A longitudinal study of the development of expressive timing

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Abstract

Tempo arches have often been reported in polished music performances, but their development during the learning of a new piece has not been studied. We examined the development of expressive timing at three levels of musical structure (piece, section, phrase) as an experienced concert soloist (the second author) prepared the Prelude from J.S. Bach's Suite No. 6 for solo cello for public performance. We used mixed effect models to assess the development of expressive timing and the effects of the performance cues (PCs) that the cellist used as mental landmarks to guide her performance. Tempo arches appeared early in practice at all three levels of musical structure and changed over time in complex ways, first becoming more pronounced and more asymmetrical and then shrinking somewhat in later performances. Arches were also more pronounced in phrases that contained PCs, suggesting that PCs reminded the cellist where to "breathe" between phrases. The early development of tempo arches suggests that they were an automatic product of basic cognitive or motor processes. The complex trajectory of their later development appeared to be the result, at least in part, of a deliberate communicative strategy intended to draw listeners' attention to some musical boundaries more than others.

Keywords: music performance; musical expression; musical interpretation; performance memory; music practice

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Performers in the Western art music tradition often use small variations in tempo to bring the music to life and delineate the nested levels of musical structure, creating tempo arches by slowing down at the ends of phrases and sections and speeding up in between (Bhatara, Tirovolas, Duan, Levy, & Levitin, 2011; Clarke,1988, 1989; Friberg, Bresin, & Sundberg, 2006; Gabrielsson, 2003; Palmer, 1997, Repp 1995). Although tempo arches have been reported for a wide variety of pieces, styles, instruments, and performers (Dodson, 2011; Repp, 1990, 1997a,b; Shaffer, 1981; Todd, 1985), there have been no studies of how they develop as a musician learns a new piece and prepares it for performance. Are tempo arches present from the start or do they develop gradually over time as the piece is learned?

Tempo arches might be present from the start. Expressive variation in timing occurs even when musicians try to play metronomically, albeit in diminished form, suggesting that it is a product of simple, automatic processes that are only partly under conscious control (Bengtsson & Gabrielsson, 1983; Gabrielsson, 1974; Palmer, 1989; Seashore, 1938, pp. 244-248). Many activities, from speech to locomotion, exhibit temporal groupings and final-phrase lengthening similar to that observed in music (Friberg & Sundberg, 1999; Palmer, 2005; Palmer & Pfordresher, 2003; Van Vugt, Jabusch, & Altenmüller, 2012). Thus, tempo arches may be an "unconscious symptom of underlying cognitive [or motor] processes" (Clarke, 2005, p. 160). If so, then they may appear early in learning, as soon as a musician is able to play through a new piece fluently and without interruption.

On the other hand, we might expect expressive timing to develop gradually over time because it seems carefully and deliberately calibrated to reflect the performer's artistic image of the music (Neuhaus, 1973, p. 17). Nuances of expressive timing are highly valued as a reflection of musicianship (Bisesi & Windsor, 2016; Cook, 2013, pp. 182-209; Fabian, 2015, pp. 42-48; Sung & Fabian, 2011; Timmers, 2007; Widmer & Goebl, 2004). They appear to be the product of a prolonged interrogation of the score to explore aesthetic possibilities and technical constraints (Chaffin & Imreh, 2002; Chaffin, Lisboa, Logan, & Begosh, 2010; Cook, 2013, pp. 37-41; Lisboa, Chaffin & Logan, 2011; Rink, 2002). If expressive timing is the product of extended, deliberate decision making, then tempo arches may evolve gradually during practice, perhaps growing taller and changing shape over time, as the performer's artistic image of the piece comes more clearly into focus.

A likely possibility is that expressive timing is shaped by both automatic, general, processes and deliberate decision making (Christensen, Sutton & McIllwain, 2016; Evans & Stanovich, 2013; Honing, 2005). Some musical choices are made more automatically and intuitively while others are more conscious and deliberate, with the proportion of deliberate decisions increasing with musical experience (Bangert, Schubert & Fabian, 2015). One case study of an experienced cello soloist found that decisions about tempo were deliberate more often than they were intuitive (Bangert, Fabian, Schubert & Yeadon, 2014). This suggests that tempo arches may be present as soon as the performer is able to play fluently through a new piece and continue to evolve over time as the performer's interpretation of the music evolves.

To see how expressive timing develops, we measured bar-to-bar tempi as a cello soloist (the second author) learned the Prelude of J. S. Bach's Cello Suite No. 6 over a period of 22 months. We had recorded the preparation of the Prelude as part of an earlier longitudinal study of expert practice (Chaffin et al., 2010). We have previously reported the presence of arches for both tempo and stability of tempo (across performances) for twelve polished performances at the end of the learning process, after preparation for public performance was completed (Demos, Lisboa & Chaffin, 2016). Here we examine every complete performance from memory (N = 28), tracking the development of expressive timing across the entire learning process. In the present study, we also examined three levels of musical structure (i.e., piece, sections, and phrases), in contrast to the single level examined in the earlier study (phrases). For evidence that tempo arches were shaped by deliberate decision making, i.e., by the performer's interpretation of the music, we examined their relationship to the cellist's thoughts about the music as she played, i.e., her performance cues.

Performance cues

Musical structure provides an abstract, bird's-eye view in which the entire musical piece is unfolded to view, displaying the relationship between its various segments. During performance, however, music is created sequentially, unfolding like a path, revealing more of itself with each step along the way (Cook, 2013, pp. 45-49). Just as walkers need a map to know where they are on their route, performers need a mental map containing landmarks that they can recognize along the way to keep track of their progress through the piece (Chaffin & Imreh, 2002; Williamon & Valentine, 2002). We refer to these musical landmarks as "performance cues" (PCs).

PCs are a metacognitive strategy for increasing the reliability of performance (Chaffin & Imreh, 2002). They are the features of the music that a performer attends to while playing. Repeatedly attending to features of the music during practice ensures that they come to mind automatically during performance, providing memory retrieval cues that remind the performer what to do and make recovery possible if something goes wrong on stage (Chaffin, 2011; Chaffin & Logan, 2006; Ginsborg & Chaffin, 2011; Chaffin et al., 2010). From the musician's perspective, however, the main function of PCs is to guide performance, ensuring that it unfolds in accordance with the artist's image of how the music should sound (Chaffin, Imreh, Lemieux, & Chen, 2003; Neuhaus, 1973, p. 17). If PCs guide performance, then they may affect expressive timing.

Evidence that PCs affect expressive timing is limited to a single study of a pianist learning Claude Debussy's Clair de Lune (Chaffin, 2007). Bar-to-bar tempo increased from early to later practice performances, and this increase was smaller in bars following PCs and at ends of sections than in other bars. PCs can be grouped into three main types, depending on which aspect of the music they refer to. Expressive PCs point to changes in musical feeling or expression (e.g., "calm"), Interpretive PCs to musical gestures (e.g., "crescendo"), Basic PCs to important details of technique (e.g., "hand position"). The effect on tempo in the Debussy study was for Expressive PCs. In another study of the same pianist learning the Presto of the Italian Concerto by J.S. Bach there were no effects of Expressive or Interpretive PCs, but there was a small decrease in tempo at Basic PCs, too small to be detectable by ear, that the investigators attributed to unwanted side effects of strategic monitoring (Chaffin, Lemieux, & Chen, 2007).

We examined how the effects of PCs developed over time, as the cellist learned the Prelude, tracking the development of phrase arches and PCs through 21 practice and 7 public performances. We looked for effects of Expressive and Interpretive PCs which we combined because exploratory analyses showed that their effects were similar. We refer to them collectively as "PCs". We omitted Basic PCs because they reflect technical issues, which may affect timing at a more micro level, not well captured by our measurement; exploratory analyses confirmed their effect was small. We compared phrases with and without PCs because approximately half of the 44 phrases into which the Prelude is divided by the musical structure began with a PC, and half did not. If PCs guide expression and interpretation, then phrases with PCs should show larger expressive timing effects than phrases without. This would suggest that expressive timing is deliberate and intentional, at least in part, rather than entirely automatic, since PCs are a deliberate metacognitive strategy.

Method

Music and Musician

The Prelude from J.S. Bach's Suite No. 6 for solo cello is a lyrical, free-form piece that displays the mellow sound qualities of the instrument. For contemporary cellists, the Prelude is a virtuoso piece because it was written for an instrument with five strings rather than the four strings of the modern cello (Winold, 2007, p. 32). The Prelude is notated in 104 bars in 12/8 time and takes about five minutes to perform (see Chaffin et al., 2010 for the score). For analysis, we divided the bars into 208 half-bars.

The cellist, Tânia Lisboa, was trained as a concert pianist and cellist in her native Brazil before continuing her study of the cello in England and France. She performs regularly as a soloist and, during the study, maintained a normal schedule of professional engagements. Prior to the study, she had performed Bach's Suites N$^{o.}$ 1-5 for solo cello but had never learned or performed Suite No. 6. She chose this piece for the study as it is the most complex of Bach's cello suites and she wanted to add it to her repertoire.

Performances

We examined every recorded performance, except as noted below, starting with the first complete performance from memory (without the score), for a total of 28. The performances were recorded by the cellist as part of a longitudinal study of expert practice during which she recorded most of her practice while preparing for public performance (Chaffin et al., 2010). All performances were fluent, without obvious hesitations or errors. Data for the 2nd public performance could not be used due to a recording error. An additional 12 performances in the laboratory in which the cellist played with different expressive styles and different bows were not included in the study.

The performances are listed in a table in the Appendix, which indicates whether the performance occurred in practice or in public and, for those that occurred in practice, the practice session in which it occurred, the cumulative number of weeks and hours spent in practice at the end of that session, and stage of development, based on the earlier description of the cellist's practice (Chaffin et al., 2010). The stages were based, in part, on breaks between periods of practice during which the cellist did not work on the piece and traveled to the USA for the later public performances. The first practice performance of the Prelude occurred after 11 weeks and 9 hours of practice and the last performance was 18 months later, after 33½ hours of practice, the last of 8 public performances.

Reports

As part of the earlier longitudinal study, the cellist marked the location of boundaries in the musical structure and PCs on copies of the score, indicating which level of structure or aspect of the music each referred to (see Chaffin et al., 2010, Figure 2 for an example). The report of musical structure was made after the 9th performance. The PC reports were made the day after the 8th public performance. For musical structure, she marked section and sub-section boundaries (*N* = 11 and 44 respectively). We refer to sub-sections as "phrases". We coded serial position with respect to three levels of musical structure by numbering half-bars from the start of the piece (top level), start of each section (middle level), and start of each phrase (bottom level).

For PCs, the cellist marked the features of the music that she had attended to during performance, indicating the type of musical feature involved. Of the seven types of feature that she identified, we examined two, expressive and interpretive. Expressive PCs were mostly (*N* = 8/10) located at the main structural boundaries of the piece where a harmonic change to a new key resulted in a change in the musical feeling. Her labels for these transitions often referred to both harmonic and expressive change, e.g., "D major, flowing", "calm, modulation, singing, melodic", "dominant, climax". Interpretive PCs were mostly located at starts of phrases (*N* = 11/17) where a change in the melody was accompanied by a change in dynamics, tempo, or sound quality, and were labeled with terms like "going down, softer", "end & beginning of phrase", and "ornament". We refer to both types collectively as "PCs".[i] One Expressive PC at the start of the piece was omitted from the analyses in order not to bias the results in favor of finding PC effects by including the opening bar.

Comments

During practice the cellist talked to the camera periodically about what she was doing, making 6780 comments that we transcribed and classified by topic as part of the earlier study (Chaffin et al., 2010; Lisboa et al., 2011). For the present study, we examined comments about expression (*N = 26*) and tempo (*N = 23*). The cellist also commented on her progress in the log in which she recorded each practice session. We report comments about the cellist's expressive intentions, two from the log and five from practice sessions.

Measurement of Tempo

We measured tempo for each bar of each performance using SoundForge, a commercial sound wave processing program, to measure inter-bar-intervals (IBI, in seconds) from the start of the first note sounded in each bar to the start of the first note of the next. Then, we converted IBIs to tempo measured in beats per minute [tempo = (1/IBI in seconds) × # beats per bar × 60s/min]. We removed the last two bars of each performance from all analyses as those bars may behave differently for a variety of reasons and removing them was conservative with respect to finding expressive timing effects.

Analysis

We used mixed effect models to examine the development of the effects of musical structure and PCs on tempo. We added predictors in stages, using a forward modelling procedure (Singer & Willett, 2003), with the LME4 package in R (Bates, Maechler, Bolker, & Walker, 2015). Model 0 contained no fixed effects (the null model). Model 1 examined the effects of time (serial order of performances) and three levels of musical structure (piece, sections, phrases). Model 2 added the interactions of each level of structure with time. Model 3 added PCs, and Model 4 their interaction with phrases. Model 5 added the three-way interaction of PCs, phrases, and time.

Time and the three levels of structure were entered into the models as proportions (0-1) expressing serial position in a sequence, as follows. Time was represented by serially ordering performances from 1st to 28th and expressing each serial position as a proportion of the total number of performances. The levels of musical structure were represented in similar fashion by proportions reflecting the serial order of half-bars within the piece (top level), within sections (middle level), and within phrases (bottom level). Each serial order predictor was tested for linear and quadratic effects using orthogonal polynomials[ii] (Mirman, 2014). The only predictor not represented by serial order was PCs, which we dummy-coded as present or absent from a phrase by coding each bar in the phrase as “1” for phrases containing PCs, and “0” for phrases without PCs.[iii]

We included the slopes for piece, sections, and phrases (linear and quadratic effects) as random effects relative to their structural level and we nested sections within the piece, and phrases within sections. This controlled for differences between different passages, making it easier to detect fixed effects. We tested whether the addition of predictors significantly improved the model fit with deviance tests (Singer & Willett, 2003). The significance of individual predictors was tested using *t*-values assessed as if they were *Z*-values[iv].

Results

Figure 1 shows the bar-to-bar tempi of each of the performances as a function of serial position in the piece. For clarity, the performances are shown in five panels, corresponding to the successive stages listed in the Appendix. The mean tempo increased over time from around 60 bpm in the early performances (top panel) to around 80 bpm in the final performances (bottom panel). Each performance shows the irregular, arch-shaped fluctuations characteristic of expressive timing. The tempo arches became more pronounced and more consistent over time. All performances were fluent, without obvious hesitations. Thus, the successive performances reflect the development of expressive timing, not learning to play the notes.

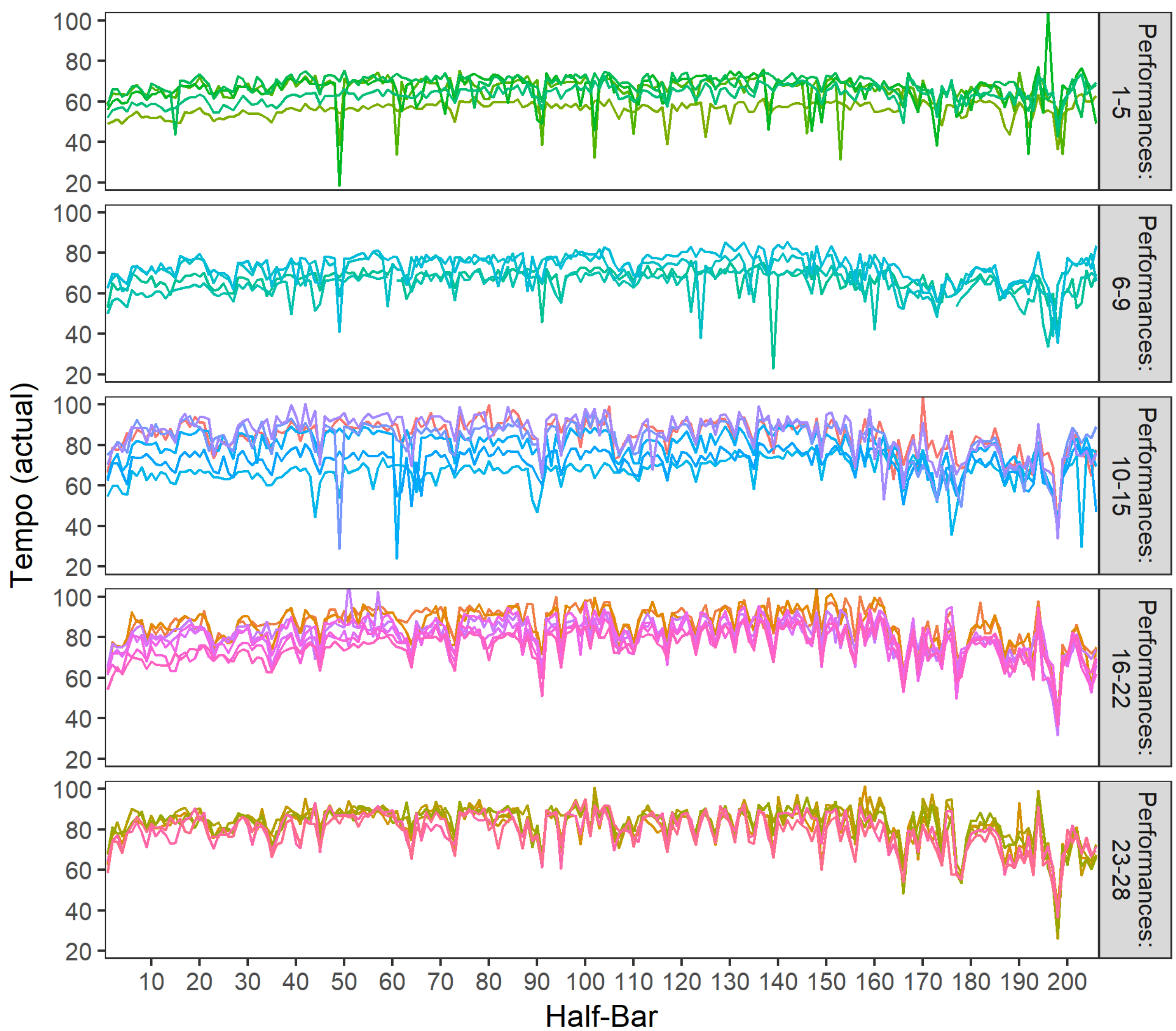

Figure 1. Bar-to-bar tempi for 28 performances of the Prelude in five temporal groupings.

The cellist's comments suggest that the increase in mean tempo and development of tempo arches evident in Figure 1 were the result of deliberate choices. After the 3rd practice performance she was, "ready to move on—I know the notes, bowing, and fingering… I need to think about phrasing [and] harmonies [to] bring them out" (Session 19). Before the 6th performance, "It's starting to feel… [like] a real performance" (Session 27). By the 11th performance, "[I am thinking about] communicating and trying to make the musical ideas clear" (Session 36). By the 13th performance, as she prepared to play in public for the first time, "[It's] been too long practicing too slowly" (Session 38). At the start of the first practice session after the initial public performances, "Although I think I played more expressively… in the concert, …I didn't feel I was breathing enough …. It just went from beginning to end, not stopping anywhere. So, I'll try refining those places" (Session 54). At the start of the next practice session, "[I will] work slowly, thinking mainly [about] breathing with every single phrase, making it very clear that it is a phrase" (Session 55). By the 21st performance, between the early and late public performances, "I'm going to… practice… very slowly. . . for technique and security" (Session 58).

The mixed models provide a more detailed picture of the development of tempo arches and mean tempo that supports the impression that both were products of deliberate choice. Table 1 summarizes the fit of each model to the tempo data. Each model fit the data significantly better than the preceding model, indicating that it accounted for additional variance. The predictors added in each model were: the main effects of time and musical structure (Model 1), the interaction between time and structure (Model 2), the main effect of PCs (Model 3), the interaction of PCs and tempo arches within phrases (Model 4), and the three way-interaction of time with tempo arches in phrases with and without PCs (Model 5).

Table 1. *Summary of comparisons between mixed effect models asking whether the additional predictors improved model fit over the previous model.*

Model Comparision	***Change in DF***	***Deviance***	χ^2	***p***
Model 1 vs Model 0 (Null) Time+Structure	+8	37617	764.036	<.0001
Model 2 vs Model 1 Time+Structure+Time*Structure	+12	37537	79.064	<.0001
Model 3 vs Model 2 Time+Structure+Time*Structure+PC	+1	37523	14.97	<.0002
Model 4 vs Model 3	+2	37453	69.706	<.0001

Time+Structure+Time*Structure+PC+PC*Phrase				
Model 5 vs Model 4	+6	37436	16.494	.0113
Time+Structure+Time*Structure+PC+PC*Phrase+PC*Phrase*Time				

Table 2 summarizes the effects of the individual predictors in each model. Predictors involving serial position were tested separately for linear and quadratic effects. Negative quadratic effects indicate arches, while linear effects indicate whether the feet of the arch are uneven. A non-significant linear effect means that the arch is even, rather than tilted, indicating that tempo was the same at the beginning and end of the arch. Significant linear effects indicate that the arch is tilted, with the right foot of the arch higher (positive), or lower (negative) than the left foot. For the lower levels of musical structure (sections and phrases), absence of tilting indicates that the tempo flowed evenly across boundaries, while tilting indicates that transitions across boundaries were marked by discontinuities in tempo. Positive effects indicate the "breathing with every single phrase" referred to in the comment quoted above. Since each serial position predictor is represented by two effects (linear and quadratic), interactions with time are represented by four effects. Significant interactions of effects of musical structure with the linear effect of time indicate that arching and/or tilting increased over time, for quadratic and linear effects of structure respectively; interactions of structure with quadratic effects of time indicate that arching, and/or tilting, first increased and then decreased. We limit our description to Model 2 (time and structure) and Model 5 (time, structure, and PCs). The other models show the construction of these models by systematic addition of predictors. Figures 2-5 show the model fitted data.

Table 2. *Summary of mixed effects models showing estimates and standard errors (in parentheses) for PCs and for orthogonal linear and quadratic effects of time (Time and Time^2 respectively) and serial position (SP and SP^2 respectively) at three levels of musical structure (Piece, Section, and Phrase).*

Fixed Effects Estimate (SE)	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
(Intercept)	75.24***	75.26***	75.60***	75.66***	75.66***
	(0.37)	(0.36)	(0.38)	(0.38)	(0.38)
Time	443.19***	448.39***	447.88***	447.71***	463.54***
	(24.14)	(27.67)	(28.13)	(28.15)	(28.93)
Time^2	-221.12***	-237.99***	-238.37***	-238.45***	-231.21***
	(24.11)	(27.65)	(28.10)	(28.12)	(28.90)
PieceSP	-57.36*	-60.68**	-57.21**	-60.44**	-61.08**
	(26.67)	(21.79)	(21.77)	(21.80)	(21.73)

PieceSP^2	-293.59***	-294.68***	-293.45***	-299.33***	-299.52***
	(18.90)	(18.32)	(18.31)	(18.27)	(18.34)
SectionSP	11.01	12.05	8.67	5.42	5.52
	(11.60)	(11.39)	(11.40)	(11.28)	(11.28)
SectionSP^2	-88.80***	-89.66***	-88.76***	-84.86***	-84.63***
	(9.62)	(9.29)	(9.18)	(9.30)	(9.30)
PhraseSP	41.65***	41.58***	41.39***	28.45***	28.47***
	(6.02)	(6.00)	(6.00)	(8.14)	(8.16)
PhraseSP^2	-103.19***	-103.13***	-103.66***	-59.84***	-59.73***
	(5.98)	(5.96)	(5.96)	(8.03)	(8.01)
Time:PieceSP		-4625.88**	-4566.48**	-4565.62**	-4667.41**
		(1666.53)	(1664.82)	(1666.65)	(1661.79)
Time^2:PieceSP		611.17	577.64	597.79	580.77
		(1659.52)	(1657.82)	(1659.65)	(1654.73)
Time:PieceSP^2		-4183.83**	-4112.09**	-4097.81**	-4141.33**
		(1401.58)	(1400.36)	(1395.98)	(1403.48)
Time^2:PieceSP^2		3492.19*	3562.95*	3600.15**	3629.65**
		(1395.04)	(1393.84)	(1389.47)	(1396.91)
Time:SectionSP		-666.03	-672.20	-659.09	-856.05
		(868.27)	(866.75)	(856.85)	(860.35)
Time^2:SectionSP		-2.11	-0.26	-9.69	-56.63
		(866.90)	(865.39)	(855.49)	(858.99)
Time:SectionSP^2		-1432.17*	-1429.06*	-1419.82*	-1304.81.
		(707.68)	(699.10)	(706.47)	(708.76)
Time^2:SectionSP^2		1886.35**	1899.32**	1880.18**	1886.13**
		(706.57)	(698.01)	(705.37)	(707.61)
Time:PhraseSP		976.55*	979.42*	976.89*	876.63
		(457.22)	(456.60)	(454.47)	(621.04)
Time^2:PhraseSP		-800.24.	-799.83.	-798.88.	-463.91
		(456.38)	(455.76)	(453.64)	(619.65)
Time:PhraseSP^2		-1993.18***	-1992.83***	-1989.76***	-761.55
		(454.14)	(453.46)	(450.12)	(609.32)
Time^2:PhraseSP^2		912.33*	910.49*	907.50*	1277.84*
		(453.30)	(452.63)	(449.30)	(608.32)
PC			-0.76***	-0.78***	-0.79***
			(0.20)	(0.19)	(0.19)
PhraseSP:PC				27.86*	27.82*
				(11.86)	(11.88)
PhraseSP^2:PC				-93.80***	-94.08***
				(11.64)	(11.61)
Time:PC					-32.74*
					(14.76)
Time^2:PC					-16.40
					(14.73)
Time:PhraseSP:PC					204.48
					(905.34)
Time^{2}PhraseSP:PC					-724.02
					(903.63)
Time:PhraseSP^2:PC					-2688.47**

					(884.04)
Time^2:PhraseSP^2:PC					-823.87
					(882.50)
Random Effects (Variance)					
Piece | PeiceSP	6661.639	371.843	150.303	157.633	0.038
Piece | PeiceSP^2	451.156	4.216	0.001	0.012	0.000
Piece: Section | (Intercept)	37.697	35.493	36.821	36.920	36.918
Piece: Section | SectionSP	23755.988	22501.024	22344.490	21660.432	21699.226
Piece: Section | SectionSP^2	15040.639	13265.459	12699.179	13355.485	13387.053
Piece: Section: Phrase| PhraseSP	0.000	8.831	0.010	251.125	664.056
Piece: Section: Phrase| PhraseSP^2	0.000	0.042	0.000	0.000	0.000
Residual	32.503	32.333	32.258	31.756	31.567

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Figure 2 shows how the mean tempo across the entire performance changed over time in an arch-shaped function that increased from about 60 bpm in the first performance to more than 80 bpm in the 19th performance and then decreased again to less than 80 bpm in the last performance. The arch is positively tilted (higher on the right), indicating that the last performance was faster than the first. The decrease in the later performances suggests that the decrease in mean tempo in the later performances was a deliberate choice, perhaps for the same reason that the cellist gave for practicing slowly, “for technique and security”. In Table 2, the tilt is reflected in the positive linear effect of Time in all models ($Time_{Model\ 5} = 463.54$). The arch is reflected in the negative quadratic effect of Time ($Time^2_{Model\ 5} = -231.21$).

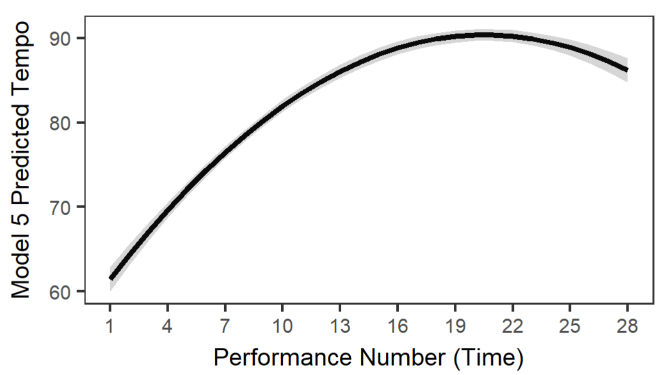

Figure 2. Mean tempo of performances over time, generated by Model 5, with shading indicating the standard error.

Figure 3 shows how tempo was affected by the three levels of musical structure (piece, sections and phrases) and how these effects changed over time. Successive panels (left to right) show every third performance. There were tempo arches at all three levels of musical structure:

the whole piece (top panel), sections (middle panel), and phrases (bottom panel). The change in mean tempo seen in Figure 2 is reflected in the changing level of the curves in successive panels.

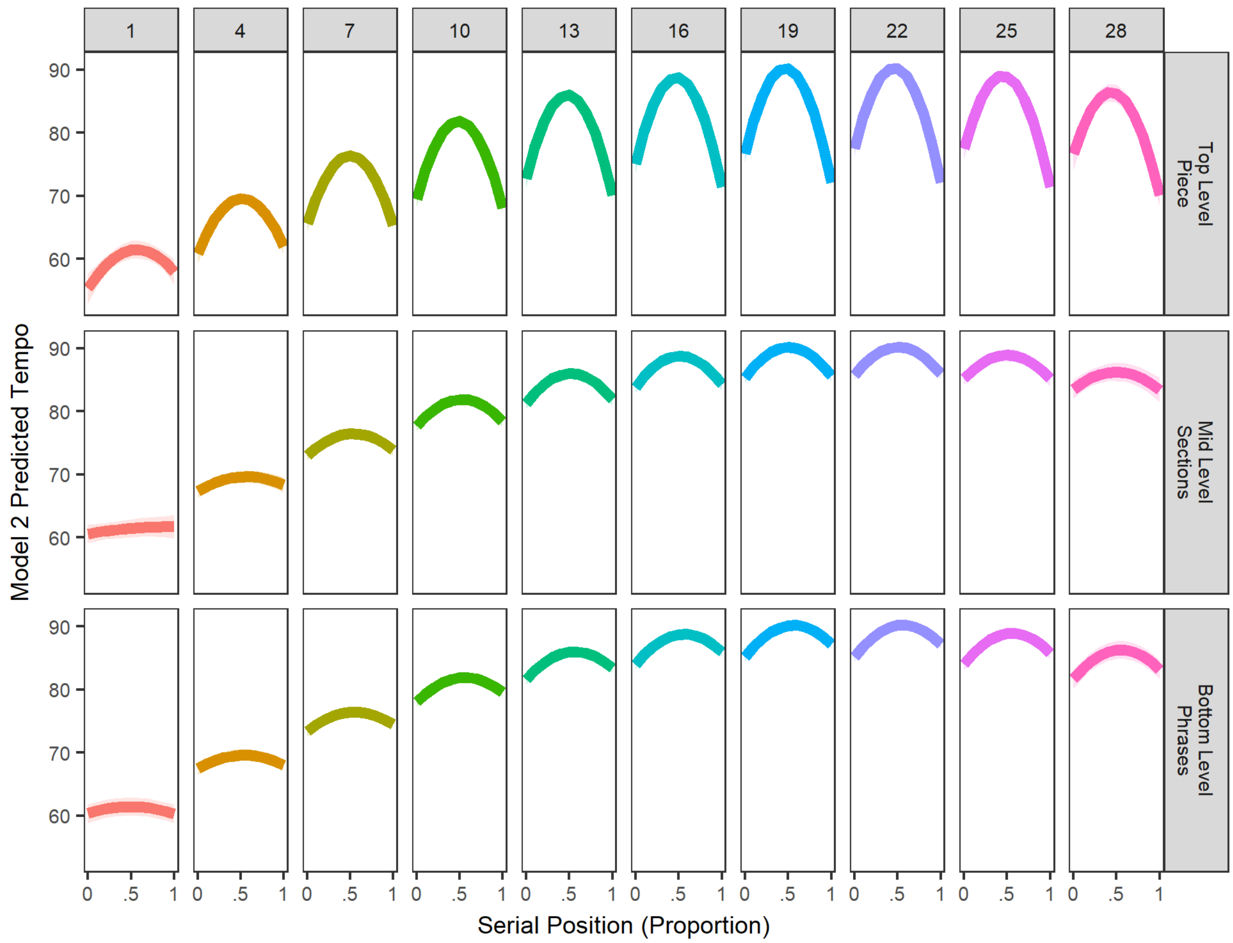

Figure 3. Tempo as a function of serial position of bars in the piece (top row), in a section (middle row), and in a sub-section (bottom row), for every 3rd performance (panels left to right), generated by Model 2.

The shapes of the arches in Figure 3 change over time in nonlinear ways that are different at each level of structure. At all three levels, arches become taller over time, reaching their zenith between the 16th and 19th performances, then shrink somewhat in later performances. As with the mean tempo, the decrease in height in later performances suggests that the height of the arch was the product of deliberate choice. The cellist did not just make the tallest arch possible but tried out different amounts of arching to discover how much she wanted. The maximum height of the phrase arch in the 19th performance coincided with her comment about needing to "breathe" more (Session 54; see Appendix). Thus, she expressed concern with the tilt of the phrase arch at the same time that she began adjusting its height.

The tilt of the arches changes differently at each level, becoming steadily more negative over time at the top level, staying the same at the middle level, and becoming more positive at the bottom level. In the top row, the positive tilt in the first performance indicates that tempo was slower at the beginning than at the end of the piece, while the increasingly negative tilt in later performances indicates the opposite, the development of final slowing. In the middle row, the arches are even, indicating that playing flowed evenly across the transitions from one section to the next. In contrast, the increasingly positive tilt of the arches in the bottom row indicates that transitions between phrases were increasingly marked by discontinuities in tempo, indicating momentary slowing at starts of phrases. We will refer to this effect as “breathing” (with quotes to indicate that we are referring to timing, not literally to breathing), adopting the term used by the cellist in her comment about “breathing with every … phrase”. Again, the comment shows that the tilting of the phrase arch was deliberate.

The arches evident in Figure 3 are reflected in linear and quadratic effects of musical structure in Table 2. At the top level, the negative tilt of the arches in the top row of Figure 3, indicative of final slowing, is reflected in the negative linear effect of serial position in the piece ($\text{PieceSP}_{\text{Model 2}} = -60.68$). The arch is reflected in the negative quadratic effect ($\text{PieceSP}^2_{\text{Model 2}} = -294.68$). The increase in final slowing, indicated by the increasingly negative tilt of the arch over time, is reflected in the interaction of the linear effects of Time and Piece ($\text{Time x PieceSP}_{\text{Model 2}} = -4625.88$). The increasing height of the arch is reflected in the interaction of the linear effect of Time with the quadratic effect of Piece ($\text{Time x PieceSP}^2_{\text{Model 2}} = -4183.83$). The changing direction of the growth of the arch, first increasing then decreasing in height, is indicated by the interaction of the quadratic effects of Time and Piece ($\text{Time}^2 \text{ x PieceSP}^2_{\text{Model 2}} = 3492.19$). The non-significant interaction of the quadratic effect of Time with the linear effect of Piece indicates that the small decrease in the tilt of the arch in the final performances was not significant ($\text{Time}^2 \text{ x PieceSP}_{\text{Model 2}} = 611.17$). Thus, final slowing at the end of the piece was maintained in the final performances, rather than decreasing along with the height of the arch. The presence of the same significant effects in all the later models indicates that final slowing at the end of the piece was not due to PCs.

The arch at the middle level of musical structure, shown in the middle row of Figure 3, is reflected in Table 2 in the negative quadratic effect of serial position in a section ($SectionSP^2_{Model\ 2}$ = -89.66). The arch was level, not tilted, and this did not change over time, as reflected in the non-significant linear effect of Section and its non-significant interaction with Time (SectionSP Model 2 = 12.05; Time x $SectionSP_{Model\ 2}$ = -666.03). However, the arch became taller over time, as indicated by the significant interaction of the linear effect of Time with the quadratic effect of Section (Time x $SectionSP^2_{Model\ 2}$ = -1432.17). Section arches reach their zenith in the 16th performance and then their height decreases again, starting at around the 22nd performance. This shrinkage is reflected in the interaction of the quadratic effects of Time and Section ($Time^2$ x $SectionSP^2_{Model\ 2}$ = 1886.35).

At the bottom level of musical structure, the positive tilt of the arches in the bottom row of Figure 3, indicating "breaths" at starts of phrases, is reflected in the positive linear effect of serial position in a phrase ($PhraseSP_{Model\ 2}$ = 41.58). The arch is reflected in the negative quadratic effect ($PhraseSP^2_{Model\ 2}$ = -103.13). The increasingly positive tilt of the arch over time, indicating larger "breaths", is reflected in the interaction of the linear effects of Time and Phrase (Time x $PhraseSP_{Model\ 2}$ = 976.55). The increasing height of the arch is reflected in the interaction of the linear effect of Time with the quadratic effect of Phrase (Time x $PhraseSP^2_{Model\ 2}$ = -1993.18).

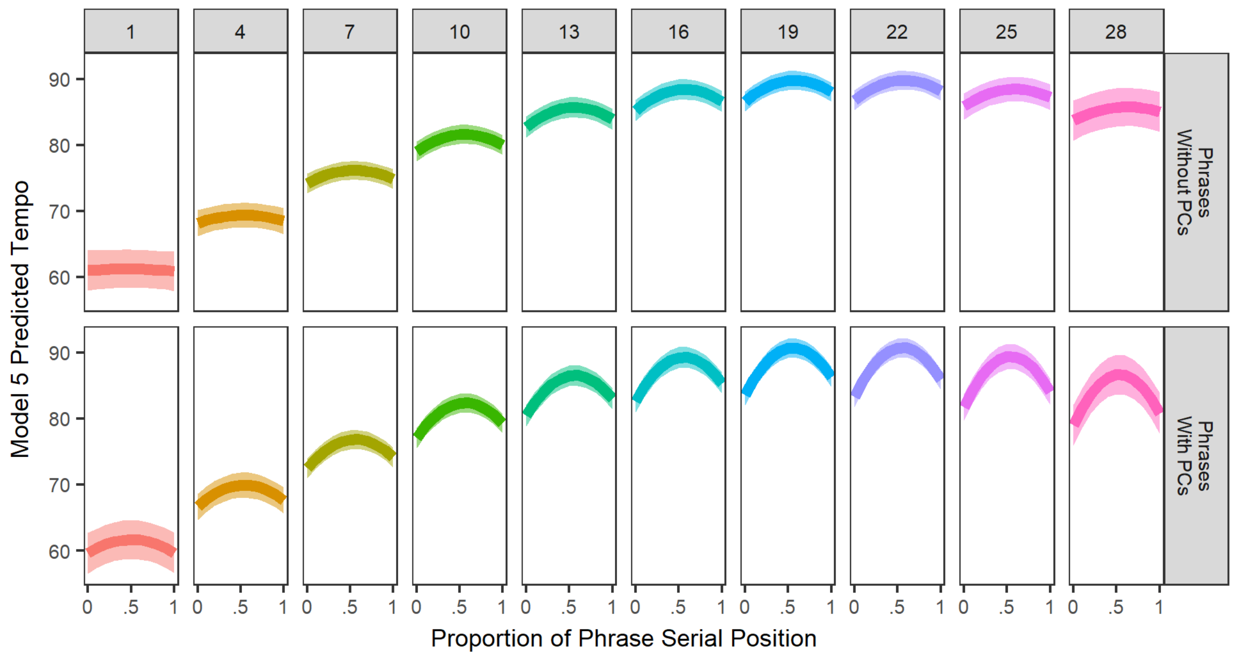

Figure 4. Tempo as a function of serial position of half-bars in phrases with PCs (bottom row) and without PCs (bottom row) for every 3rd performance (panels left to right), generated by Model 5, with shading indicating the standard error.

For phrases, we also asked how the development of the arch was affected by PCs. Figure 4 shows the effects of serial position in a phrase separately for phrases with and without PCs, based on Model 5. The presence of a PC in a phrase increased the height of the arch and gave it a negative tilt compared to phrases without PCs, suggesting a relationship between the cellist's phrasing and her thoughts while playing.

In phrases containing PCs, tempi were slower than in phrases without PCs ($PC_{Model\ 5} = -0.79$), and the difference increased over time ($Time \times PC_{Model\ 5} = -32.74$). Arches were taller in phrases with PCs ($PhraseSP^2{:}PC_{Model\ 5} = -94.08$), and this difference from phrases without PCs increased over time ($Time \times PhraseSP^2{:}PC_{Model\ 5} = -2688.47$), and did not shrink again in the later performances, as indicated by the non-significant quadratic three-way interaction ($Time^2 \times PhraseSP^2{:}PC_{Model\ 5} = -823.87$). Arches with PCs were also more tilted, starting slower than they ended, indicating larger "breaths" in phrases with PCs than in phrases without PCs ($PhraseSP{:}PC_{Model\ 5} = 27.82$). Although it appears in Figure 4 that the tilt in phrases with PCs increased over time, this difference from phrases without PCs was not significant ($Time^2 \times PhraseSP{:}PC_{Model\ 5} = -724.02$).

Discussion

Although the use of tempo arches by performers in the Western art music tradition has been extensively documented, our study provides the first description of their development over time during the learning of a new piece. Tempo arches were already present in the first performance at the top and bottom levels of musical structure, and soon afterward for the middle level. This suggests that they were a product of basic motor or cognitive processes, either the simple mechanics of starting and stopping (Friberg & Sundberg, 1999) or grouping processes necessary for perception, memory, or movement (Palmer & Pfordresher, 2003; Palmer, 2005; van Vugt et al., 2012). Subsequently, the arches followed nonlinear developmental trajectories, different at each level of musical structure, suggesting that they were also shaped by more complex cognitive processes.

It is tempting to see the orderly, elegant arches at three levels of musical structure as support for the view that the main job of the performer is to reveal musical structure to listeners, thereby interpreting the musical ideas of the composer (Cook, 2013, pp. 37-55). Revealing the musical structure was clearly one of the cellist's goals for the Prelude, since she wanted to emphasize her understanding and interpretation of the phrases and the harmonic and melodic lines. However, this does not mean that tempo arches are a universal prescription for every piece or every performer. She might approach another piece very differently; another cellist might approach the Prelude differently.

The effect of PCs on the height and tilt of the tempo arches is the clearest evidence to date that musicians' thoughts during performance shape the highly practiced movements of highly polished performance (Chaffin, 2007). This is consistent with the subjective impression of performers that their musical intentions during performance (including their PCs) affect their playing (Bangert et al., 2014, 2015; Chaffin & Imreh, 2002; Chaffin et al., 2007; Chaffin et al., 2010). Including PCs as predictors gave a more accurate picture of expressive timing than the musical structure alone. By providing information about the performer's interpretation of the musical structure, PCs supplemented the perspective of the music theorist to provide a more complete explanation of the relationship between timing and musical expression (Cook, 2013, pp. 43-55; Gabrielsson, 1999, p. 550; Palmer, 1996).

The shaping of the tempo arches for phrases appears to have been a product of careful deliberation (Bangert et al., 2014; Christensen et al., 2016; Evans & Stanovich, 2013). First, the arches were associated with PCs, i.e., with the cellist's thoughts during performance about her musical intentions for each phrase. Second, their shape evolved continuously over a long period of time during which the cellist prepared and polished the Prelude for public performance. During this time, the cellist expressed concern about projecting her understanding of the phrasing, announcing her intention to "[breath] with every single phrase, making it very clear that it is a phrase". She wanted to project her understanding of the phrasing, and "breathing" was a way of doing this. We infer that tempo arches were part of this effort and were, in this respect, "deliberate". Even if the initial tempo arches in the early practice performances were a product of basic, automatic processes, their subsequent development was the product of more deliberate, strategic decision making (Cook, 2013, pp.37-55; Rink, 2002).

The relationship between intentions and behaviour is often complex and the present case is no exception (Sato, 2009). The conclusion that tempo arches were a product of careful deliberation does not mean that the cellist was deliberately trying to create tempo arches. Rather, tempo arches were an unintended product of her effort to project her phrasing more clearly. What was deliberate was the effort to project phrasing. A cellist has many ways to project phrasing besides tempo, e.g., articulation, bowing, dynamics, note duration, rhythm, and tone color (Bangert et al., 2014, 2015). When the cellist thought of projecting her phrasing, she was thinking of the overall quality of her sound, not about tempo.

We measured tempo; other measures and methods of analysis might have revealed other relationships between the cellist's intentions and the musical sound (Spiro, Gold, & Rink, 2010). We found "breaths" and arches because they occurred consistently across phrases that started with a PC; i.e., every PC was associated with the same effects. We did not identify unique effects of individual PCs because our analysis was not designed to do so; detection of unique effects requires different methods (e.g., Chaffin et al., 2007). We controlled for differences between phrases, ignoring differences between them that make music interesting to listen to (Demos et al., 2016; Repp, 1992). Tempo arches provide a partial, idealized picture of one aspect of the detailed reality of the musical sound (Desain & Honing, 1993, 1994). They are simplified, mathematical abstractions, "real" in the sense of being based on objective measurement, but shaped by choice of measure (tempo), unit of measurement (half-bars) and mathematical function (polynomials) (Honing, 2001; 2005; Todd, 1985).

There are other questions that we do not answer. We leave for future study questions about how the contributions of automatic and deliberate processes are integrated (Christensen et al., 2016); whether obtaining reports after each performance might capture differences between repeated performances (Demos, Chaffin, & Logan, 2017); how expressive timing develops at levels of musical structure lower than the sub-sections referred to here as phrases; the effects of other properties of the music, such as technical difficulties; as well as the effect of musical expression on measures other than tempo.

In summary, the simplification provided by tempo arches revealed that expressive timing was present as soon as the cellist was able to play the piece fluently from beginning to end without the score, and that the size and shape of the arches evolved continuously as her playing became more polished and her interpretation of the music developed. The cellist's expressive and interpretative intentions were reflected in the PCs that she reported attending to during performance. The continuous development of the tempo arches throughout the 22 months of the study suggests that, while they may have originated in basic, general processes, in polished performance they reflected an ongoing process of musical interpretation based on complex problem solving and decision making.

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Appendix A

Table A1. *Performances of the Prelude showing the number of practice sessions and public performances, cumulative weeks since start of practice and cumulative hours of practice.*

Performance #	Practice session/ Public perf	Weeks since start	Cum. Practice (hrs)	Stage
1	Session 15	11	9.27	Smoothing out
2	Session 16	12	9.67	
3	Session 17	12	10.13	
4	Session 21	13	12.70	
5	Session 22	13	13.20	
6	Session 30	57	16.53	Listening
7	Session 31	57	17.07	
8	Session 32	58	17.25	
9	Session 32	58	17.25	
10	Session 36	73	20.05	Prepare performance
11	Session 36	73	20.05	
12	Session 37	74	20.33	
13	Session 38	74	21.08	
14	Session 45	77	22.08	
15	Public perf. 1	77	22.45	Early public performances
16	Session 52	88	25.07	
17	Public perf. 3	88	25.07	
18	Public perf. 4	89	25.48	
19	Session 54	90	26.18	
20	Session 55	90	26.40	
21	Session 58	91	29.08	
22	Session 59	91	29.42	
23	Session 61	92	31.92	Late public performances
24	Public perf. 5	92	32.02	
25	Session 63	92	32.18	
26	Public perf. 6	92	32.18	
27	Public perf. 7	92	33.55	
28	Public perf. 8	92	33.55	

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i We did not examine Expressive and Interpretive PCs separately because they were confounded with level in the musical structure.

ii Orthogonal polynomials allow for the higher-order polynomial (e.g., quadratic) to be interpreted independently from the lower-order polynomial (e.g., linear term). However, this makes the estimated slopes values difficult to interpret. To interpret them, we generated graphs from the models.

iii We coded for the presence or absence of PCs in phrases because exploratory analyses showed that this provided the clearest picture of the effects of both musical structure and PCs. This suggests that effects of PCs were not limited to the particular location where the PC was reported but extended across the entire phrase. The same may have been true for sections, but we were not able to examine this question because every section began with a PC.

iv The interpretation of the fixed-effect intercepts and slopes in this hierarchical growth curve analysis are the same as that of intercepts and slopes in a multiple regression. The significance of the lower order terms are tested against zero and the higher order terms (interactions) are tested to see whether they differ from the lower order terms. The directionality is assessed relative to the sign of the estimate.