Memory and expression: A longitudinal case study of performing Chopin's *Barcarolle, Op. 60*

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Abstract

Experienced musicians can perform reliably from memory because they prepare performance cues (PCs) that allow them to recover when performance is disrupted. We describe a longitudinal case study in which a pianist (the second author) learned and performed Chopin's *Barcarolle,* op. 60, over a 12-year period. The pianist provided PC reports for 28 performances, starting a month before her first public performance. Shortly after each performance, she marked the features of the music that guided her playing (PCs) on a clean copy of the score, distinguishing five types of PC: structural, Schenkerian (tonal elaborations), expressive, interpretive, and basic. Structural PCs predominated at first and were later replaced by expressive and Schenkerian PCs. PCs were more frequent at structural boundaries than at other locations. This boundary effect was larger under typical, compared to atypical performance conditions, and increased over time, suggesting that the main function of PCs was promoting expression rather than guarding against mistakes. Although the pianist's initial purpose in learning to use PCs was to have a safety net in case of memory failure, she was surprised to find that she enjoyed playing with PCs and believed they helped her to play more expressively.

How secure memorization promotes expression: A longitudinal case study of performing Chopin's *Barcarolle, Op. 60*

At some point, every musician who performs routinely without a score has a memory lapse. When it happened to the pianist in the present study (the second author), after decades of successful performances, those brief seconds on stage seemed like an eternity in which she felt crushed and worthless; then she regained her composure and went on. She took it as a warning. Simple repetition was no longer enough. She needed a better way to memorize, one that would allow her to recover when the fog suddenly came down and she was lost.

The pianist had relied on serial cuing, allowing the sounds and actions of each passage to elicit memory for what came next (Lindsey & Logan, 2021). Now, she wanted to supplement this with content addressable retrieval–to be able to think of anywhere in the music and start playing there (Ginsborg, 2022). This requires having a mental map of the piece and monitoring progress during performance, so you always know where you are. We refer to the musical landmarks in such a mental map as *performance cues (PCs;* Chaffin & Imreh, 2002*)*. PCs are thoughts during performance that act as retrieval cues, activating the associated musical ideas and sensory-motor sequences in long term memory. PCs are established by consistent attention to features of the music and their interpretation during practice, integrating them into the automatic sensory motor sequence of the performance (Christensen et al., 2016; Lisboa et al., 2018). When serial cuing fails and the fog comes down, the musician thinks of the next PC and carries on (Chaffin et al., 2021).

PC theory originated in a longitudinal case study in which pianist Gabriela Imreh recorded her practice as she learned the Presto from J. S. Bach's Italian Concerto in 57 sessions, over a 10-month period. Later, she marked the features of the music that she attended to during performance––her PCs––on copies of the score. *Expressive PCs* referred to feelings to be expressed (e.g., surprise, excitement), *interpretive PCs* to musical gestures that conveyed those feelings (e.g., staccato, forte), and *basic PCs* to critical details of technique that enabled the gestures (e.g., fingering, big leaps). Separately, she marked the location of structural boundaries and labeled the sections and subsections, A_1, A_2, B_1, B_2 etc. Two years later, she tested her memory by writing out the first page of the score from memory. PCs and musical structure affected starts, stops, and repetitions during practice, tempo and dynamics during performance, and accuracy of written recall, with the effects on performance and recall mostly due to expressive PCs (Chaffin et al., 2007; Chaffin & Imreh, 2002).

Later case studies found similar effects of PCs for other pieces and musicians (Chaffin, 2007; Chaffin et al., 2010; Chaffin et al., 2021; Chueke & Chaffin, 2016; Demos et al., 2014, 2016; Fonte, 2020; Ginsborg & Chaffin, 2011; Ginsborg et al., 2012; Noice et al., 2008). The effects of PCs in these studies are broadly consistent with experimental studies showing positive effects of verbalization and metacognition on memory for music performance (Concina, 2019; Lisboa et al., 2015; Timperman & Miksza, 2019), and with general theories of serial learning and expert memory (Ericsson & Kintsch, 1995; Logan, 2021), and with the positive effects of organization on memory (Tulving, 1962).

The motivation of the Presto study was the idea that "in the last weeks before the performance . . . [you] remap your thinking to emphasize the artistic inspirational elements" (Chaffin et al., 2002, p. 27), a process referred to as "re-chunking" (pp. 234-235). Despite the pervasive effects of PCs, direct evidence of re-chunking in the weeks before the first performance was missing (Chaffin et al., 2002, p. 251; Chaffin et al., 2006, pp. 205-211). Musicians did not focus exclusively on basic and structural PCs in early practice sessions and interpretative and expressive PC in the weeks before the performance (Chaffin et al., 2002, p. 27). Instead, re-chunking was inferred from the early effect of structure on practice and later effects of expressive PCs on written recall, timing, and dynamics (Chaffin et al., 2006; Chaffin & Imreh, 2002).

One goal of the current study was to examine re-chunking more directly. As in previous studies, the pianist recorded her practice as she learned and memorized a new piece, in this case, Chopin's Barcarolle, Op. 60 (Chaffin et al., 2013). Unlike most previous PC studies, in which the musician made a single PC report at the end of the study, the pianist made 28 PC reports over a 10-year period, starting a month before the first public performance.[1] We expected earlier reports to contain more PCs referring to musical structure and basic technique and later reports to contain more PCs for expression (Chaffin et al., 2006, 2010; Chaffin & Imreh, 2002). Before summarizing the data quantitatively, we describe examples from the reports to illustrate how they reflected the pianist's thoughts about different aspects of the music (*PC-types*), and evolved over time.

A second goal was to see how PCs respond to conditions during performance. Does the use of PCs increase when conditions are worse, or when they are better? On the one hand, since the pianist's motivation for using PCs was having a safety net in case of memory failure, she might rely on PCs more when the risk of memory failure is higher, that is, in earlier performances or under more difficult conditions. On the other hand, the main goal of any performance is to play expressively. If PCs promote musical expression, then the use of PCs may increase as mastery of the piece increases over time or when performance conditions are better, allowing the pianist to focus more on musical goals.

To vary performance conditions, we asked the pianist to play in a music laboratory and deliberately change her typical way of playing in some of the performances by minimizing use of PCs, varying amplitude of movement, or following along with a recording of an earlier performance. Serendipitously, there were unplanned distractions in several performances. So, rather than analyzing the effects of the laboratory manipulations, we compared performances under *typical* and *atypical* conditions, grouping together as atypical those performances in which there were unexpected distractions or in which the pianist altered her typical way of playing.

We expected more PCs at structural boundaries than at other locations because this is where most effects of PCs occurred in previous studies (Chaffin et al., 2021; Demos et al., 2016; Ginsborg et al., 2012; Lisboa et al., 2018). We refer to this as the *boundary effect.* We looked at whether the boundary effect changed over time and in response to conditions during performance. If the boundary effect was larger in earlier performances or under atypical conditions, it would suggest that the main role of PCs was as guardrails, keeping the performance on track. Alternatively, if the boundary effect was larger in later performances or under typical conditions, it would suggest that the main role of PCs was to promote musical expression.

We also examined the effect of performance conditions on the *overlap* between PCs in different reports to see how much the reports agreed with each other. If PCs are affected by performance conditions, then they should overlap more when conditions are more similar. In this case, there would be more overlap between two typical performances than between a typical and an atypical performance. Likewise, if there was more overlap between two typical performances than between two atypical performances, this would indicate that performance conditions were more similar for typical than for atypical performances.

Overlap provided another way to examine the effect of performance conditions by comparing the overlap between adjacent, *successive* performances and between *non-successive* performances (i.e., more distant in the temporal sequence of performances). There should be more overlap between successive than between non-successive performances because PCs evolve from one performance to the next. In this case, overlap should decrease with temporal distance across the whole temporal sequence of performances. Alternatively, there may be more overlap between successive performances because each performance is affected by the memory of the last one (Logan, 2021). In this case, there

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[1] Musicians made two PC reports in three studies (Ginsborg et al., 2012; Lisboa et al., 2013 & Fonte, 2020), and four PC reports of one passage in one study (Chueke & Chaffin, 2016).

would be more overlap between successive performances, but overlap would be unrelated to distance in the broader temporal sequence.

Method

Pianist and music

The pianist (second author) was trained in classical piano and music theory in Brazil and the USA. She is a Professor of Music at the Federal University of Rio Grande do Sul in Brazil where she performs regularly as a soloist and as a chamber musician. She has recorded five solo albums mostly focused on classical music of South American composers.

The Barcarolle Op. 60 is one of Chopin's last and greatest works, capturing the essence of his pianism, profound knowledge of counterpoint, and achieving new heights of sophistication and expressive power in his treatment of dissonance. Chopin chose the Barcarolle for his last recital in Paris in 1848, shortly before his death. Notated in 116 bars in 12:8 time, the Barcarolle takes approximately 8½ minutes to perform. The simple ABA song form (with short introduction and extended coda) is further elaborated by long transitional passages, as shown in Table 1 (Kopp, 2014; Rink, 1988; Schmalfeldt, 1990).

Table 1: *Barcarolle op. 60 Formal Structure and Harmonic Plan.*

Bars	Formal Division	Harmonic Structure
1.1 - 3.4	*Introduction*	V - (C#)
4.1 - 16.1	Theme A	I - (F#)
16.2 - 24.2	*Continuation* (b)	
24.3 - 35.1	Theme A´	
35.2 - 38.4	*Transition*	I - ♭III (F# to A)
39.1 – 50.1	Theme B	♭III - (A)
51.3 – 61.1	Theme B´	
61.2 – 70.4	Theme C	
71.0 – 78.1	*Transition*	V - (C#)
78.2 - 84.1	*Dolce sfogato*	
84.2 - 93.1	Theme A´´	I- (F#)
93.2 – 101.4	Theme C´	
102.1 – 111.1	Coda B´´	
111.1 - 116.4	Coda	

Reports

The pianist was asked to report the PCs she used during a performance by marking a clean copy of the score with vertical arrows or lines to indicate locations in the music that she thought about during performance. Most reports were done immediately after the performance.[2] The pianist used a different color for each PC-type, employing different colors and labels across reports, and provided a color key for each report. We standardized 10 labels into five PC-types: formal structure [*structure*], Schenkerian

[2] Reports 5,8, 24, and 27 were made the following day, and Report 28 was made three days later.

tonal elaborations [*Schenker*], *expression, interpretation*, and *basic* technique).[3] Examples in Figures 2-4 were redrawn to standardize score edition and replace color with greyscale coding of PC-type.

The pianist also provided a report of the formal musical structure by marking the starts of sections, subsections, and phrases on a clean copy of the score. Unlike the PC reports, which were done 28 times, the formal structure was reported once, between PC reports 25 and 26 (see Table 2, below).

Learning and performances

Table 2 enumerates the 28 PC reports the pianist made after performances of the Barcarolle, indicating the nature of each performance (practice, private, public, or lab). For purpose of description, PC reports and performances are organized into three temporal groupings: an *early period* lasting for five weeks during which the pianist made five reports; a *middle period* lasting for four days during which she made 17 reports; and a *late period* lasting for 10¼ years in which she made six reports, four over a four-month period, and two more after a break of 9¼ years. Also listed are the 16 performances in Years 3-15 for which the pianist did not report PCs, for a total of 44 performances. On the right, are the practice sessions up until the first public performance, the report of formal structure, mentioned above, and the tonal analysis and Schenkerian linear reduction described below.

Table 2: *Timeline of learning and performing the Barcarolle with PC reports divided into three time periods. Reports of PCs and performances of four types (practice, private, public, and lab) are numbered separately. Also listed are the practice sessions that were recorded, harmonic analysis, Schenkerian linear reduction, and report of formal musical structure.*

Report Num.	Time period	Year. Month	Performances				Recorded practice duration, structural analyses & reports	
			Practice	Private	Public	Lab		hr: min
		1					Practice session 1-4	3:31
							Harmonic analysis	
		2		1			Practice sess. 5-18	13:49
1-4	Early	3.1	1-4				Practice sess. 19-24	8:15
5	"	3.2			1		Practice sess. 25-34	9:14
		3.2			2		Schenker reduction	
		3.9			3, 4			
		4.2			5, 6			
		5.1					Practice sess. 35-41	3:00
6-7	Middle	5.2				1-2		
8	"			2				
9-10	"					3-4		
11-18	"					5-12		
19-21	"					13-15		
22	"			3				
23-25	Late	5.4			7-9			
							Structural reports	
26	"	5.8			10			
		11&12			11-19			
27	"	14.11		4-5				
28		15.7			20			

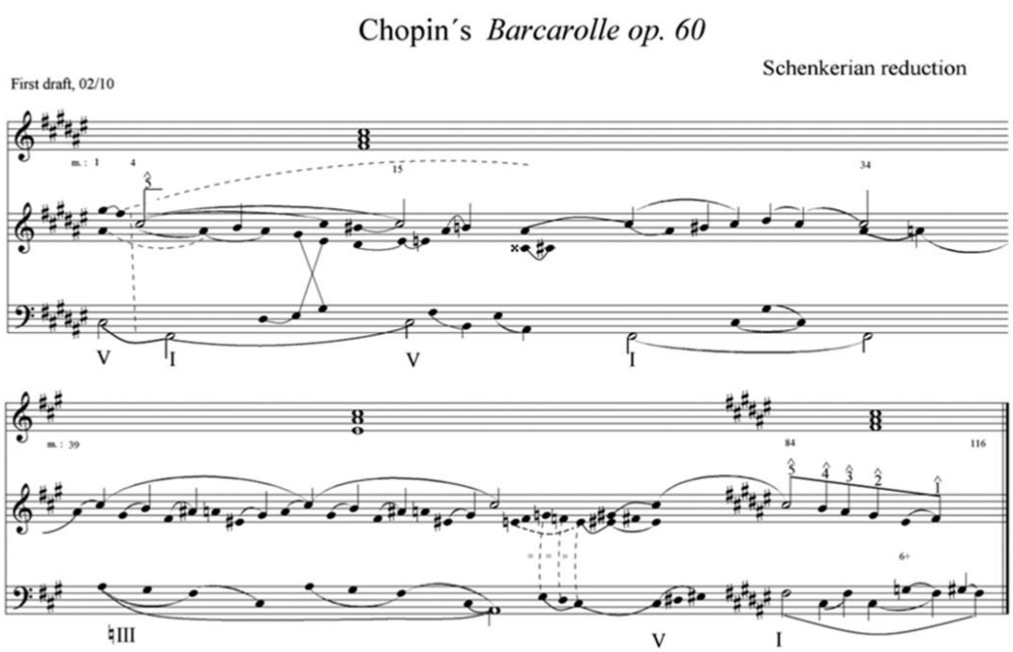
[3] We merged labels as follows: section, subsection, switch → *structure*; harmonic → *Schenker*; dynamics, accent, heightening, tempo change → *interpretation*; fingering, body → basic. *Expression* was labelled consistently.

At the start of the study, the pianist was already committed to a full schedule of performances and limited work on the Barcarolle to vacations. She had always loved the Barcarolle and wanted to play it, and had listened to many performances, so she was surprised to find herself struggling to make musical sense of the score at the piano. After four practice sessions, she interrupted work at the piano to make a detailed tonal analysis tracing the basic harmonic plan of the piece from F# to A Major and back to F# through the complexities of the intricate counterpoint, harmonic ambiguities, and the various types of cadences with which Chopin molds the formal structure. When she resumed practice in February of Year 2, she made rapid progress and after a month's work played the Barcarolle for her research colleagues, from memory, before setting it aside for another year.

Our study started in January of Year 3, with the five early period PC reports made as the pianist prepared the Barcarolle for a series of public performances in 15 practice sessions, totaling 17½ hours. She made PC Report 1 at the end of the first of these practice sessions. Two weeks later she made Report 2 at the end of 8 practice sessions lasting 7¾ hours in total. Another two weeks later she made Report 3 at the end of 7 practice sessions lasting 6 hours. The next day she made Report 4 after the final, hour-long practice session. Then the pianist travelled from her home in Brazil to the US for the first public performance, as part of a house concert involving other musicians, at the first author's home before an invited audience of around 30 people, after which she made PC Report 5, the last of the *early PC reports.* We later classified conditions during this performance as "atypical" because the pianist was distracted by loud creaking sounds from the pedal and reported that she "reverted to serial cuing." The next day, she performed again at a Northeastern Piano Teachers Association (NEPTA) meeting in Boston. She did not report PCs for this or the next four public performances, which took place in Brazil over the next two years.

Soon after returning to Brazil, the pianist created the Schenkerian-type linear reduction of the score shown in Figure 1 (Schenker, 1969). This graph became the source of Schenkerian PCs that increasingly replaced PCs referring to formal structure, as reported below.

Figure 1: *Schenkerian-type linear reduction of the Barcarolle.*



In February of Year 5, the pianist returned to the US for the 17 *middle period performances*, which took place over a four-day period during which there were 15 *lab performances* in the Music Performance Laboratory at the University of Connecticut, and two private performances (Reports 8 & 22). In the lab, the pianist played on a Yamaha Clavinova digital piano, without an audience, under three sets of instructional conditions described below. The first private performance, at the end of the first day, at the first author's home, was later classified as atypical because the pianist was again distracted by the vintage piano, this time by vibrating sounds. The second private performance was at the end of the fourth and last day, in a recital hall at the university, in preparation for two public performances a month later when the pianist returned to the university (Reports 23 & 24) for the start of the *late period*.

During the late period, the pianist provided six PC reports: 23 and 24 after recitals at the university, 25 after another recital in the US two weeks later, and 26, after a final recital in Brazil four months later. At the time, we expected this to be the end of the study. However, six years later (2018-2019), the pianist decided to include the Barcarolle in nine recital programs. So, in preparing to write this paper the pianist relearned the piece again and made two more PC reports, ten years after the last report: Report 27 after playing for her students and a colleague in her practice studio, and Report 28 after performing the Barcarolle as part of a recital program at a conference on music teaching. Before relearning the piece, the pianist tried to write out the score of the Barcarolle from memory and was chagrined to discover substantial gaps and uncertainties in her recall.[4] She then relearned the piece in approximately two hours of practice.

During the middle period, the pianist played in the lab under three instructional conditions alternating with normal (typical) playing, in counterbalanced order, as shown in Table 3. Table 3 also includes the two middle period private performances and shows whether performance conditions were typical or atypical. On each of the first two days of lab performances, the pianist performed the Barcarolle twice, once attending normally to PCs and once without attending to PCs (*with PCs/without PCs*). When playing without PCs, the pianist tried to play automatically, responding spontaneously to the sound of her own playing without thinking about what came next. On Day 3, she played eight times while moving less than normal, or normally, or more than normal (*no move/normal move/extra move*), changing the magnitude of her postural sway and other extraneous movements, e.g., of hand and head. On Day 4, she played three times while following along (*follow*) with three different audio recordings of her performances from the previous day, one performance from each of the three movement conditions (as shown in the table [normal/extra/no move]).

Table 3: *Middle period performances showing (1) the day of the performance, (2) the PC report number, (3) the type of performance, (4) the instructional condition of lab performances, with locations of private performances (in parentheses), and subscripts indicating the movement condition of the recorded performance followed on Day 3, (5) performance condition (typical/atypical) with superscripts indicating nature of atypical conditions (i = instructed to play in unusual way, d = disruption).*

[4] The recall will be reported separately.

Day	PC Report #	Perf. Type	Instructional Condition/(location)	Performance Condition
1	6	Lab	With PCs	Atypical[d]
	7	Lab	Without PCs	Atypical[id]
	8	Private	(1st author's home)	Atypical[d]
2	9	Lab	Without PCs	Atypical[id]
	10	Lab	With PCs	Typical
3	11	Lab	Normal Move	Atypical[d]
	12	Lab	Normal Move	Typical
	13	Lab	No Move	Atypical[id]
	14	Lab	No Move	Atypical[i]
	15	Lab	Extra Move	Atypical[i]
	16	Lab	Normal Move	Typical
	17	Lab	Extra Move	Atypical[id]
	18	Lab	No Move	Atypical[i]
4	19	Lab	$\text{Follow}_{\text{Normal Move}}$	Atypical[i]
	20	Lab	$\text{Follow}_{\text{Extra Move}}$	Atypical[i]
	21	Lab	$\text{Follow}_{\text{No Move}}$	Atypical[i]
	22	Private	(Recital hall)	Typical

Table 3 also identifies middle period performances as typical or atypical. Atypical performances were those in which the pianist deliberately played differently from normal or in which there were unexpected disruptions. Otherwise, performance conditions were classified as typical. On Day 1, there were loud creaks from the pedal in the lab performances and strange vibrating sounds from the piano during the private performance (Report 8), later the same day. On Days 2 and 3, there were sudden changes from piano-sound to string-orchestra-sound during four performances when the pianist accidentally struck a control button on the electronic keyboard. Rather than discard these data, we treated disruption as an experimental condition and compared typical and atypical performances. In the middle period (Table 3), there were 13 atypical and 4 typical performances. Together with the first public performance (Report 5), which was atypical due to the loud creaking sounds from the pedal, there were 14 atypical and 14 typical performances.

Analysis

As described below, typical performances differed from atypical performances. Also, middle period performances appeared atypical, different from both the early performances in the practice studio and the late performances for live audiences. We therefore compared typical and atypical performances across all 28 performances (omitting three to avoid biasing the outcome) and examined the evolution of PCs over time by comparing typical performances in the early and late periods.

Counting of reports

We summarized the 28 PC reports by dummy coding dichotomous variables to represent the presence (1) or absence (0) of PCs of each type (structure, Schenker, expression, interpretation, and basic) in each bar, creating a 116 (bars) x 28 (PC reports) x 5 (PC-types) matrix of binary values. All coding was done at the level of bars, with no more than one PC of each type coded for each bar, regardless of the number of marks and annotations in it.

Type of PC

To see if PCs changed over time, we used a 5 x 2 logistic mixed-effects model to compare the probability of PCs of each type (structural, Schenker, expressive, interpretive, basic) in the early and late periods (time), with presence/absence of PCs in a bar as the dependent measure. We omitted the middle period because most of the performances were atypical; we omitted Report 5 from the early period for the same reason. Time and PC-type were coded as contrast sums (i.e., ANOVA coding). The model included the random slopes of time and PC-type relative to the performance, and of time relative to the bar.

Boundary effect

To look for a boundary effect, we collapsed across PC-types to create a 116 (bars) x 28 (PC reports) matrix of binary values representing the presence or absence of PCs (one or more of any type) in each bar. After preliminary analysis, PC reports 19-21 were removed to avoid biasing the outcome, since almost no PCs were reported when following along with a recorded performance.

We used a logistic mixed effects analysis with boundary/no boundary as a within-subject variable, performance condition and time (early/middle/late) as between-subjects variables, and presence/absence of PCs (one or more of any type) as the dependent variable. We coded the first bar of each section, subsection, and phrase as boundaries (N = 14) and other bars as no boundaries (N = 102). For each report, we coded performance conditions as typical/atypical based on the criteria already described (N = 14 each), and time as early/middle/late (see Table 2). We tested the Time x Boundary and Performance Condition x Boundary interactions, but not the three-way interaction because the data were too unbalanced—most atypical performances were in the middle time period. The model included the random slopes of boundary and time relative to the performance and also boundary and time relative to the bar.

Overlap

To examine the overlap between PC reports, we used the 116 x 28 matrix described above to compare each performance with earlier performances, creating a new 28 (PC reports) x 27 (PC reports) matrix of binary values representing whether each pair of PC reports overlapped significantly or not (0 = non-significant overlap, 1 = significant overlap). Significance was determined with a hypergeometric test based on co-occurrence of PCs in each bar with the alpha level for declaring a significant overlap between two PC reports set to 0.01. This binary measure of significant overlap was statistically independent of the number of bars with PCs.

We used via logistic regression to test whether the likelihood of significant overlap between pairs of PC reports depended on (1) whether conditions for the two performances were typical or atypical (performance condition), (2) whether the two performances were successive or non-successive (*succession*), and (3) whether they were in the same time period (time). We coded each of the three predictors as contrast sums. For performance condition, we coded three types of comparison: *atypical-to-atypical*, *typical-to-atypical* (merged with atypical-to-typical), and *typical-to-typical*. For succession, we coded whether the performances for each pair of reports were *successive* (adjacent in the sequence of performances) or *non-successive* (non-adjacent in the sequence). For time, we coded six types of comparison: early to early, early to middle, early to late, middle to middle, middle to late, and late to late. Interactions between the factors were not tested because the data were unbalanced.

General analysis procedures

All logistic mixed effects models were fit with the glmmTMB (1.1.5) package in R (4.2) and the logistic model was calculated with base-R (glm function). Figures were generated with ggplot2 packages (3.4.1) and estimated probabilities (controlling for random effect bias) were calculated with the emmeans

(1.8.4-1) package. The model was then summarized with the car (3.1-1) package using type III sums of squared to test for the main effects and interaction, which are reported below as likelihood ratio tests against a chi-square distribution. We report odds ratios for specific comparisons using the emmeans package.

Results and Discussion

Qualitative description: Examples of PC reports

To illustrate how PC reports revealed the evolution and variation of PCs across performances, we begin with the pianist's description of examples from the reports at three structural boundaries where she consistently reported PCs.

Bars 1-6

The opening bars of the Barcarolle provide a good example of how PCs focused my mind during performance. Like most great Romantic pieces, the Barcarolle demands a powerful gesture at the very beginning. As seen in Figure 2, the first two sounds, the low octave C# and the ensuing G# minor chord, are composed in a startling, dissonant, assertive manner. Each time I performed the Barcarolle to my satisfaction, with conviction and authority, I used PCs to summon the dramatic burst of energy needed to launch the piece.

Figure 2: *PCs for bars 1-6 from Reports 4, 5, 24 and 25 (from top left to bottom right, respectively). Report 4 was the last practice performance, one week before Report 5, the first public performance. Reports 24 and 25 were late period public performances, two weeks apart.*

Figure 2 shows my PCs for the opening gesture from four PC reports, two each from the early and late periods (top and bottom panels, respectively). I have no difficulty saying what I was thinking.

Similar ideas are still with me when I play today. The top two panels show my PCs for the last practice performance before my first public performance, and the public performance itself, one week later (Reports 4 and 5, respectively). In both reports, the greyscale coding indicates that I was thinking about musical structure. In Report 4, I marked the low C# pedal as the dominant of F# major, which I labelled conventionally as "V", and sketched the descending diatonic octave scale, from B^5 to B^4, that leads to the real start of the Barcarolle with the tonic F# on the first beat of bar 4, labelled conventionally as "I" (tonic) and "A" (start of the first section). Thus, I summoned the opening gesture by thinking about its role in the formal musical structure—a harmonic descent into the first main section.

A week later, in the first public performance, Report 5 shows that I was still thinking about the formal structure but my markings are more telegraphic—a single upward arrow at the start of the piece, labelled "Intro." I just thought "Introduction", and went with the flow, playing with resolution and listening to the sound of the piano. This kind of abbreviation is possible because of the content-addressable nature of long-term memory. Memories (chunks) are activated in long-term memory by content addresses (names/labels) that can then be further unpacked, or not, as necessary.

The bottom two panels of Figure 2 show my PCs for the last two public performances in Year 5, that we expected, at the time, to conclude the study (Reports 24 and 25). My thinking about the Barcarolle had undergone an important transformation. The greyscale coding indicates that I was now thinking in terms of expression, rather than formal structure. The change in my thinking is further revealed in a small but significant change in how I sketched the linear descent of the opening gesture in the two left-hand panels of Figure 2—the addition of the long vertical line connecting bar 2 with bar 6 in the bottom left panel. In the earlier Report 4 (top left), my sketch of the linear descent in bars 1-3 leads to the start of the A section, in bar 4. This connection is still present in Report 24 (bottom left), but now, in addition, the long vertical line connects the linear descent in bar 2 to the entry of the A theme in the right hand in bar 6. This reveals the change in my thinking.

In my mind, the Barcarolle tells the story of a momentous sea voyage by the boat referred to in the title, in which return to safe harbor is often in doubt. The A section begins, in bar 4, with an F# major figuration in the left hand that invokes the moving watery surface that sustains the boat. However, the voyage itself does not begin until bar 6, where the entry of the A theme in the right hand evokes the elusive song that runs through the whole piece, perhaps heard by the boat's passengers. Thus, in Report 24, I was thinking of the opening gesture as an introduction to the musical narrative of the whole piece. Rather than thinking "Introduction", as in Reports 4 and 5, I now summoned the opening gesture by thinking "Let the voyage begin!" Of course, I had been aware of this musical story two years earlier, but my PC reports show that I did not use it to summon the opening gesture. Two years later, I did—I thought about musical expression. The change was not a deliberate choice on my part; it reflected the slow evolution of my ability to listen to the music as I played.

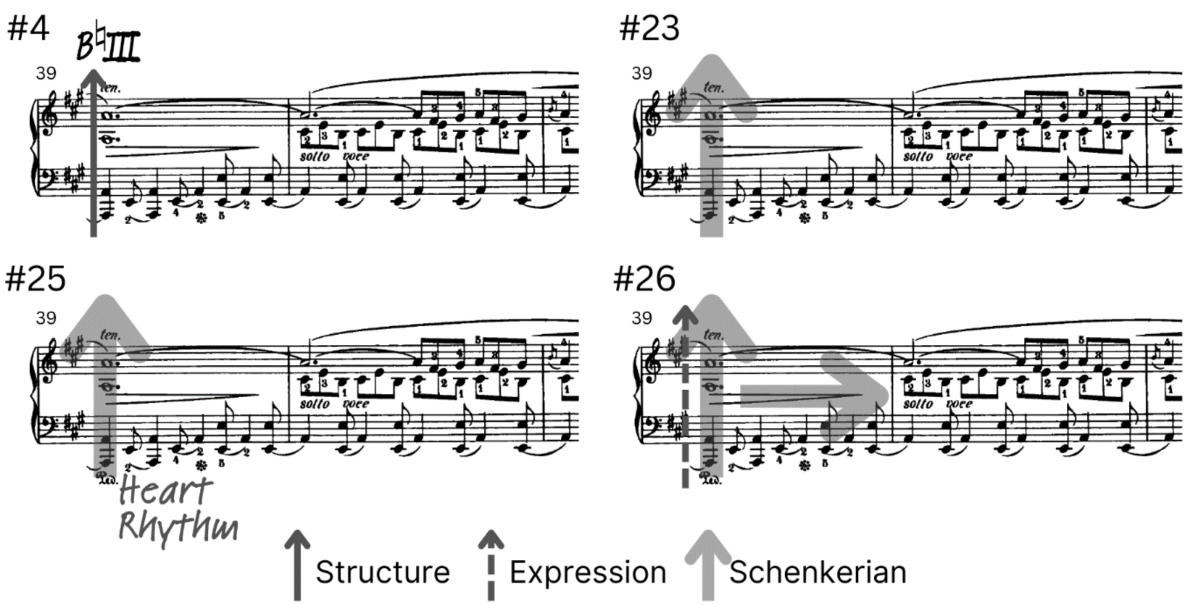
In the bottom right panel, the single arrow in the first bar of Report 25—the next public performance two weeks later—provides another example of more telegraphic thinking. I was still thinking about expression, but instead of thinking of how the harmonic descent leads into the start of the voyage, as in Report 24 (bottom left), I simply thought "Let the voyage begin" and played the opening gesture without further unpacking it.

Bars 39-40

Figure 3 shows how Schenkerian PCs served as a stepping-stone to expressive PCs at the start of the B theme in bar 39. In Report 4 (top left), the start of the B theme is marked with a structural PC. In the later reports, structural are replaced by Schenkerian PCs, with the addition of an expressive PC in Report 26 (bottom right). The Schenkerian PC in Report 23 (top right) refers to the arrival on

A, the main note of the B section, after the linear descent, in bars 35-38, from C#, the fifth degree of F# and the main tone throughout the first section A. Two weeks later, in Report 25 (bottom left), the Schenkerian PC is labelled "heart rhythm." Rather than thinking about the linear descent, I was thinking instead of the steady, rhythmic pulse in the left hand, carrying me towards the return to the home key of F# at the end of the piece. This is one of my favorite moments in the piece and became a constant in my PC reports from this point on.

Figure 3: *PCs for bars 39-40, the start of the B theme, from Reports, 4, 25, 23, and 26 (from top left to bottom right, respectively). Report 4 was a week before the first public performance; Report 23 was the first performance in the late period; Reports 25 and 26 were later the same year.*



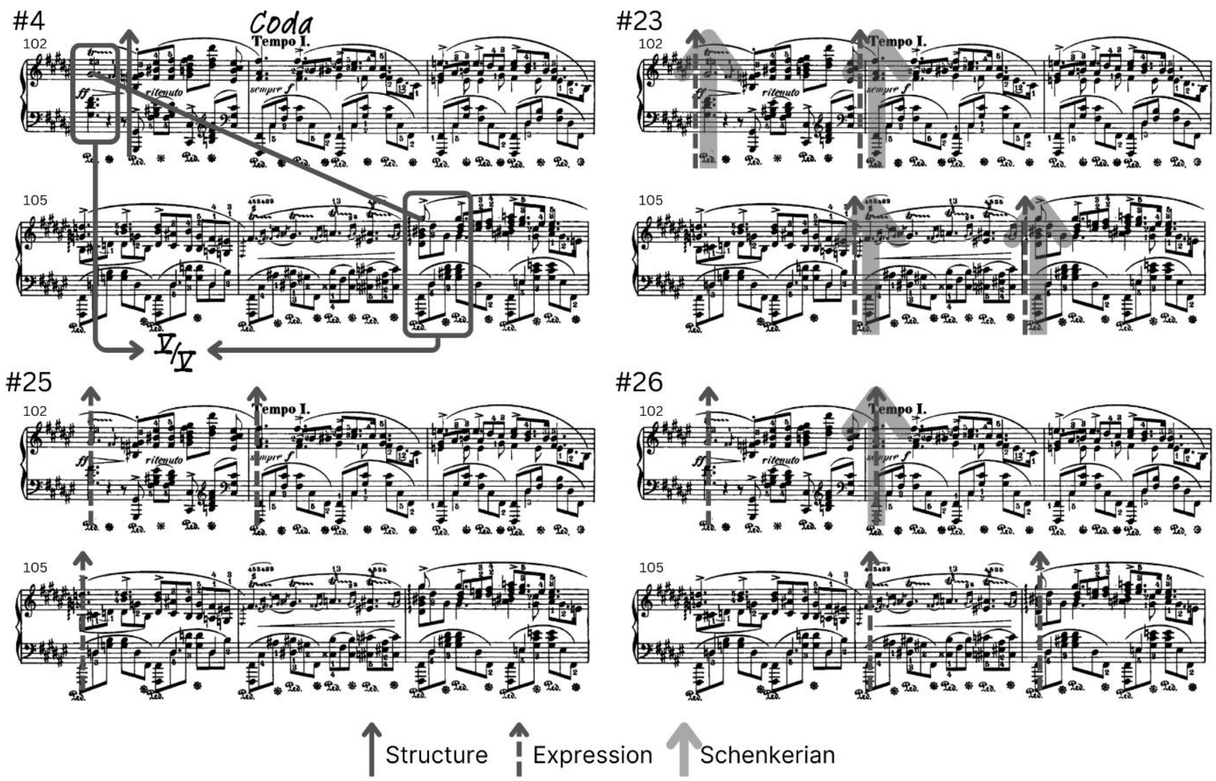
Four months later, in my next report (Report 26, bottom right), I marked the same passage with two PCs, Schenkerian and expressive. The Schenkerian PC again refers to the "heart rhythm" pushing me forward. The expressive PC refers to renewed hope that, after the uncertainty of the sorrowful chain of notes centered on F# minor during the transition in bars 35-38, the confident, reassuring pulse of the beating heart will push me and the boat forward all the way to safe harbor of F# at the end of the piece. Almost ten years later, when I made my next report (Report 27, not shown), I marked the transition in bar 39 with only an expressive PC, completing the evolution from structural, to Schenkerian, to expressive.

Bars 102-107

Figure 4 shows a similar evolution at the start of the coda in bar 103. In Report 4 (top left), I annotated the structural PC in bar 102 by writing "Coda" and putting boxes around the two versions of the dominant of the dominant chord for the section, in bars 102 and 107, which I labelled conventionally, "V/V". Two years later, in Reports 23, 24, and 26 (top right and bottom left and right, respectively), these structural PCs are replaced by Schenkerian and expressive PCs, the former referring to the grand linear descent to the cadence at the tonic in bar 113 (not shown), the latter indicating relief that the worst of the storm has passed, and that the safe harbor of F# is in sight.

The differences between the three reports reflect my spontaneous choice of what to attend to. In Reports 23 and 26 (top and bottom right), I attended to local events—Chopin's pretense of a grand resolution marked by the expressive PCs in bars 106 and 107—whereas, in Report 24 (bottom left), I attended to more distant relationships—the emotional tension marked by the expressive PC in bar 105, marking the reintroduction of melodic material in G#, from earlier in the piece, that continues until the reiteration of F# in bar 111 (not shown).

Figure 4: *PCs for bars 102-107, including the start of the Coda in bar 103, from Reports 4, 23, 24, and 26 (from top left to bottom right, respectively). Report 4 was a week before the first public performance; Report 23 was the first performance in the late period; Report 24 was the next day; Report 26 was four months later.*



This is how I like to play, sitting back and enjoying the music as I play, following the musical threads in my inner ear, and choosing which direction to take, a seamless flow of coordinated music and thought, like an orchestral conductor. These choices are my spontaneous, artistic response to the musical possibilities of the moment. However, the ability to make such choices in the heat of the moment is the product of careful, deliberate preparation, both in practice and in reflection after each performance. With the Barcarolle, making PC reports was a useful discipline that helped me to reflect after the performance, while simultaneously strengthening my musical landmarks (PCs).

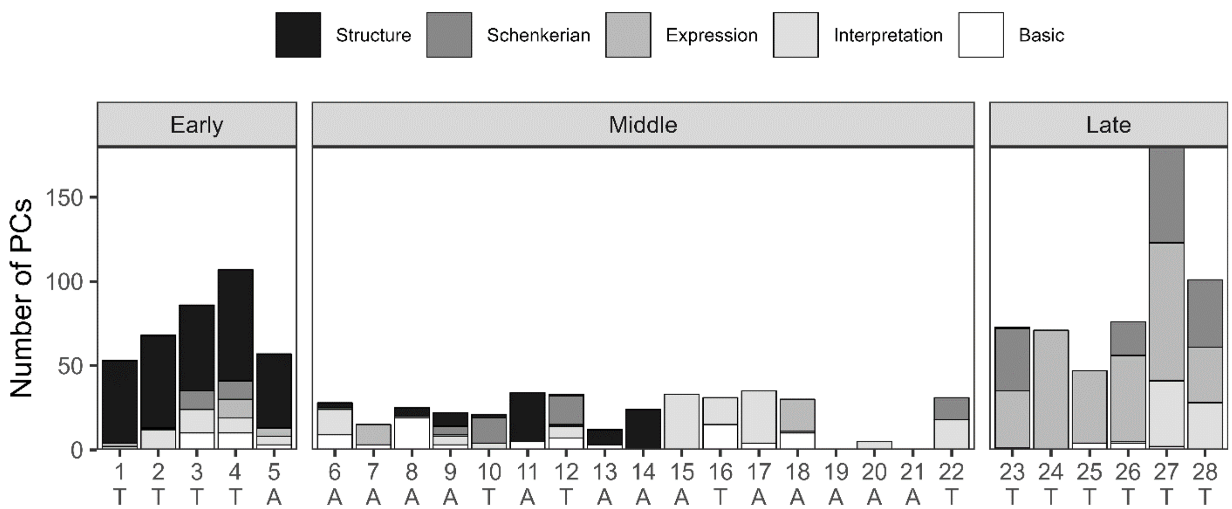
Quantitative summary and analysis

The quantitative analyses show that the examples described above were characteristic of the PC reports as a whole and reveal additional properties of the reports. We discuss each result as it is presented.

PC-type

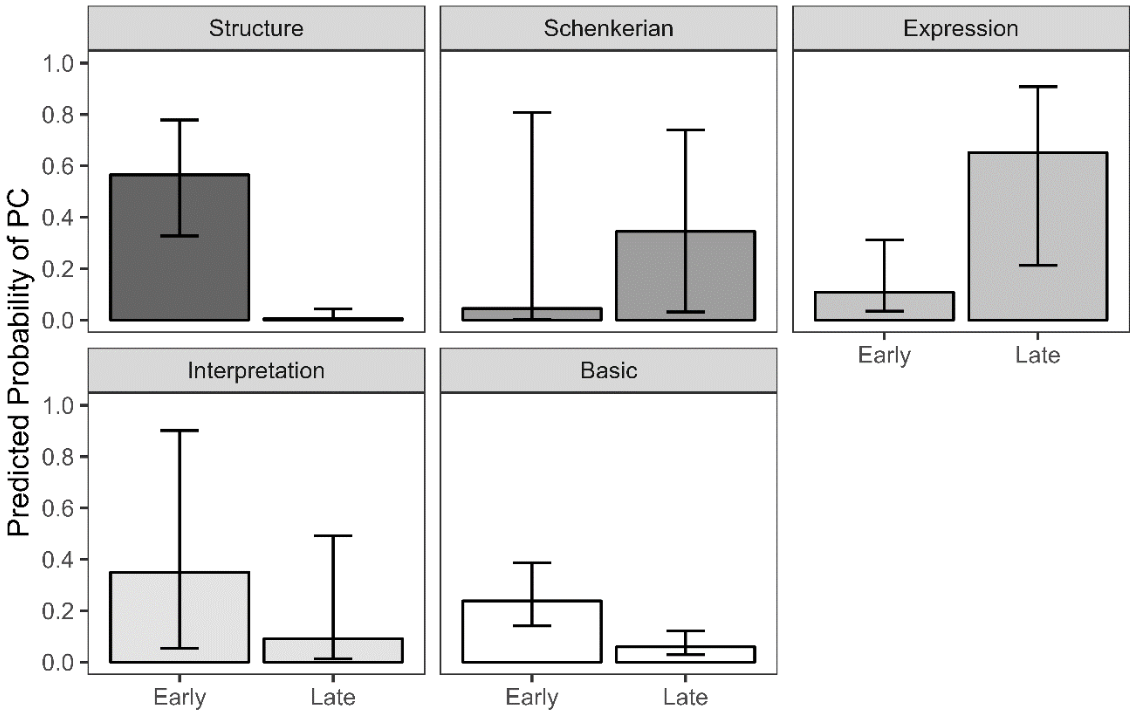
Results. Figure 5 shows the number of PCs of each type for each performance. As expected, structural PCs predominated in early reports, expressive and Schenkerian PCs in late reports. Inspection shows that there were fewer PCs in the middle period reports, perhaps due to giving multiple performances in quick succession. There were also fewer PCs for the first public performance (Report 5), when conditions were also atypical. So, we examined the change in PC-types over time by comparing the number of PCs of each type in the early and late periods for typical performances.

Figure 5: *Number of PCs of each type in each report, with reports numbered (1-28), labelled by performance condition [typical (T) and atypical (A)], and grouped into three time periods.*



In Figure 5, the frequency of PCs was based on simple counting. In Figures 6-8, probabilities are represented by values generated by the relevant logistical model. Figure 6 shows the predicted probability of each type of PC in the early and late periods, generated by the 5 x 2 logistic mixed-effects model. Overall, there was no significant difference in the number of PCs between the early and late time periods, χ^2 (1, *n* = 5800) = 1.62, *p* = .21. There was a main effect of PC-type, χ^2 (4, *n* = 5800) = 23.11, *p* <.001, qualified by a significant interaction between PC-type and time, χ^2 (4, *n* = 5800) = 94.45, *p* <.0001. As seen in Figure 6, there were more PCs in early than late performances for basic PCs, OR= 35.18, se = .85, *z* = 3.19, *p* < .005, and structural PCs, OR = 9854.88, *se* = .0007, z = 6.868, *p* < .0001; and more expressive PCs, in late than in early performances OR = 442.92, *se* =312, *z* = 5.69, *p* < .0001. Schenkerian PCs were 72.56 more likely in the late than in the early performances, but the difference was not significant, probably due to their complete absence in Reports 24 and 25, OR = 72.56, se =152, *z* = 1.05, *p* = .29. The difference between time periods was also not significant for interpretive PCs, OR = 1.87, se =258, *z* = -1.05, *p* = .29.

Figure 6: *Predicted probability of PCs of each type in early and late time periods, with error bars showing 95% confidence intervals.*



Discussion. Structural PCs predominated in the early period and disappeared in the late period, when they were replaced by expressive and Schenkerian PCs, although the increase in Schenkerian PCs was not significant. The change reflects re-chunking (Chaffin et al., 2002, p. 27, 234-235). In the early period, the pianist thought of the music in terms of its formal structure; in the late period, she thought in terms of musical expression, i.e., the emotions evoked by the music. Although the change over time was not statistically significant for Schenkerian PCs, they provided a way of articulating the relationship between musical structure and expression that we used in describing examples of PCs above.

The relatively small number of basic PCs in the early period suggests that the pianist had resolved most of the technical difficulties before the start of our study. Despite this, the significant decrease from early to late periods shows that technical issues continued to intrude occasionally, requiring recourse to the higher level, conscious control provided by basic PCs.

It may seem surprising that interpretative PCs were not more numerous, since playing Chopin requires constant attention to dynamics, tempo, and projection. However, these thoughts were mostly too fleeting and numerous to be useful in monitoring progress through the piece, so the pianist did not regard them as PCs. She made an exception for the last two performances (Reports 27 and 28) when she reported interpretive PCs after making a deliberate decision to pay more attention to the composer's dynamic markings after listening to recordings of her performances.

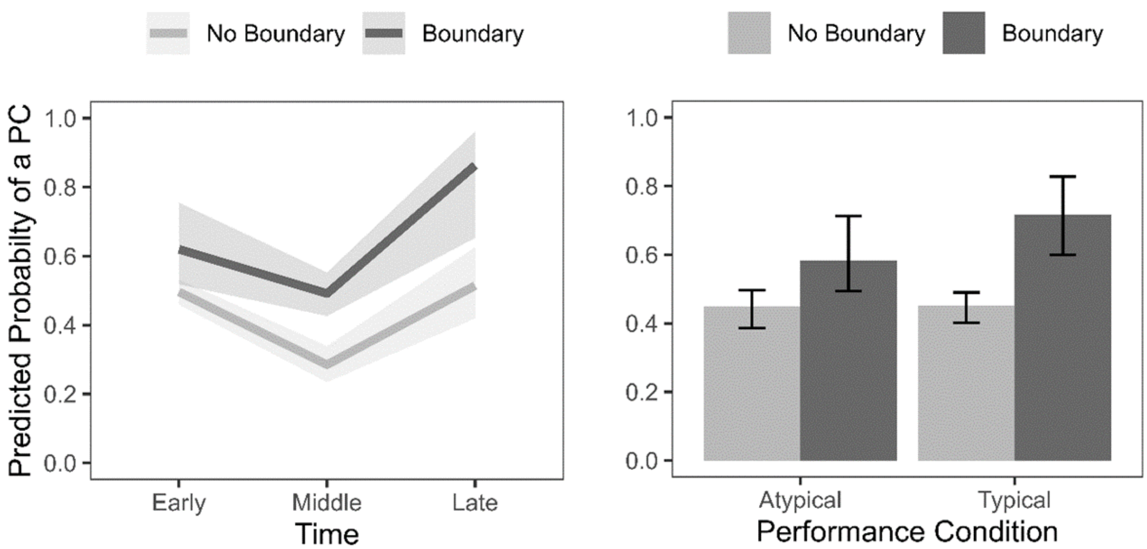
Boundary effect

Results. Figure 7 shows that, as expected, PCs were more frequent at structural boundaries than at non-boundary locations), $\chi^2(1, n = 2900) = 26.19, p < .0001$.[5] This boundary effect was qualified by interactions with time, $\chi^2(2, n = 2900) = 5.44, p = .066$, and performance condition, $\chi^2(1, n = 2900) = 5.10, p = .024$. The left panel shows a small but significant boundary effect in the early period, OR = 6.40, se = 2.67, z = 2.52, p = .012, a larger effect in the middle period, OR= 10.03, se =3.09, z = 4.87, p < .0001, and

[5] As noted earlier, we excluded Reports 19-21 to avoid biasing the outcome of this analysis. The pianist reported almost no PCs for these atypical performances in which she followed along with a recorded performance. Thus, excluding them was conservative with respect to the finding of fewer PCs under atypical performance conditions.

the largest effect in the late period, OR= 26.27, *se* =15.55, *z* = 4.16, $p < .0001$. The right panel shows a small but significant boundary effect for atypical performances, OR = 7.89, *se* = 3.11, *z* = 3.07, *p* = .001, and a larger effect for typical performances, OR = 17.96, *se* = 6.33, *z* = 5.91, $p < .0001$.

Figure 7: *Predicted probability of a PC at structural boundaries and at other, non-boundary locations as a function of time (left panel) and performance condition (right panel). Error bars represent 95% confidence.*



Discussion. The boundary effect was larger under typical than under atypical performance conditions and increased, albeit not significantly, over time.[6] Both effects suggest that the main function of PCs was to guide musical expression and communication rather than to act as guardrails keeping the performance on track. Although the pianist's initial goal in using PCs was as a safety net in case of memory failure, during the middle period she discovered that playing with PCs was more enjoyable than playing without them. Rather than being an extra burden, PCs assured the pianistic realization of her musical plan. Again, this was not a deliberate choice but reflected a slow change in attitude.

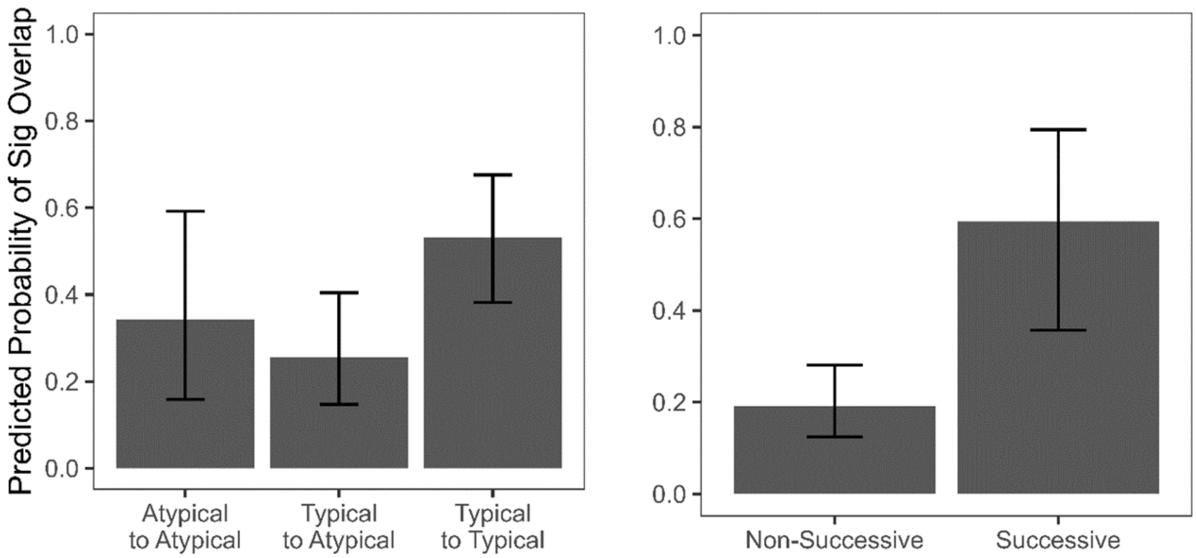
Overlap

Results. Figure 8 shows two ways in which performance conditions affected the probability of overlap between PC reports. The left panel shows the significant effect of performance condition, χ^2 (2, *n* = 300) = 10.35, *p* = .006. The probability of overlap for typical-to-typical comparisons was significantly higher than for typical-to-atypical comparisons, OR= 3.31, *se* = 1.24, *z* = 3.20, *p* = .001, and did not differ significantly from atypical-to-atypical comparisons, OR = .66, se = .33, *z* = .831, *p* = .41. The right panel shows the significant effect of succession, OR = 6.20, se = 3.34 z = 3.38, $p < .001$. The chance of overlap was 6.20 times higher between successive performances than between non-successive performances.

[6] The boundary effect was larger for typical than for atypical performances in the middle period (*n*=4 and 13, respectively) and in the early period (*n*=4 and 1, respectively). In the late period, conditions were typical for all performances.

Figure 8 does not include the non-significant main effect of time period, χ^2 (5, n = 300) = 7.14, p = .21, indicating that overlap was not affected by temporal distance over longer periods.

Figure 8: *Predicted probabilities of significant overlap for atypical-to-atypical, typical-to-atypical, and typical-to-typical comparisons (left panel), and for comparisons between successive performances and between non-successive performances (left panel). Error bars represent 95% confidence.*



Discussion

The greater overlap for typical-to-typical comparisons validates the division of performance conditions into typical and atypical and provides further evidence that performance conditions affected PCs, which overlapped more when performance conditions were similar (typical-to-typical and atypical-to-atypical) than when they were different (typical-to-atypical). Surprisingly, typical-to-typical and atypical-to-atypical comparisons did not differ. Surprising, because atypical conditions varied widely—distractions, without PCs, no/extra movement, and following another performance. Despite the variety, overlap was not significantly different than typical-to-typical comparisons. Apparently, any distraction from the normal goal of playing expressively reduced the number of PCs.

Overlap also revealed another way in which performance conditions affected PCs—successive performances overlapped more than non-successive performances. We suggest that this is because an important part of the context for each performance was the memory of the performance that preceded it (Logan, 2021). The greater overlap of successive performances was not simply due to the evolution of PCs from one performance to the next because overlap did not decrease with temporal distance at longer distances in the temporal sequence.

For present purposes, the importance of these effects is to validate the division of performances into typical and atypical by showing that they differed on a second measure that behaved in an orderly and psychologically plausible manner. In this context, the absence of a significant difference between typical-to-typical and atypical-to-atypical comparisons shows that the wide variety of atypical performances conditions were all similar in decreasing use of PCs.

General Discussion

The pianist's goal in using PCs to learn the Barcarolle was to provide a safety net in case of memory failure. She was surprised to find that she also enjoyed playing more when she used PCs. It was not just that she felt that she memorized faster and more securely. She also felt that she played better; that always knowing what came next allowed her to listen more closely to the music, following the musical threads in her inner ear and choosing which to attend to. Playing from memory may promote playing expressively because both involve similar metacognitive skills—both require thinking about what you are doing (Christensen et al., 2016; Lisboa et al., 2018). Playing from memory requires keeping track of where you are in a mental map of the music. Playing expressively after long hours of practice requires renewed attention to the feelings evoked by the music to avoid falling into the trap of mindless virtuosity (Hennion, 2012). Expressive PCs served both these disparate goals, securing memory while also enhancing expression.

Our study differed from previous longitudinal case studies of PC development in two ways. First, previous studies mostly focused on testing the validity of PC reports by examining their relationship with behavioral measures, such as starts and stops in practice, tempo fluctuation during performance, and recall of the score (e.g., Chaffin & Imreh, 2002; Chaffin et al., 2010, 2021; Demos et al., 2016; Ginsborg & Chaffin, 2011; Ginsborg et al., 2012; Lisboa et al., 2018). In an earlier report on the present study, we similarly found that the pianist started playing more often at harmonic transitions than at other locations during practice (Chaffin et al., 2013). In contrast, in this paper we have taken PC reports at face value and used them directly to describe the evolution of the performance. Second, previous studies indirectly inferred the evolution of PCs from musical structure to expression from the early effects of musical structure on practice and later effects of expressive PCs on performance and recall. We observed the same evolution more directly by comparing PC reports. PC reports are an economical and minimally intrusive way to study performance that also appears to increase self-understanding and self-awareness in the musician.

Four findings together suggest that the main role of PCs, for the pianist, was to promote musical expression, rather than simply to keep the performance on track. The first two findings are consistent with earlier studies, while the last two have not been reported before. First, PCs evolved from being mostly about musical structure in the early period to being mostly about musical expression in the late period; this suggests that one role of PCs was to evoke musical expression. Second, PCs were more frequent at transitions in the musical structure, suggesting that PCs served as landmarks in a mental map of the music. Third, the pianist reported more PCs for the early and late performances, when performance conditions were generally good, than for the middle performances, when conditions were less optimal—she was asked to play multiple times each day, often in unusual ways, sometimes with distracting noises from the piano. This suggests that the pianist wanted to attend to PCs and was inhibited from doing so when conditions were atypical. This conclusion is further supported by the fourth finding, that the boundary effect was larger under typical than under atypical performance conditions and increased (non-significantly) over time.

Each of these findings merits further study. Longitudinal case studies tracking PC development have included only a very small number of musicians (e.g., Chaffin & Imreh, 2002; Chaffin et al., 2010; Fonte, 2020; Ginsborg & Chaffin, 2011). The statistical tests in each study show only that another study would likely observe similar effects for the same musician learning a similar piece. Additional case studies, and group studies, are needed to allow generalization across musicians. Similarly, the range of instruments studied has been limited to piano, prepared piano, cello, and voice. Additional case and group studies are needed to allow generalization across instruments, and across musical genres and types of performance. We expect that the evolution from structural to expressive PCs and the clustering of PCs at structural boundaries that we observed will generalize to other musicians and instruments because these effects have been observed in other studies.[7] In contrast, the unexpected effects of performance conditions on the number of PCs and on the boundary effect have not been observed before and invite further exploration. At the least, they require replication in studies in which performance condition is systematically manipulated over time, unlike our study, in which most of the atypical performances were in the middle period.

The study of music performance is still in its infancy. Although PC theory is rooted in well-established principles of human memory, based on controlled laboratory studies, we do not yet know how well those principles apply to music performance in real-world settings. Indeed, the unanticipated difference between typical and atypical performance conditions in the present study suggests that PCs are strongly affected by context. A better understanding of the factors that affect music performance in everyday settings will help to bring it into the laboratory for more systematic study.

We conclude with the pianist's description of how the study changed her playing:

Since learning the Barcarolle, all my practice has become more deliberate. As a young pianist I just played. Now, I try different solutions, ponder options, and allow myself more time to learn. I make sure to know where I am at all times: big A's, little b's, transitions, and switches. After more than a decade of using PCs, I feel very confident that I can trust my memory again. Memorization is no longer something that I take for granted. I work at it diligently and deliberately. It requires effective planning and enough time to let all the information set in my mind. I do the work with a good feeling of calm resolution. I have become addicted to planning and to having a good plan. Once done, it is long lasting and, best of all, the musician that lives inside my head can soar to new heights.

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[7] We also expect PCs to operate similarly for most professional musicians, and differences between instruments to be reflected in different types of basic PCs, e.g., fingering, bowing, breathing.

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