, though the departure of each excerpt generally appears to feature more motion than the buildup in Excerpts C2 and C4. We subsequently examined the joint distance traveled in each PC using three-way rmANOVAs with factors of *half* (first, second), *salience* (local, global), and *segment* (buildup, departure). A condensed summary of the results of these three-way rmANOVAs can be found in Table 2.

Figure 7A shows the joint distance traveled in PC1 across the different conditions. There was a significant main effect of *segment*, $F(1, 6) = 21.89$, $p = .003$, $\eta_p^2 = .78$, where departure segments featured more motion in PC1 than buildup segments ($M_{\text{buildup}} = 18{,}300$, $M_{\text{departure}} = 30{,}400$). The main effect of *salience* was also significant, $F(1, 6) = 6.88$, $p = .04$, $\eta_p^2 = .53$, with excerpts incorporating globally important cadences featuring more motion in PC1 than those incorporating locally important cadences ($M_{\text{local}} = 20{,}300$, $M_{\text{global}} = 28{,}400$). There was a significant main effect of *half*, $F(1, 6) = 9.90$, $p = .02$, $\eta_p^2 = .62$, with second-half excerpts performed with more PC1 motion than first-half excerpts ($M_{\text{first}} = 19{,}000$, $M_{\text{second}} = 29{,}800$). The two-way interaction between *segment* and *salience* was significant, $F(1, 6) = 13.45$, $p = .01$, $\eta_p^2 = .69$: in the global condition, departure segments featured more motion than buildups ($p = .001$), but there was no significant difference in motion between buildup and departure in the local condition ($p = .78$). A second post hoc test revealed that global departure segments featured more motion than local departure segments ($p = .007$), but the reverse was true for buildup segments ($p = .034$). This means that while the main effect of *salience* was partly driven by the increased motion in the global departure segment, there was still a difference between global and local PC1 motion in the buildups. The interaction between *half* and *segment* was significant, $F(1, 6) = 9.45$, $p = .02$, $\eta_p^2 = .61$. The first half of the piece featured a significant increase in PC1 motion from buildup to departure segments ($p = .006$); the

[2] The two-way PC3 rmANOVA showed the same pattern of results with and without the data from the outlier violinist. All the post hoc comparisons showed that the effects were in the same direction both with and without this violinist.

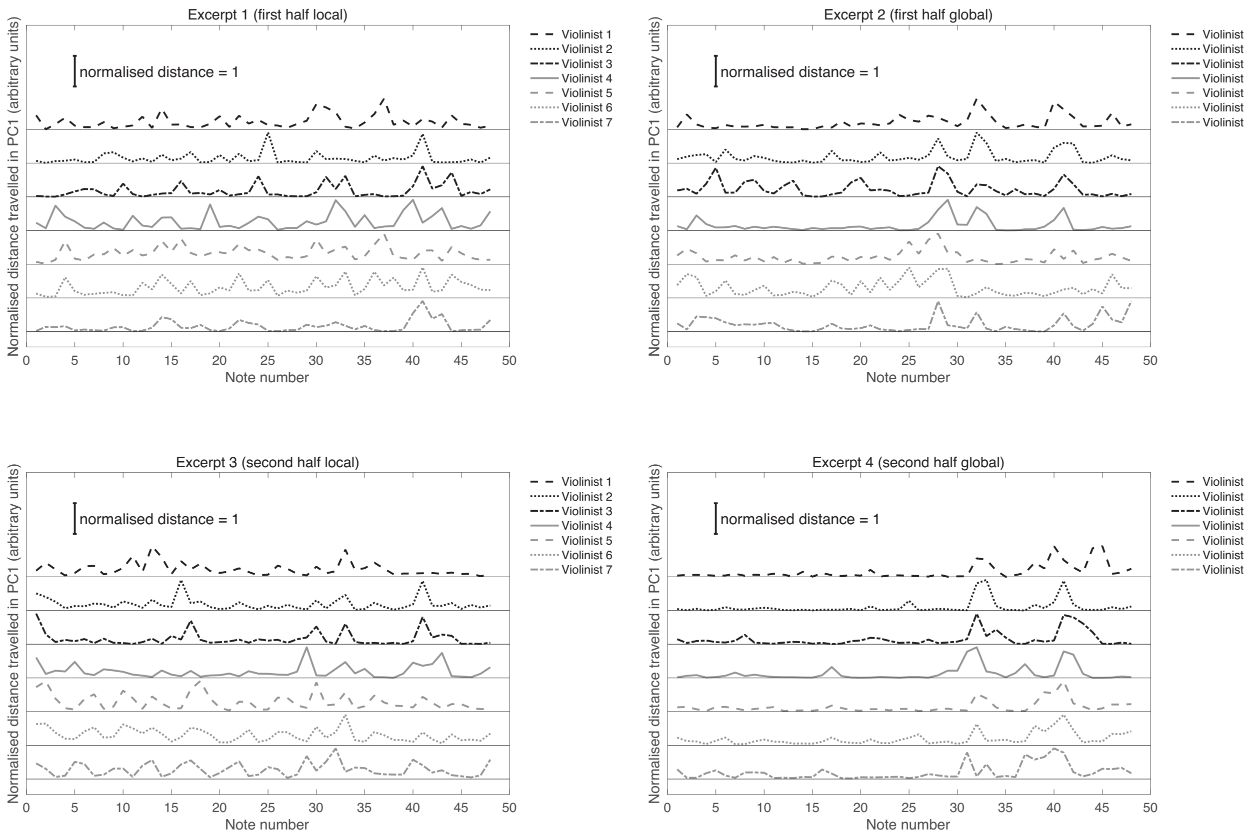

FIGURE 6. Normalized joint distance traveled in PC1 by note for each violinist in each cadential excerpt. For ease of visualization, each violinist's note-to-note distances were also normalized within each excerpt by dividing by the maximum distance traveled between two note onsets in an excerpt, but our statistical analysis was conducted on the values before this normalization.

TABLE 2. *Summary of Three-Way rmANOVAs on PC1, 2 and 3 Motion Data: Significances and Post Hoc Results*

		Component	
Predictor	PC1	PC2	PC3
Segment	** D >> B	ns	** D >> B
Salience	** G > L	ns	ns
Half	* H2 > H1	ns	ns
Segment x Salience	* D: G >> L B: L > G	ns	* D: G > L B: G ∼ L
Segment x Half	* H1: D >> B H2: D > B	ns	ns
Salience x Half	* L: H2 > H1 G: H2 >> H1	ns	ns
Segment x Salience x Half	** H1: D > B H2: GD > GB, LD ∼ LB	ns	* H1: nsr H2: GD >> GB, LD ∼ LB

Note. Significance levels are indicated as $^{**}p < .01$, $^{*}p < .05$, ns = not significant. For post hoc results: D = departure, B = buildup, G = global, L = local, H1 = first half, H2 = second half, >> = significantly greater ($p < .01$), > = significantly greater ($p < .05$), ∼ = not significantly different, nsr = no significant post hoc results.

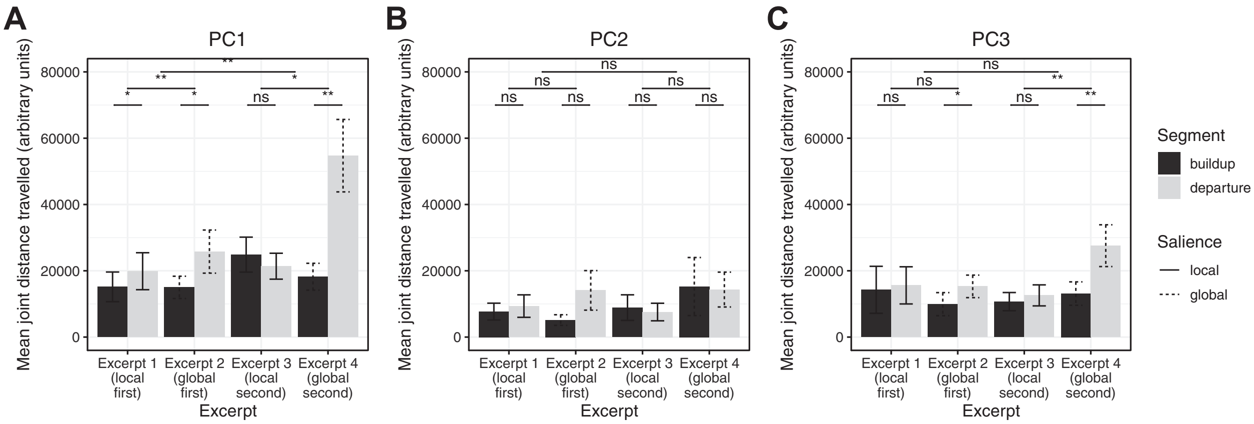

FIGURE 7. Mean joint distance traveled in (A) PC1, (B) PC2, and (C) PC3 for globally and locally salient buildup and departure segments in each half; **$p < .01$, *$p < .05$. The error bars represent the standard error of the mean.

second half also had a significant increase from buildup to departure segments, but this result was weaker ($p =$ .03) owing to individual differences in movement profiles. There was a significant interaction between *half* and *salience*, $F(1, 6) = 10.01$ $p = .03$, $\eta_p^2 = .63$. There was a weakly significant increase in motion in locally salient excerpts from the first half to the second ($p =$ .05), but a much more strongly significant increase in motion in the globally salient excerpts from the first half to the second ($p = .008$).

Finally, the three-way interaction between *half, segment* and *salience* was significant, $F(1, 6) = 19.75$, $p =$ .004, $\eta_p^2 = .77$). Two-way rmANOVAs with factors of *segment* and *salience* were performed as post hoc tests in each half. In the first half, the *segment* was the only significant main effect, $F(1, 6) = 10.72$, $p = .02$, $\eta_p^2 =$ .64, with the departure segment featuring more motion than the buildup ($M_{\text{buildup}} = 15{,}100$, $M_{\text{departure}} =$ 22,800). In the second half, both main effects were significant, and the interaction between *segment* and *salience* was significant, $F(1, 6) = 18.27$, $p = .005$, η_p^2 $= .75$: less PC1 motion in the buildup was observed compared to the departure in the global condition (p $= .004$) but no significant difference occurred in the local condition ($p = .13$). Thus, there was a greater differentiation in PC1 motion between Excerpts C3 and C4 than between C1 and C2. We ran an additional two-way rmANOVA on the buildup segments alone, with factors of *salience* and *half* to further explore this interaction. The main effect of *half* was significant, $F(1, 6) =$ 7.47, $p = .03$, $\eta_p^2 = .55$, with more buildup motion in the second half than the first ($M_{\text{first}} = 15{,}100$, $M_{\text{second}} =$ 21,500). While the main effect of *salience* was not significant, $F(1, 6) = 5.07$, $p = .07$, $\eta_p^2 = .46$, the interaction between *salience* and *half* was significant, $F(1, 6) = 23.19$, $p = .003$, $\eta_p^2 = .79$. In the excerpts with locally salient cadences, the PC1 buildup motion was significantly greater in the second half than the first half ($p = .008$), but there was no significant difference for the globally salient excerpts ($p = .29$). Excerpts C1 and C3 were thus differentiated by the increased PC1 buildup motion in C3, but C2 and C4 were not differentiated.

The joint distance data similarly derived from PC2 and PC3 are shown in Figure 7B and C, respectively. In PC2, which was identified as technical motion related to string crossing with the bow, none of the main effects of *segment*, *salience* and *half* were significant, nor were their interactions. Notably, Excerpt C4 has increased technical difficulty compared to the other excerpts with its string crossings over two strings, but this had no effect on PC2.

In PC3, also identified as nontechnical motion, we observed a similar pattern of results as in PC1. The rmANOVA for PC3 data revealed a significant main effect of *segment*, $F(1, 6) = 31.73$, $p = .001$, $\eta_p^2 = .84$, where buildup segments featured less motion in PC3 than departure segments ($M_{\text{buildup}} = 12{,}000$, $M_{\text{departure}} =$ 17,800). While the main effect of *salience* was not significant, $F(1, 6) = 2.09$, $p = .20$, $\eta_p^2 = .26$, the interaction between *salience* and *segment* was significant, $F(1, 6) =$ 6.98, $p = .04$, $\eta_p^2 = .54$: the contrast between the increased motion in the departure segments within PC3 was greater in the global condition ($p < .001$) than in the local condition ($p = .38$). A second post hoc test revealed that there was no significant difference in PC3 motion between the local and global buildup segments ($p = .68$), while there was increased PC3 motion that approached significance in global departure segments compared to local departure segments ($p = .06$). Though the main effect of *half* was not significant, $F(1, 6) = 0.67$, $p = .44$, $\eta_p^2 = .10$, and its associated two-way interactions were not significant, there was a three-way interaction between *half*, *segment* and *salience*, $F(1, 6) = 9.19$, $p = .02$, $\eta_p^2 = .61$. As post hoc tests, additional two-way rmANOVAs with factors of *segment* and *salience* were performed in each half. While there were no significant main effects or a significant interaction in the first half, both main effects and the interaction were significant in the second half. Considering the interaction between *segment* and *salience*, $F(1, 6) = 11.63$, $p = .01$, $\eta_p^2 = .66$, there was more PC3 motion in the global departure segment than the global buildup segment ($p = .004$; $M_{\text{buildup}} = 13{,}100$, $M_{\text{departure}} = 27{,}600$), but no significant difference between local buildup and local departure segments ($p = .32$). Therefore, the significant main effect of *segment* was driven primarily through the considerable increase in PC3 motion at Excerpt C4's departure segment. We ran another two-way rmANOVA with factors of *salience* and *half* on the PC3 data to see if there was a similar differentiation of the buildups between the local and global conditions in this component of motion. However, this time, there were no significant main effects nor a significant interaction.[3]

Our analyses revealed that nontechnical motions represented in PC1 and PC3 emphasized the buildup-departure distinction throughout all excerpts, but most prominently for the most globally salient cadence during Excerpt C4. This shows a sharp contrast with the data in technical motions represented in PC2, for which the rmANOVA revealed no significant main effects or interactions. The greater motion observed in Excerpt C4 is therefore most likely accounted for by its musical significance, rather than its technical difficulty. Additionally, we observed a differentiation of the local buildup segments, with increased PC1 motion in Excerpt C3 compared to Excerpt C1. This pattern was not observed in the global buildup segments.

PRACTICE LOG

Four violinists (labeled S09, S10, S11, S12) logged their practice of the Bach Allemande. There was an average of six entries per practice log ($SD = 1.41$). Over the course of their preparation period, the total duration of the practice that each player logged was 145 min on average ($SD = 47$ min). While all violinists began the practice process mainly focusing on the technical aspects of the piece (particularly intonation), all violinists made analytical comments and incorporated those observations into the practice routine at some stage of the process. Some of these comments addressed mapping the gestures of each half the music into the playing and maintaining sensitivity to the long trajectories of the phrases (S09), bringing out the phrasing and the different implied voices (S10 and S11), and emphasizing the different key areas of the piece through expressive timing, vibrato and dynamics (S12). These results suggest an awareness of and sensitivity to musical structure during the practice process.

POST-PERFORMANCE QUESTIONNAIRE

Five performers (labeled S09, S10, S11, S12, S13) filled out the questionnaire. Although S13's performance data were not included in the motion analysis, the questionnaire data are included here. We were primarily interested in whether the violinists identified any moments from our four excerpts as being important to their interpretation.

Three violinists (S09, S12, S13) acknowledged the importance of Excerpt C1 in their interpretation, with S09 describing it as a moment of structural change, S13 noting its contrast with m. 28, and S12 considering Excerpt C1 and m. 28 as "mini-climaxes." Two of those violinists (S09 and S13) provided comments about Excerpt C3 that paralleled those they made about Excerpt C1. Four violinists (S09, S10, S11, S13) referenced Excerpt C2 in their interpretation. S09 and S13 noted that it contained the most musical tension and drive, S10 said that it was their favorite moment of the piece, and S11 interpreted its descending melodic contour as contrasting with the rising motion preceding it. Three of those violinists (S09, S12, S13) mentioned the role of Excerpt C4 in their interpretation, with S09 and S13 describing it in the same way as they described Excerpt C3 and S12 noting that it functioned as a moment of drama toward the close of the piece. S09 specifically marked the cadential resolutions indicated in the small diagonal boxes from Figure 1 on the provided score, circling the cadences in Excerpts C2 and C4 and parenthesizing the cadence in Excerpt C3 to indicate their differing hierarchical roles. S12 marked the cadential resolution in Excerpt C4 on the score and described it as a culmination point.

Aside from the specific musical analysis, S09 acknowledged the hierarchical nature of the music,

[3] In the three-way rmANOVA, the significant interaction of *segment* and *salience* obtained from all participants' data became marginal when the outlier violinist was removed ($p = .08$). However, the main effect of *segment* and, critically, the three-way interaction remained significant. The post hoc tests revealed that the effects were in the same direction both with and without this violinist; this was also true for the marginal *segment-salience* interaction.

describing its structure as containing "phrases within phrases." S11 noted Bach's use of repetition in the music and related this to a desire to create contrast in her performance. She also looked for moments of tension and release. Overall, our results suggest that most of our violinists found the cadential excerpts that we identified to be of musical significance in their conception of the piece.

Discussion

In this study, we examined how highly trained violinists embody the structural salience of musical phrases in performance through their expressive timing and nontechnical motion. It was found that cadential excerpts featured more stretching of note durations (ritardando) and increased nontechnical motion compared to noncadential excerpts, and that excerpts with globally salient musical cadences featured more ritardando and nontechnical motion compared to those with locally salient musical cadences. Interestingly, for the globally salient cadences, increased ritardando and nontechnical motion took place in segments that incorporated the moment of musical cadence and the subsequent departure, as compared with the buildup to the cadence, far more so than was the case for the locally salient cadences. The overall pattern of the results was quite similar in the timing and motion data.

Our finding that nontechnical motion systematically reflects the structural salience of the cadence is novel in the literature. It confirms our hypothesis and extends previous findings of musicians' increased nontechnical motion around phrase endings (Buck et al., 2013; Juchniewicz, 2008; MacRitchie et al., 2013; Vines et al., 2006; Wanderley et al., 2005). Further, it aligns with the results from Thompson and Luck (2012), who examined what happens if musicians are asked to suppress their motion. Since performers initially exhibited increased nontechnical motion around globally salient moments in the music, suppression of that motion in the deadpan condition resulted in a greater difference in nontechnical motion at those moments. The enriched expressive motion at the globally salient cadences is additionally accompanied by increased ritardando. Our data clearly show that both locally and globally salient cadences exhibited longer note durations than the overall average, in agreement with previous work (Davidson, 2012; Palmer, 1989, 1996; Palmer & Krumhansl, 1987; Timmers et al., 2006). Our results further show exaggeration of the ritardandi according to the music's hierarchical structure, thus extending this previous work. They also lend empirical support to the predictions of theoretical models of expressive timing that suggest increased ritardando at structurally salient moments (Todd, 1985, 1989).

Separating the cadence into buildup and departure segments further revealed their interaction with salience. First, there was more contrast between buildup and departure segments in excerpts with globally salient cadences compared to those with locally salient cadences, both in the level of ritardando and the amount of nontechnical motion. Since our departure segments contained the final resolution from the dominant chord to the tonic chord, our results show that the violinists expressed the cadence's structural importance to contrast with the music that immediately preceded it. While our recording session did not involve an audience, it is possible that this embodied expression could also convey the emphasis to audiences. Music listeners may not readily process nonadjacent tonal dependencies (Granot & Jacoby, 2011, 2012; Tillmann et al., 1998), but are sensitive to the embodiment of phrase structures (Vines et al., 2006) and melodic discontinuity (Huberth et al., 2019; Thompson et al., 2005). A perceptual experiment may confirm whether the magnified variation in nontechnical motion and ritardando between buildup and departure segments around globally important cadences could accentuate the hierarchical musical structure.

The global-local contrast is not only made by the longer note duration and increased nontechnical motion in the global departure segment compared to the local, but also how the buildup-departure contrast is performed. Specifically, the buildups in globally salient cadences are played faster, and their deviation from the average tempo are larger than the amount of deviation for the local cadence departure tempo. This is accompanied by less nontechnical motion in buildups to globally salient cadences compared to locally salient cadences, especially in the second half where the movement finally cadences in the home key of G minor. While these results generally confirm our hypothesis that the departure segments would mainly carry the weight of the structural emphasis, they add the nuance that the contrast between buildup and departure segments matters more in emphasizing the difference between local and global salience, especially when highlighting the return to the home key (as was the case in Excerpt C4). A faster tempo has been shown to result in a heightened perception of musical tension (Ilie & Thompson, 2006), so our violinists may have been expressing the increased tension before the globally important cadence with their faster buildups. The decreased nontechnical motion in the buildups to globally salient cadences may also be the result of an effort to highlight the release of tension at the cadence. Reduced differentiation between local and global buildup segments as compared with the equivalent departure segments may also point to the individual differences during the buildup segments. As the questionnaire data show, several of the violinists identified important moments in the score that matched our excerpt selections closely, even without any explicit markings on the score. Notably, not every violinist identified moments in the region of Excerpts C2 and C4 as the most structurally important. Thus, the results may follow the pattern that individual differences in embodied musical interpretation are most pronounced midphrase while players agree with each other more at phrase endings (Buck et al., 2013; Desmet et al., 2012; MacRitchie et al., 2013).

Taken together, our findings show how performers mediate between expressing recursively nested hierarchical structures and playing the notes of a composition in a fixed temporal sequence. In order to express that structure, performers must differentiate between cadences that appear in sequential order. Performers leverage the expressive devices of nontechnical motion and rubato and exaggerate the contrast between cadence buildups and departures when highlighting a globally salient cadence whose most recent predecessor is a locally salient cadence. This suggests that having knowledge of the entire tonal context is important in relating sequential and hierarchical cadence organization. Listeners who hear scrambled musical fragments lack that knowledge and hence are unable to recover the original cadence hierarchies (Granot & Jacoby, 2011, 2012; Tillmann et al., 1998).

It is worthy of note that Excerpt C4 did not result in increased technical motion in the departure segment at least in the PC2 measures despite its successive large intervals. Our violinists were highly trained, and successfully played this passage without deviating far from the prescribed tempo, as shown in Figure 3. In other words, our violinists could have taken more time in the departure segment to accommodate the large intervals, but in reality they did not (in fact, they tended to take more time in the departure segment of Excerpt C2 than that of Excerpt C4). The additional right-arm motion for playing larger intervals still involved no substantial arm height changes, since wrist and finger flexibility is usually employed by skilled players to reduce the need to move the right arm up and down so much, as explained in violin pedagogy (Galamian, 1985). This is supported by the PC2 data (right arm height change) which did not show a substantial increase from the buildup to the departure segment. In contrast, the movement increase was found in both PC1 (side-to-side swaying) and PC3 (left-right rotation), lending further support to the musical significance of this passage.

Our violinists did not only differentiate cadences through their nontechnical motion in the departure segments. In fact, they exhibited considerably more PC1 motion in the buildup to Excerpt C3, an excerpt with a locally salient cadence in the second half, than its counterpart in the first half, Excerpt C1. These excerpts fulfill similar functional roles in the musical structure of each half, as they both reintroduce the main motive, but the buildup to the cadence in each of these excerpts is quite different. While Excerpt C1 features a continuously rising diatonic sequence up until the moment of cadential resolution, Excerpt C3's buildup features considerable chromaticism and modulates from D minor to C minor in the space of just two bars of music. The melodic contour also undulates considerably more than the corresponding buildup in Excerpt C1. This additional musical complexity may explain why our violinists moved more in the buildup of Excerpt C3 to express its heightened tension. Similarly, the buildups of Excerpts C2 and C4 exhibit considerable thematic parallelism, which may explain why there was no significant difference in PC1 motion in the global buildups. Overall, these results show that violinists approached the cadences holistically to utilize the contrast between the buildup and departure for expressing the saliences and overall form.

The present study extends our previous work (Huberth et al., 2019) by exploring the role of larger phrase structures in shaping violinists' whole-body nontechnical motion and rubato. It also considers the common motion between all performers by performing PCA on a grand average performance created from every time-warped take. Although performing PCA on a grand average performance is generally similar to eliciting PCs from a stacked individual performance matrix, making an explicit grand-average motion model with PCs allows us to extract specifically what is shared across participants' movement patterns and compare different parts of the music. In order to be able to create such a grand-average take, it was necessary to time-warp the motion data so that each performance was temporally aligned; this procedure has a basis in previous work (Thompson & Luck, 2012; Wanderley et al., 2005). The group averaging technique has also been applied in studies of music-related motion. Wöllner et al. (2012) showed that their participants were able to follow the gestures of several conductors averaged together into a single "prototypical" point-light video more easily than to the individual conductors' point-light videos from motion capture. Our group-based PC motions may therefore provide useful pedagogical resources for learning violin, as the resulting footage may serve as exemplars for both technical and nontechnical motion schemes. We additionally extend previous findings of the embodiment of hierarchical musical structure to violinists' whole-body motion, adding to a body of literature on pianists (Buck et al., 2013; Juchniewicz, 2008; MacRitchie et al., 2013; Massie-Laberge et al., 2019) and clarinetists (Vines et al., 2006; Wanderley et al., 2005). The primary advantage of this group-based PCA is that the individual differences in motions can be considered in the shared component space because individual performances are always projected onto the group-based PCs.

There are a few potential limitations of our study. One is that our sample size was small. It proved to be difficult to recruit enough players with the requisite level of training. However, our measures are relative rather than absolute (we explored within-subject variation in rubato and a shared component space for motion). Also, our analyses were conducted over eight excerpts each containing 48 notes, corresponding to 53% of the entire piece, while our timing and motion measures are based on the whole performance as we employ log-transformed mean-centered IOIs and PCA from all notes. Thus, our analyses likely capture the violinists' characteristics reasonably well and we do not believe that individual variation led to artifactual results. Another possible limitation is that we recorded participants in a sound-isolated booth with only experimenters present, rather than on a concert stage with audience members; as such, their performance might be still different from how they might play in a real performance. However, musicians in general must be accustomed to such differences in space and scenario, including practicing alone in a studio or playing for a teacher. Future work could examine the effects of performing in different situations and venues on nontechnical motion and rubato, as some of the differences may arise consciously while others may manifest unconsciously. That said, our violinists mostly identified the music-theoretic significance of our excerpts in the practice stage. Thus, we suspect that the overall patterns of our findings would be replicated during public performance, but the nature of nontechnical motion might be subtly different from those in the practice stage. This would reflect the results of Moelants et al. (2012), who found that a singer and a viola da gamba player could reproduce the musical interpretation from their rehearsal in concert, but the singer changed their posture more often during the concert than in the rehearsal and stood with a more open stance. Additionally, while we analyzed motions as primarily technical or nontechnical, such a distinction is somewhat artificial from a biomechanical and musical perspective as mentioned earlier, and even nontechnical motion may serve acoustic correlates such as timbre. Performers are generally unable to suppress their nontechnical motion completely (Davidson & Correia, 2002; Thompson & Luck, 2012; Wanderley et al., 2005). Thus, all motor correlates may be linked intimately to their musical plans and goals for expression. Finally, while our violinists demonstrated their sensitivity to the excerpts of interest explicitly in their practice logs and implicitly in performance, it is not clear at what stage of the learning process they began to recognize and perform these structural features. Thus, we are unable to draw any conclusions about when performers began to integrate their theoretical knowledge into their practice, as we only had access to the final performances. Nakajima (2013) found that even when musicians felt that analysis was important when practicing for a performance, several of the musicians recruited for her study had not analyzed the music they were asked to prepare for a lesson, and none of those who had analyzed the music had written down anything explicitly. Thus, there appears to be a substantial amount of individual variation in how analysis serves the music learning process, even for skilled performers, which may result in different expressions of the musical structure. An example of individual variation in our data can be found in Figure 3. It shows that Violinists 3 and 4 took substantially more time on note 41 of Excerpt C2 (the note before the restatement of the main motive) than on note 33 (the moment of cadential resolution), while the other violinists tended to take more time on note 33 than on note 41. Nonetheless, it is worth noting that our performers mostly identified our cadences of interests as moments that were important to their interpretation without prompting. Players who were more specific about the excerpts they highlighted also did not express them profoundly differently from anyone else. Future work could involve asking performers about their intentions more directly, as it would provide insights into whether musicians are conscious of their movements and timing at different types of cadences and other interesting tonal events.

In conclusion, our results demonstrate that highly skilled violinists perform the hierarchical structure of tonal music through their use of rubato, particularly ritardando, and nontechnical motion. Our work offers new insights into the role of embodied cognition in expressive performance, extending previous research in this field through our novel analysis techniques and the examination of the salience of various cadences in an entire piece of music.

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We have no known conflict of interest to disclose.

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Appendix

We asked participants to complete a practice log prior to their participation in the experiment. A partial template for this log is shown in Table A1. After their performances, participants were asked to complete a questionnaire evaluating their performance and the prescribed piece. The questions are shown in Table A2.

TABLE A1. *Template for the Practice Log Provided to Violinists Before the Experiment*

Day number before experiment	Date (YYYY-MM-DD)	Time practiced (minutes)	Comments
1			
2			
3			

Note. Only the first three days of the template are shown; the original form allowed violinists to fill in up to 21 days' worth of practice.

TABLE A2. *Questions Asked in the Post-Performance Questionnaire*

What did you like about the piece? Please explain why you liked these aspects.
What didn't you like about the piece? Please explain why you didn't like these aspects.
Which parts were easiest to play? Please explain why they were easy to play.
Which parts were most difficult to play? Please explain why they were difficult to play.
Please describe a couple of moments in the music that are most important in your interpretation. If there are more than a couple, please describe all of them, as long as there is at least one moment that you describe. Mark their locations on the provided score.
Please describe your strategy in practicing this piece. Did you have any goals or milestones in the practice process that you wished to reach at a particular stage?
How did you feel about your performances during the experiment itself? Please evaluate each take.
Any other comments?