

Analysing playing using the note-time playing path

Deborah L. E. de Graaff · Emery Schubert

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Abstract This article introduces a new method of data analysis that represents the playing of written music as a graph. The method, inspired by Miklaszewski, charts low-level note timings from a sound recording of a single-line instrument using high-precision audio-to-MIDI conversion software. Note onset times of pitch sequences are then plotted against the score-predicted timings to produce a Note-Time Playing Path (NTPP). The score-predicted onset time of each sequentially performed note (horizontal axis) unfolds in performed time down the page (vertical axis). NTPPs provide a visualisation that shows (1) tempo variations, (2) repetitive practice behaviours, (3) segmenting of material, (4) precise note time positions, and (5) time spent on playing or not playing. The NTPP can provide significant new insights into behaviour and cognition of music performance and may also be used to complement established traditional approaches such as think-alouds, interviews, and video coding.

Keywords Practice · Instrumental music performance · Measurement and analysis · Performance analysis

Performing musicians, music educators, and researchers frequently seek ways of enhancing the efficiency of instrumental music practice. Studies of children, advanced students, professional players, and (less commonly) elite performers have demonstrated in recent years a growing interest in understanding the processes involved in deliberate practice, or time spent alone on an instrument (e.g., Ericsson, 2003, 2007; Ericsson, Krampe, & Tesch-Römer,

1993). The tools commonly used by researchers to assess such processes include analysis of practice diaries (Renwick, McPherson, & McCormack, 2002), interviews and think-alouds (Ericsson & Simon, 1993), and analysis of video data of practice or performance sessions (Chaffin & Imreh, 2002; Chaffin, Imreh, & Crawford, 2002; Nielsen, 1999a, 1999b; Renwick, 2008).

These much-used techniques, while providing valuable insights into the practising process, are reliant on the memories of the participant during an action or event and on comments about actions, such as justifications or explanations (Ericsson & Simon, 1993). But what if the self-reported perception of the performer manifests itself in a different way, in the actual execution and cognitive processing? What if the performer does not have direct access to their subconscious processes through their introspections alone (Gaillard, Vandenberghe, Destrebecqz, & Cleeremans, 2006)? It would be useful for researchers to examine precisely what musicians are playing, without relying so heavily on the introspections and interpretations of the player (or the researcher, for that matter). Are there ways to analyse the playing and strategies of the performer, without the previously necessary intermediate step of self-analysis by the performer and without the subjectivity of the researcher?

Because we believe that a range of implicit and phenomenological approaches should be embraced to help understand the practice and playing process, we seek to develop a detailed analysis method that allows direct visual inspection of playing for various performance parameters. We also seek an objective analysis of the data themselves, without the intermediate self-conscious introspections of the participant. In this way, we shall use new technology to improve research methods into music practice (Gobet, 2005, p. 183). Valuable precedents exist in the area of practice research. We review two that are most relevant to

D. L. E. de Graaff (✉) · E. Schubert
University of New South Wales,
Sydney, New South Wales, Australia
e-mail: deborahdegraaff@optusnet.com.au

the kind of instrument we wish to develop, one by Miklaszewski and the other by Chaffin and colleagues.

Miklaszewski's graphic practice analysis

Using a combination of self-evaluation (video-prompted think-alouds) and behavioural indicators (video and coded behaviours), Miklaszewski (1989) analysed the stages of practice on a previously unfamiliar composition. A 21-year-old piano student in his 2nd year at the Chopin Academy recorded all of his practice work while learning the prelude 'XII Feux d'Artifice' from the *Second Book of Preludes* by Claude Debussy. This 5-min work is 98 measures long and has roughly (depending on the criteria used) 25 segments containing structural boundaries, contrasting piano textures, and differing technical complexity. The study was spread over one week, during which time the student practised in four main periods, up to the point when he was ready to present his preparation of the piece to his teacher. Each recording was watched later by the researcher and analysed. Sixty-nine minutes of Session I were also watched by the student, in the presence of the researcher. The student's comments while viewing the tape were also recorded, notated, and used in the analysis. These comments were used to provide descriptions of musical material and actions that were added.

Miklaszewski (1989) set out to discover whether the practised segment lengths of the score changed over the time of the study, whether the student's actions evolved over the same time, and whether any systematic relationship existed between the musical material, the actions of the student, and the comments about his goals. He concluded that formal structure and texture influence the divisions of the musical material into workable segments suitable for practice. This is consistent with research on observational practice in which

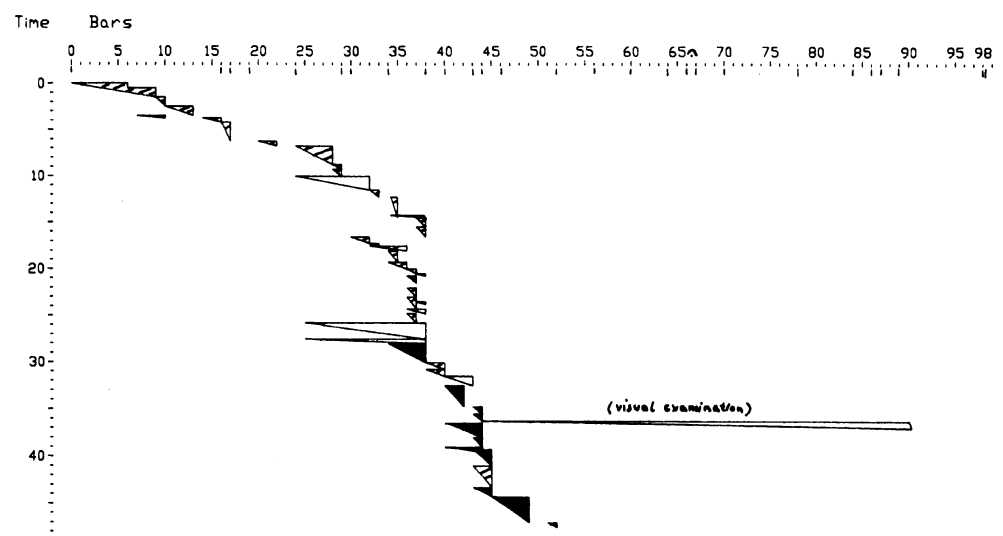
longer pieces have been divided into workable units of shorter length (Gobet, 2005; Gruson, 1988; Nielsen, 1999a; Rubin-Rabson, 1945; Sloboda, 1985).

The graphic practice analysis by Miklaszewski (1989) showed many actions: the time spent on each particular measure, the play-through of segments, and the overlapping and extension of these segments into longer sections for joining the whole work (Gruson, 1988; Miklaszewski & Sawicki, 1992; Nielsen, 1999a). Detailed examination by the performer of the difficult passages throughout the piece (as they received more attention with more repetitions) and the speed of the practice are also broadly identifiable. The plot (example shown in Fig. 1) showed how the subject, through practice, built up a performance plan, or what Chaffin et al. (Chaffin, Demos, & Crawford, 2009a) refer to as a set of 'performance cues', as he mastered the necessary procedures of motor performance to execute this plan.

Miklaszewski (1989) chose to focus on a more detailed analysis of measures 35–38. A Brüel and Kjaer graphic register was used to plot the occurrences of three categories of behaviour on moving paper (separate-hand practice, changes in tempi, and checks to see whether the student practised notes from the actual passage or made excursions elsewhere in the score). Miklaszewski described the mechanics of producing these plots:

The register was used in a very primitive way: simply, I observed the video recording of my subject practicing and was pressing the button when a given activity started and releasing it when it was over. The register put a line on a paper, time running at a predefined speed when a button remained pressed, thus helping me in my elementary observation job. Thus I watched a video recording several times, each time for spotting one selected category of behaviour. (Miklaszewski, pers. comm., September, 2009)

Fig. 1 The graphic practice analysis by Miklaszewski (1989) showed: the time spent on each measure; segmenting the work; joining the segments to build the whole work; detailed examination of difficult passages; use of repetitions and the tempo of the practice. Reprinted from page 100, OA Case Study of a Pianist Preparing a Musical Performance' by K. Miklaszewski, 1989, *Psychology of Music*, 17, 99–109. Copyright 1989 by Sage Publications Ltd. Reproduced with permission



Miklaszewski's graph was unique in revealing performance tempo, which is shown in two ways (see Fig. 1). The first is by manually blackening the triangles to indicate where the segment is played more slowly (striped triangles indicate irregularities in tempo, according to Miklaszewski). The second way he indicates tempo is more specific. The hypotenuses of the black (slower) triangles have larger angles with respect to the horizontal than do the hypotenuses of the white (faster) triangles (see Fig. 1). The graph also shows time unfolding down the page. Miklaszewski's approach has not been commonly used to analyse practice scenarios, perhaps largely because of the time-consuming nature of recording and then annotating the duration of each measure.

Chaffin's 'Studying Your Music Practice' (SYMP) system

Looking at the measures, relative to time spent practising, has been a common feature of several influential observational practice studies (Chaffin & Imreh, 2002; Gruson, 1988; Nielsen, 1999a). Most recently, practice shown as a graphic illustration has been used in research to highlight the use of certain actions and strategies (Chaffin, Demos, & Crawford, 2009a, 2009b). A software tool called 'SYMP' (Studying Your Music Practice) is available at www.htfdcc.uconn.edu/psyclabs/musiclab.html. Using video recordings of practice or performance, significant points of information are entered (measure by measure or beat by beat), recorded first onto a score and then onto spreadsheets. The points can be chosen to reflect actions by the performer: which hand was used, whether the score was viewed or played from memory, how many measures were played, and what performance cues the performer used for learning and memorizing the music (Chaffin et al., 2009a, p. 4).

Performance cues were defined by Chaffin and Imreh (2002) as landmarks in the mental map of the piece, set up during the practice and memorizing, that a musician then monitors during performance. Particular features (dynamics, mood, harmonic structures, key changes, tempo changes, etc.) are mentally marked during practice with the intention of linking specific thoughts and actions into the player's memory. These actions are then recalled automatically during the performance (Chaffin, Lisboa, Logan, & Begosh, 2010).

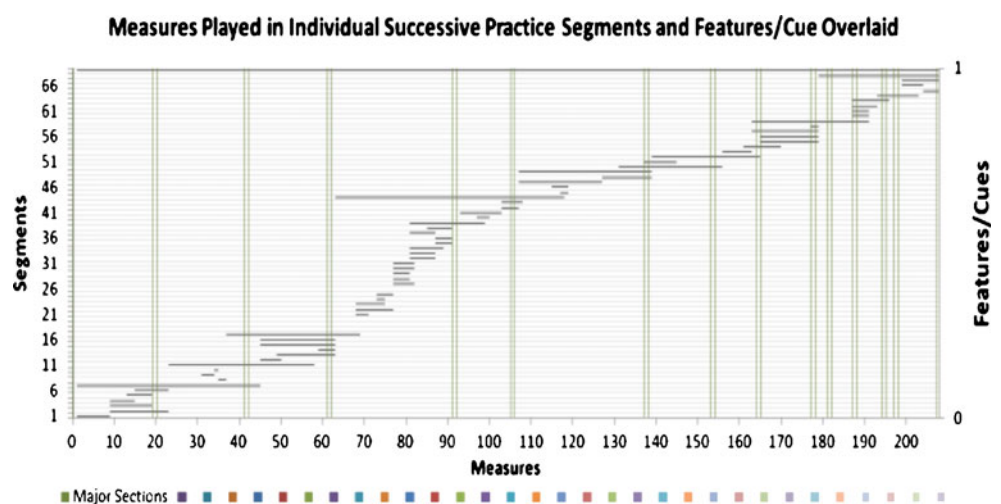
An example of the kind of plot generated by the SYMP system is shown in Fig. 2 (Chaffin et al., 2009b). It shows unfolding sequences (left to right) of segments of measures (sections) that were practised. The technique allows visual identification of the length of measure segments; sections of the piece where the longest, or shortest, measure segments were played; and, of most interest to Chaffin et al., where and how these segments correlated with performance cues.

Chaffin et al. (2009a) mentioned that the musicians were typically not able to report the locations of their practice cues until much later on in the process—that is, at about the time of their performance. From observing the graphs, however, it is clear that there was an influence from these areas in the musicians' practice prior to their reported awareness of the cues. Chaffin et al. (2009b) confirmed that practice graphs provide a useful way of visualising the relationship between the musicians' actual practice and the features of the music that they later report.

Aims

Our review of the literature has demonstrated that the techniques for graphically representing and examining issues concerning music practice have advanced considerably. While the reviewed methods provide high-level

Fig. 2 Measures played in practice segments. Reprinted from 'Sources of Variation in Musicians' Use of Performance Cues' by R. Chaffin, A. Demos, & M. Crawford, 2009, pages 109–112 in C. Stevens, E. Schubert, B. Kruithof, K. Buckley, & S. Fazio (Eds.), *Proceedings of the 2nd International Conference on Music Communication Science (ICoMCS2)*. Sydney: Australia HCSNet, University of Western Sydney. Reproduced with permission of the authors



musical feature information (such as segment length and performance cues) at the entry level to the system, we aimed to augment these developments by capitalising on advances in audio extraction technology to produce greater degrees of detail, flexibility, objectivity, and automaticity to the process of analysing practice. Specifically, in addition to the techniques we have reviewed, we wanted to produce a system that

1. Offered a more automated system of data entry that is less time-consuming for researchers.
2. Could produce graphs of performance, directly generated from the low-level, note-timing-based information extracted from sound recordings of the musician's performance, reducing the need for mediation (judgement or introspection) from either the player or researcher.
3. Could be extended to provide high-level information such as tempo fluctuation, expressive tempo change, segment length, and performance cues, and thus could aid in identifying practice strategies and expression.
4. Could be used as an entry point for coding other practice behaviours and strategies (such as errors, types of errors, or time used in not playing, beating pulse, nonmusical sounds, etc.)
5. Could be incorporated into and compared with more traditional data collection methods (such as think-aloud and interview) to validate and increase the depth of information.
6. Could provide comparisons of different types of performance, such as a sight read and a final performance (by superimposing two graphs), or of performance of the same piece by several performers.

We named our visualisation technique the 'Note-Time Playing Path' (NTPP; de Graaff & Schubert, 2007), and describe here the technical details of the system by way of an analysis of actual learning and performance of a piece by elite musicians.

Method

Participant

In describing the NTPP, we will initially use real data from sight-read, practice, and performance sessions by an elite oboe player who regularly performs as an orchestral principal, broadcasts for radio, and records as a recitalist and concerto soloist. The code name we used for this musician was Bob. The task assigned him was to prepare to the best of his ability (within an 8-min time limit) the set piece for performance. Once we describe the basic technique of creating an NTPP, we will compare Bob's playing with

that of another elite musician, a bassoonist with the code name Boris, to address Aim 6 above (comparing NTPPs of different performances and different players).

Musical material and procedure

The musical material had to be technically challenging and short enough to allow a complete practice preparation to enable potentially errorless playing. The selection of music used to exemplify the NTPP was from *Glass Bury Documents*, by Australian composer Moya Henderson (Fig. 3). Henderson's note patterns in this excerpt are mostly demisemiquavers (32nd notes) and use enharmonic material with unusual intervals. The piece places even elite performers well out of their comfort zones (Ericsson & Delaney, 1999) and therefore provides the potential for errors that may be interesting to analyse on an NTPP. The piece is not repetitive and deliberately undermines expectations of pitch direction (Narmour, 1990; Schellenberg, 1997). The upper range required of the performer is extreme. In addition, the phrases are slurred against the beam groupings of each beat, requiring both an unusually uncomfortable articulation and irregular accents (see Fig. 3).

The musician was instructed to play the piece as a sight read (playing the unfamiliar piece without preparation and without stopping to make corrections, etc.), followed by 8 min of practice in which he could do as he wished. Finally, the musician was asked to play the piece one final time, as though for a performance.

Technical apparatus and procedure

A Sony ECM-MS957 microphone recorded the performance directly into a Canon MV830i digital video camera. Video data, not used directly for the NTPP, were imported into iMovie HD [Version 6.0.3 (267.2), Apple Computer, Cupertino, CA]. Sound recordings were extracted from the audio track of iMovie. After editing, the audio file was analysed by the note recognition software Melodyne 3 Cre8 (Celemony, Muenchen, Germany; Neubaeker, Kreutzkamp, & Granzow, 2007). The data processed by Melodyne were exported as a MIDI event list (referred to as the *Raw MIDI Event List*). This list was then pasted into a Microsoft Excel spreadsheet for preparation and plotting. A separate score-generated output (deadpan, without expression) was produced by entering the music score into Sibelius (Version 4; Sibelius Software Ltd) and exporting it as a MIDI file, which was then also converted to a MIDI event list (the *Quantised MIDI Event List*). The played (raw) and score (quantised) generated event lists were plotted against one another to produce the NTPP in a spreadsheet (Microsoft Excel). This process consisted of three steps, as summar-

Glass Bury Documents no. 1

Moya Henderson

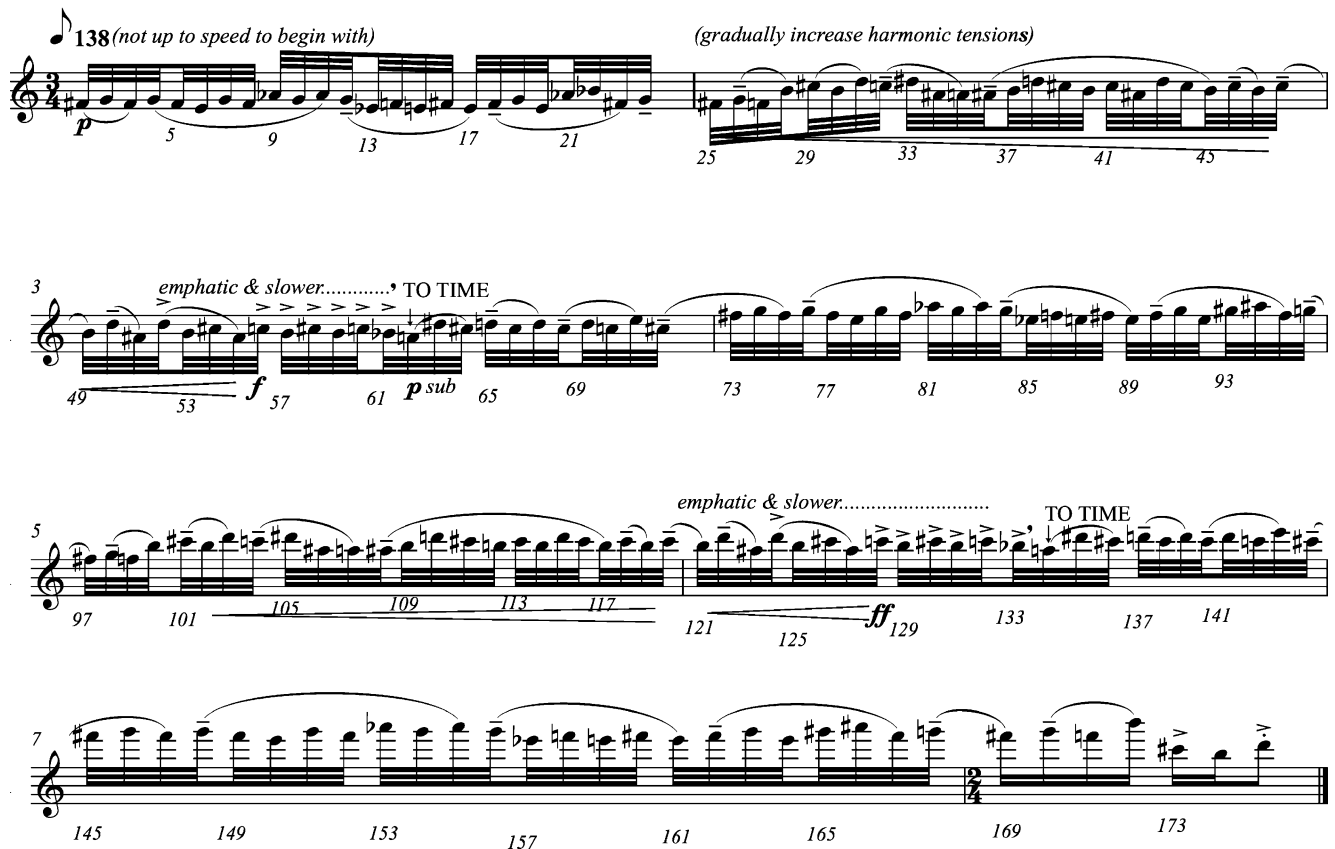


Fig. 3 The excerpt from Moya Henderson’s Glass Bury Documents No. 1, used for the study. Numbers below staff indicate note number (n)

used in the flow chart (Fig. 4) and described in detail below in the context of the example using the elite musician.

Step 1 *Create sound recording.* The elite oboe player was instructed to sight read the music score material,

Step 2 *Extract list of note onset times.* Melodyne Cre8 software was used to recognise acoustic instrument sounds and convert them to a sequence of note events. The sound file was imported without tempo or pitch correction (that is, raw, without quantising). A sample of the Melodyne interface after a conversion process is shown in Fig. 5. Once the audio track was converted by Melodyne, it was exported as a MIDI event list.

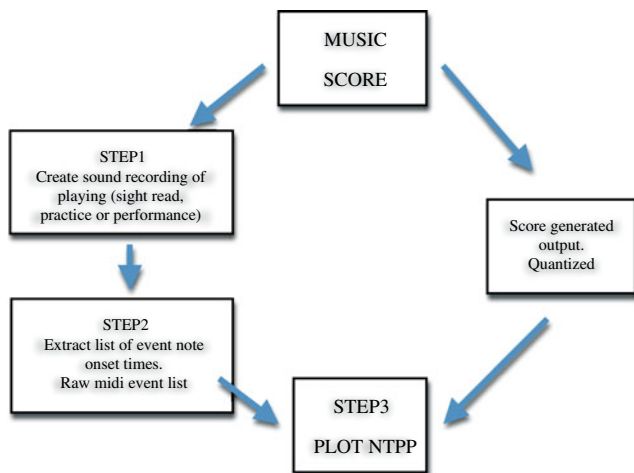


Fig. 4 Steps for producing a note-time playing path from a performance of a music score

practise it for 8 min, then perform the piece. A sound recording was made of the three sessions: sight read, practice, and final performance.

In the event list, each event was numbered according to the sequence of note numbers in the score (see ‘Event Number’, column 3 of Fig. 6). The software recognition of real instruments is prone to occasional inaccuracies, and it was necessary to carefully check the audio recording against the event list. In some situations, the octaves would be ‘misheard’, or harmonic disturbances, reed noises, or pencil sounds were interpreted by the programme as incorrect pitches.

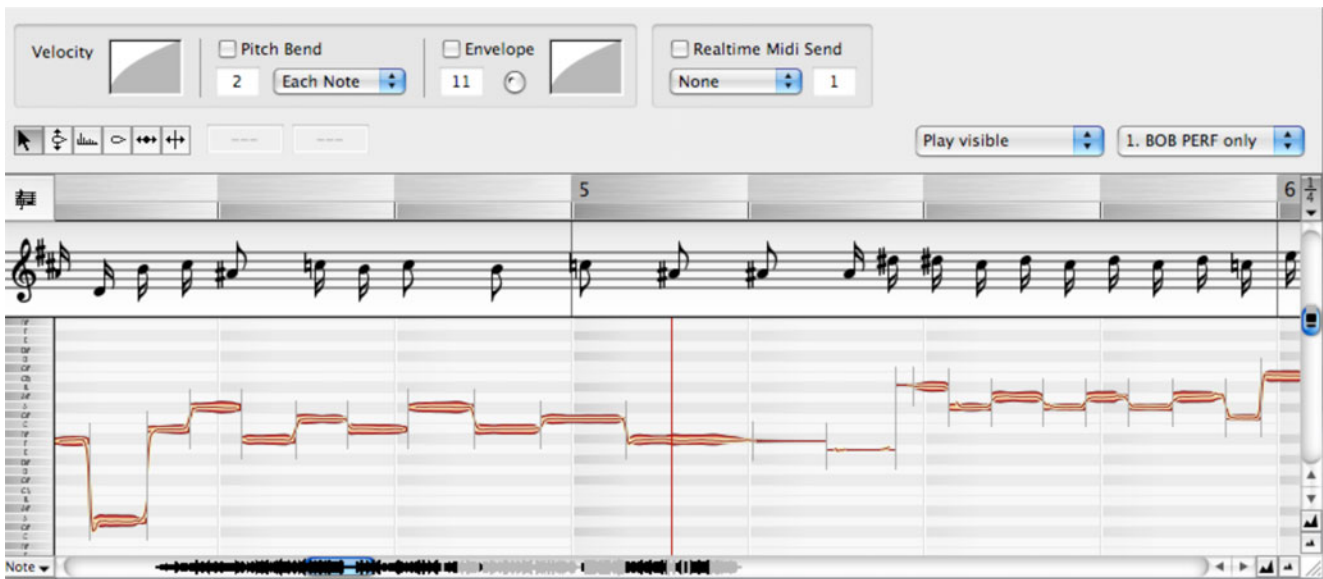


Fig. 5 Sample screen of Melodyne audio-to-MIDI conversion software interface

These were corrected or deleted, as required. A note that was played but not part of the original score, or a note that was missing from the score, was identified and labelled as an error (see ‘Error’, column 4 of Fig. 6).

The raw notes played in the audio recording of the sight-read and performance renditions were recognised ‘instantly’ by the software and could be tagged with corresponding, consecutive event numbers with relative ease on the spreadsheet. Coding for errors in the sight read and the performance took more time, as these needed to be checked against their location in the score on a note-by-note basis and therefore entered manually.

Coding of the practice session was more complicated and also had to be manually tagged. This tagging had to be done in such a way that played notes (raw) remained more or less correctly aligned with the score (quantised) version. Correcting played notes, not aligned with the score, was not a time-consuming process. In the practice session, however, each note had to be located by ear, with the event number of the corresponding location in the score inserted. Repeating event numbers, errors, segment locations, and other practice behaviours were then coded on the spreadsheet. This was a time-consuming process. For this sample of Bob practising, the estimated time of coding was 4 h. Coding also varied greatly in time, depending on the behaviour during practice of different participants.

We defined an error as a note produced by a performer in an unintended way, according to the musical score. In the current version of the NTPP, intonation is not assessed (suggesting a pitch error of ± 0.5 semitones). Out-of-tune notes are not reported as errors. Reporting of intonation deviations will be an area for future development (see, e.g., Gunawan & Schubert, 2010). The tagging of errors could be done in several ways. One method of error tagging, shown in Fig. 6 as Event 27, labels the error with the same number of the actual intended note from the score, but moved into the rightmost error column. The other method tags an erroneously inserted additional note after Event 14. The additional note played by the performer occupies a separate row and is reported as Event 14.1 in the Error column.

In parallel with Step 2 (see Fig. 4), the score-generated output was created to produce a list of ‘mechanically’ generated (quantised) note timings. The event list produced by this process was in the same format as the event list of the played (raw) session exemplified in Fig. 6, but without an error code column.

Step 3 Plot NTPP. At this step, we had two sets of event lists: the raw list from the player’s actual recorded performance and the quantised score-generated output. The score-generated output onset timings formed the horizontal-axis values, and the player’s event list onset timings formed the vertical-axis values. The numbering system for the horizontal axis needed to indicate the proportional length of

Recording time of note onset [HH:MM:SS]	Pitch [As recognised by audio to MIDI software]	Event Number	Error
`11:57:02.681	F# 3	1	
`11:57:02.863	G3	2	
`11:57:03.062	F# 3	3	
`11:57:03.245	G3	4	
`11:57:03.416	F# 3	5	
`11:57:03.547	E3	6	
`11:57:03.713	G3	7	
`11:57:03.861	F# 3	8	
`11:57:04.016	G# 3	9	
`11:57:04.164	G3	10	
`11:57:04.352	G# 3	11	
`11:57:04.490	G3	12	
`11:57:04.656	D# 3	13	
`11:57:04.831	F3	14	
`11:57:04.917	D# 3		14. 1
`11:57:05.087	E3	15	
`11:57:05.232	F# 3	16	
`11:57:05.393	E3	17	
`11:57:05.568	F# 3	18	
`11:57:05.783	G3	19	
`11:57:05.910	E3	20	
`11:57:06.076	G# 3	21	
`11:57:06.291	A# 3	22	
`11:57:06.441	F# 3	23	
`11:57:06.613	G3	24	
`11:57:06.822	F# 3	25	
`11:57:07.094	G3	26	
`11:57:07.293	F# 3		27
`11:57:07.452	B3	28	

Fig. 6 MIDI event list of ‘raw’ playing data, showing time of each note onset in column 1, the software-recognised pitch (column 2), the note event number (corresponding to note number in the music score) in column 3, and nearest event number where an error was identified (column 4). The first 28 recognised notes are shown for the Henderson piece as played by Bob in his sight-read session

notes according to the music score. We therefore numbered this axis by the pulse number elapsed, n , in units of ‘pulses from the beginning of the piece’. A pulse was defined as the shortest musical duration unit of the piece in question. For the piece by Henderson, the shortest duration was the demisemiquaver (32nd note), meaning that each numerical increment along the horizontal axis represented one demisemiquaver increment in the

score. A crotchet (quarter note) would therefore occupy eight consecutive pulses on the horizontal axis. By using pulse number, the NTPP is able to be generated for music that is highly rhythmically complex. It is worth noting that this piece consists of nearly all demisemiquavers, making the pulse number generally aligned with the note number. We produced the plots using the scatterplot chart option in Microsoft Excel. (A copy of the template spreadsheet is available at the UNSW Empirical Musicology Web site, <http://empa.arts.unsw.edu.au/research-and-creative-practice/research-projects/empirical-musicology/>.)

Results

General principles of the NTPP







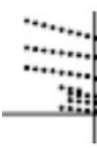
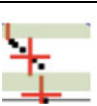
Some general shapes of the NTPP can be treated as categories to aid in the analysis of the playing. A diagonal, descending line to the right indicates a mechanical, deadpan performance—accurate but possibly expressionless. Various alternative curve shapes are indicative of speeding up and slowing down, with steep (large negative gradient) lines or curves indicating a slow or slowing tempo, and shallow lines or curves indicating a fast or speeding-up tempo. Finally, vertical gaps in the NTPP are indicative of no playing, where the player may be performing other tasks, such as writing on the music, thinking, resting, and so forth. A summary of these categories (taken from the NTPP examples in this article) is provided in Fig. 7.

Description of performance using NTPP

What follows is an explanation of the NTPPs used to examine the sight-read, performance, and practice behaviour of the elite musician Bob. References to timings are made in units of seconds for convenience and ease of reading; however, the resolution of the software for detecting onsets is in the order of tens of milliseconds.

The sight-reading section (Fig. 8a) shows the demisemiquaver notes played in sequence as per the music score. Pitch errors are marked with a crosshair and can be identified over the course of the sight read (e.g., at n [pulse number] = 66 pulses elapsed, t [player time] = 13 s). Tempo variation within the sight-read session can be identified on the graph. A gradual increase in negative gradient indicates some slowing down (at circles A and B, Fig. 8a). When the performer slows down at any point within the sight read, the graph curves downward more steeply (particularly at circle C, from $n = 158$, $t = 43$, to $n = 180$, $t = 54$). Conversely, the graph straightens out, with a lower negative

Fig. 7 An aid to interpreting small sections and patterns identified along the NTPP. Note that the horizontal axis is note number, increasing to the right, and time is unfolding down the page, vertically (see Fig. 8). Note also that it is not possible for a line to move upward from left to right because time is one-directional

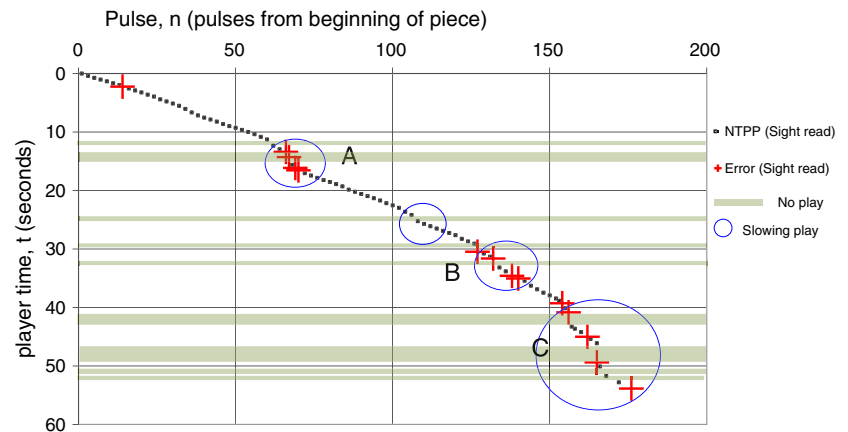
<i>Shape</i>	<i>Description of shape</i>	<i>Interpretation</i>
	Straight, diagonal line from top left to bottom right.	Playing at a precise, steady tempo, without error, without expressive variation in tempo.
	Straight line, with crosshair and with slight downward curve.	Playing at an even tempo from the start of the piece, with slight <i>rall</i> towards end of illustrated section. The example shown contains an error (at centre of the crosshair).
	Straight, shallow line. Vertical line is a time division marker.	Fast playing: More notes are being played in time, and at a steady tempo.
	Line curving downwards.	Slowing play: Gaps in the line indicate fewer notes played over time.
	Gentle, curved drop; followed by two short dashes below each other, to the right light, horizontal line is a grid	<i>Ritardando</i> : Gradually fewer notes are played over time in the top, longer segment. The two segments below have fewer notes and some overlap with the end of the long segment.
	Slight flattening curve	<i>Accelerando</i> : Gradually more notes played over time
	Lines go from steep to more straight	Each even tempo repetition of each segment is played faster. The top (first) 3 segments each contain more notes than each of the following four segments. This suggests a more focussed practice on a difficult passage consisting of a few notes as time unfolds.
	Vertical gap	No-play – shown as shaded horizontal bands. The centre point of the crosshairs indicate pitch errors.

gradient, when any speeding up occurs (e.g., at $n = 74$, $t = 17$). Circle C also shows increased time occurring between each note onset and that periods of no play occur more frequently towards the end of this difficult piece (e.g., shaded band of no play from $t = 47$ to $t = 49$ in Fig. 8a). Here, the music score and recorded performance ascend in pitch into the altissimo register and required difficult chromatic and awkward fingering. Perhaps the effort in

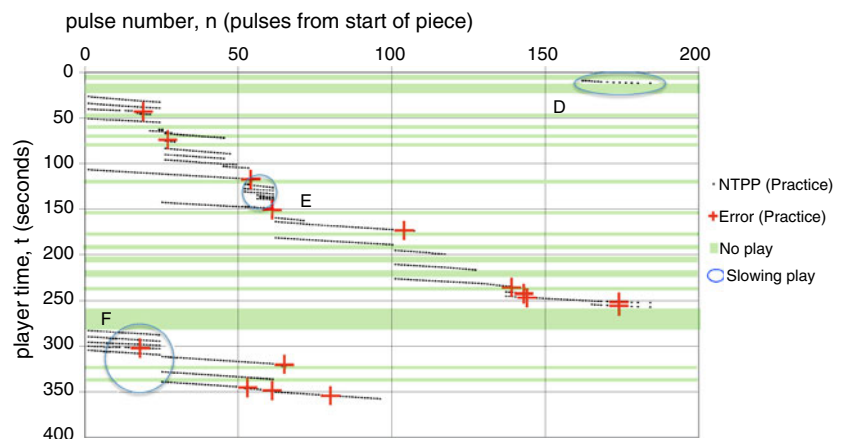
high cognitive demands necessitated the visible tempo variation, or slowing down. In interviews with the performer immediately following the playing, it was confirmed that these tempo alterations were some of the strategies used to process the musical material in the most careful manner. They were acknowledged by the performer as an attempt to sight read with the most accuracy. This provided an example of how our approach satisfies Aim 5.

Fig. 8 Note-time playing paths of an elite oboist (Bob) (a) sight reading, (b) practising within an 8-min time limit, and then (c) performing the same section of a highly challenging composition by Moya Henderson (Fig. 3). Each note in the work is measured against a demisemi-quaver pulse (x-axis), numbered consecutively. Red cross hairs indicate pitch errors. Blue circles indicate sections of slowing in tempo. Pale green horizontal shading indicates periods of no play referred to in the text

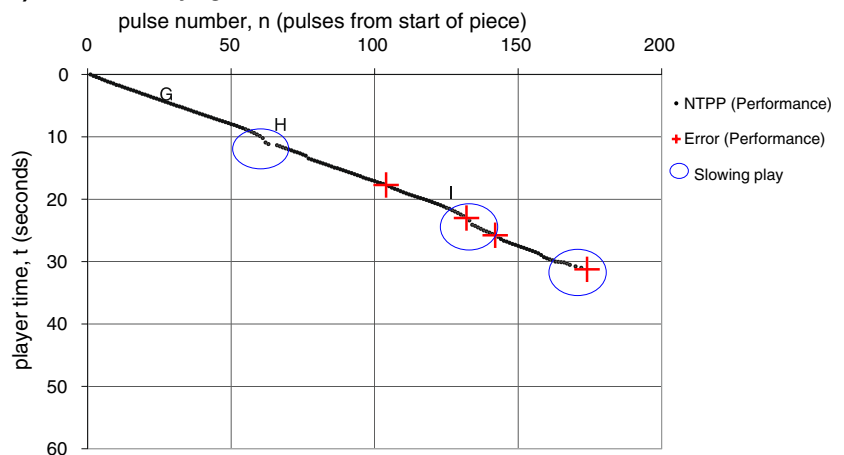
a) Note Time Playing Path -Bob's Sight read of Henderson



b) Note Time Playing Path - Bob's Practice of Henderson



c) Note Time Playing Path - Bob's Performance of Henderson



The NTPP practice graph (Fig. 8b) looks strikingly different from both the NTPP sight-read (Fig. 8a) and performance (Fig. 8c) graphs in three general ways: (1) The lines of the practice are shorter and broken rather than the continuous flow of the sight read and performance. These shorter lines in the practice session show that the note

segment lengths vary. (2) There are many repetitions of material in the practice, in immediate contrast with the continuous-line paths of the sight read and performance. (3) Segments in the practice are usually played in a fairly even tempo (similar gradient), except for some repetitions of note segments, whereas in the sight read the tempo fluctuates

with the difficulty of the passage. (4) Although segments are usually practised by the performer in sequential order, exceptions occur at D (Fig. 8b) and before and after E (Figs. 8b and 9) where notes are retraced; there are many more periods of (shaded) no play and more time spent in no-play in the practice session, compared with small silent gaps of no play as the musician slows in the sight read and performance.

In the practice session, small segments of notes are retraced repeatedly and are repeated two times or more (e.g., E and F in Fig. 8b). When practice finishes and starts repeatedly at these particular segments, they can be seen to indicate the possible building of performance cues {e.g. Chaffin, Demos & Crawford, 2009a; Chaffin, Demos & Crawford, 2009b}. These note segments are expanded by the performer to include larger note groupings ($n = 20 - 45$ over $t = 65 - 106$, just before E in Fig. 8b), and then used to join the work as a whole ($n = 1 - 55$ over $t = 107 - 117$). The smallest segments in the graph illustrate the isolation of individual interval groups (e.g., near E from $n = 59 - 61$ over $t = 139 - 139.6$) and enable identification of the segmented treatment of problem passages. D in Fig. 8b ($n = 160 - 183$) shows the player's immediate preoccupation with the most difficult section toward the end of the piece. This section is practised twice more later in the practice session (at $t = 250$).

Tempo variation can be identified in the practice process by observing the different gradients of the NTPP. Some repeats are played at varying tempi, such as section E ($n = 54 - 61$ over $t = 117 - 133$), where the first play of the note segment is slower (shown by a steeper negative gradient), the second played faster, (shown by a more horizontal gradient), and the third played moderately again (a return to the steeper negative gradient). This is more easily viewed when the graph is magnified into region E, as shown in Fig. 9.

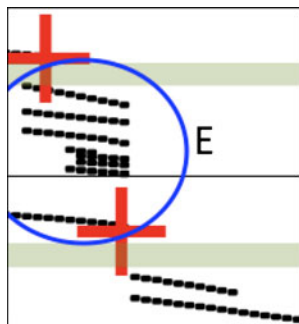


Fig. 9 A magnified view of a region in a blue circle, E (Fig. 8b), where the top 'line' of note pulses is played slower. The second 'line' of note pulses is increased in tempo, and the third 'line' returns to the slightly slower tempo. Time is unfolding down the vertical axis and note (pulse) along the horizontal axis. See the text and Fig. 8 for more information

While fragmenting the piece into learnable segments for repetition, the player may be already building performance cues of the kind Chaffin and colleagues suggest (Chaffin et al., 2009b, 2010). Longer repeated segments show the player working through the piece to join the segments and are visible on the graph of the practice session below E (from $n = 62$, $t = 163$, through to $n = 184$, $t = 252$) and at the very end of the practice, at F (from $n = 1$, $t = 305$, through to $n = 95$, $t = 357$).

At the top of Fig. 8b, just above D is a silent no-play practice period of light shading (from $t = 1$ to 9) and another immediately after (from $t = 11$ to 26). Several no-play periods occur in the practice session. These were shown to be where the participant took time to write notes and mark fingerings in pencil upon the score (e.g., from $t = 174$ to 181). The sounds of the pencil are clearly heard on the audio and were picked up as arbitrary notes by the audio-to-MIDI conversion software, thus acting as an auditory marker of the nonplaying activity. Another significantly large no-play period occurs from $t = 257$ to 282 (marked at F). In this way, various practising strategies can be identified on the graph (repetition, tempo variation, no play, segmenting), as per Aim 4. Evidently, these periods of no play were highly cognitively active problem-solving periods and focussed on particular issues presented by the musical score. The NTPP allows visualization of these no-play periods. Similarly, the location in the score of the player's silent preoccupation is identifiable, because these are the notes usually played straight after the no-play period.

For example, it is interesting to observe that after the silent no-play, Bob immediately started practising (near D, Fig. 8b from $n = 162$, $t = 9$, to $n = 180$, $t = 11$) with the final altissimo section of notes from the score that had caused such problems during the sight read (Fig. 8a from $n = 162$ to 180). He then takes a large no-play period ($t = 11 - 27$) to plan a solution. At this point on the NTPP, it is possible to identify some of the practising techniques used by the participant in this most difficult section of the score and later at $t = 250$ by examining the (nonplaying) activities in the audio, video, and think-aloud data. It could be concluded that as these notes comprised the first section practised, the performer gave them priority in the limited time available. In his practice, this participant immediately transposed this particular passage down an octave. In later interviews with the participant, this section was also discussed.

This practice approach led to a more accurate (yet partially transposed) performance (as shown in Fig. 8c). The final performance demonstrates markedly improved playing when compared with the initial sight read. In Fig. 8a and c, the sight read and performance are displayed at the same scale to allow visual inspection of gradient

(tempo changes) of the performance. The two playing paths illustrate that the length of time taken for the performance was shorter in the final performance (total time of 31 s, scanning down the vertical axis) than in the initial sight read (total time of 54 s). The steadier line (Fig. 8c) indicates that the tempo was more stable and, after a reasonably successful 8 min of practice by the elite performer, there were only six pitch errors (crosshairs, some not visible in Fig. 8c due to overlapping at the magnification shown) in the final performance after practising, compared with 14 in the prior sight read. The performance session also shows more expressive, controlled tempo variation (illustrated with the circled sections in each graph at H and I). The score required the performer to *rallentando*, to return ‘TO TIME’, and two specific breathing spots were indicated. The slight *ritardandi* requested on the score before each breath can be identified as slight dips in the NTPP (at $n = 61$, $t = 10$, and $n = 133$, $t = 23$).

Given the utility of comparing performances in such a way, we now turn to a further application of the NTPP to allow direct graphical comparisons of two playing sessions (Figs. 10 and 11).

Comparing playings

1. *NTPP comparison of the sight read and performance.* Another feature of the NTPP method is that ‘before’ and ‘after’ data from the same performer, such as sight read and performance sessions, may be combined on one graph, allowing immediate visual comparison. An example combining and superimposing data from Bob’s sight read and practice is shown in Fig. 10. Immediate comparison between the number of errors in

the sight read and the improved postpractice performance is possible. The sight-read tempo is similar to tempo in the performance in the note pulses from $n = 1$ to 140, although the sight-read graph line has more of a wobble, indicating more fluctuation in tempo/pulse. From pulse $n = 140$ many errors accumulate, and the green-dotted sight-read line separates dramatically from the brown performance line. Playing slows down in the sight-read session, and there are numerous no-play periods (shown as gaps in the blue circled ‘Slowing play’ section L in Fig. 10). As mentioned, the final performance is faster than the sight read, demonstrating a more stable tempo throughout (even gradient), has fewer errors, and is more musically observing the required *ritardandi* and nuances of the score (slowing play is shown at J and K in Fig. 10).

2. *NTPP comparison of different performers.* Similarly, contrasting data between different performers is possible using the NTPP method. Figure 11 shows a sight read of the same musical material by two different players: Bob (whose playing we have been discussing so far) and a newly recruited elite bassoon player code named Boris (who performed identical tasks to Bob).

Bob the oboist (lower dotted line), played at a slower tempo with fewer errors and observed the musical *ralls* at pulses $n = 60$ and $n = 133$. His performance slows towards the higher, more difficult ending of the piece (towards the bottom right of the NTPP plot), has periods of no play, and shows a concern with pitch accuracy upon first reading of the material. Boris the bassoonist (upper line), plays much faster with a less wobbly (i.e., more even) tempo that he is

Fig. 10 Combined NTPPs of the same performer, Bob, showing his sight read and his after-practice performance of the same piece of music. The dotted green line is his sight read, and the brown line is his final performance after a short period of practice. The NTPPs show how direct comparisons can be made between the two renditions. The steadier tempo of the performance, fewer errors, and observance of the required *rallentandi* (locations J and K) can all be observed in comparison with the sight read. The sight read deteriorates after pulse $n = 140$, with many more errors and much slowing of play (blue circle at L)

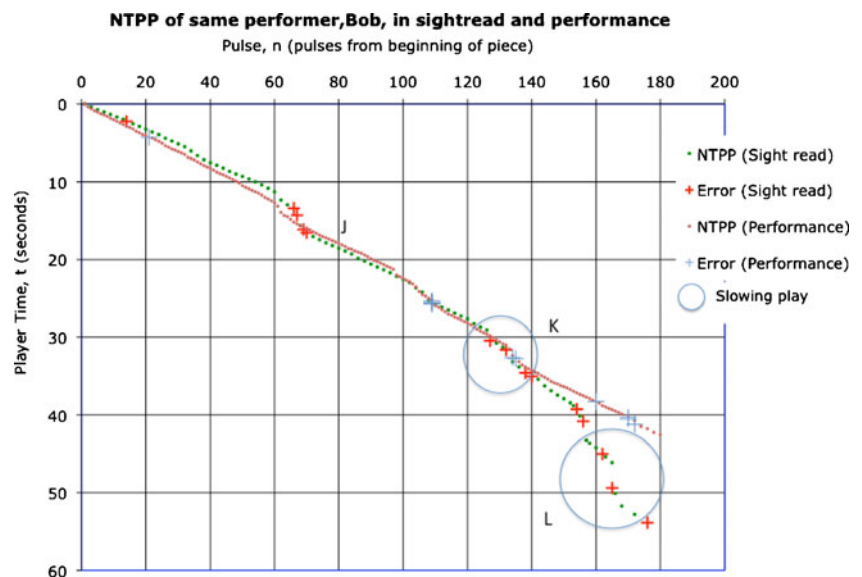
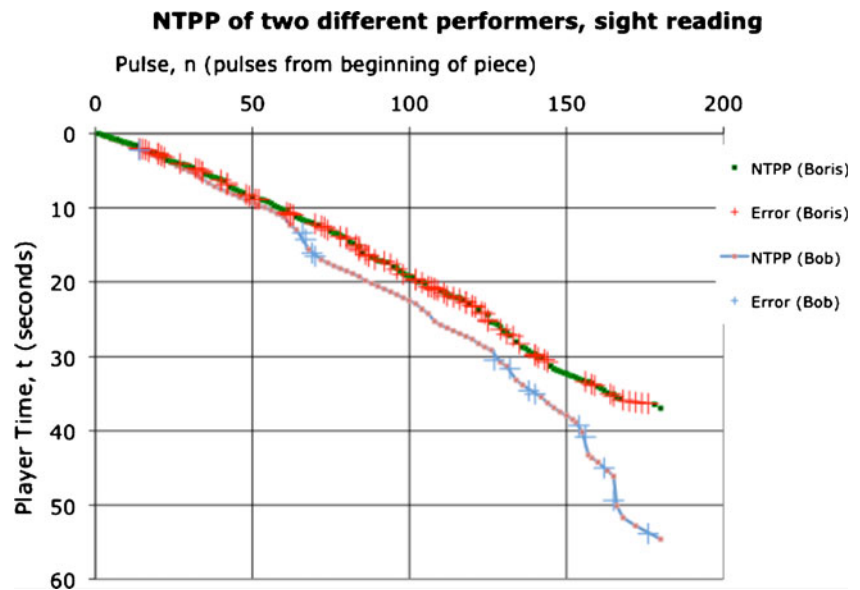


Fig. 11 Superimposed NTPPs of two different players, Boris and Bob, showing sight reading of the same musical material. One player attempts to maintain tempo, the other is more accurate, but at a slower and more variable speed.



attempting to maintain. Consequently, Boris observes fewer nuances in his sight read and plays many more pitch errors by including many additional notes. A pitch–tempo trade-off is evident in the comparison of these two players’ sight reading of the same piece.

Despite two quite different strategies in the two players’ sight reads, the error tallies are similar when the *performance* sessions of the two elite players are compared (Fig. 12). Both players maintain even tempi of their chosen performance speed (although at two different tempi from each other—Bob plays faster than Boris); both observe nuances required in the score (dips in the NTPP lines at $n = 60$ and $n = 133$ - compare with the score in Fig. 3). Interestingly, some errors occur in similar areas of the score for both performers, highlighting the areas of greatest difficulty.

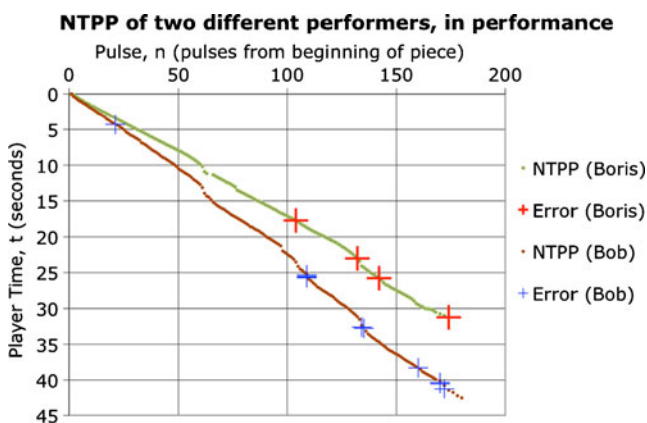


Fig. 12 Superimposed NTPPs of two different players, Boris and Bob, in performance after the practice period. Similar postpractice results can be observed, despite very different sight-read strategies.

Discussion

The Note-Time Playing Path provides a new way of visualising performance data of a musician that can help researchers better understand the behavioural and cognitive strategies used in performance, without relying solely on self-report techniques. As such, it is an enhancement of the techniques of Miklaszewski and Chaffin and colleagues that we reviewed above. The key differences are that the NTPP allows analysis of sound recordings of the performance and provides note-by-note information unfolding in time. The most important distinguishing features are that the NTPP uses low-level (note-timing) information taken directly from the audio recording of the playing sessions and that both playing and nonplaying periods are plotted. The subsequent shapes and gaps in the NTPP plot provide a visual interface allowing identification of higher-level features and behaviours, such as tempo changes, practice strategies (e.g., chunking of segments), and periods of no play where other musically relevant problem-solving cognitive activity may be taking place.

In addition to the identification and plotting of errors, we can directly compare playing of the same work at different times by the same performer by superimposing different sessions (such as sight read and performance) and also directly compare two or more performers playing the same work. Like SYMP and Miklaszewski’s graphic practice analysis, the method can also be used to report features such as segment length and practice strategies, but it also provides a visual representation of tempo fluctuations and periods of nonplaying, and allows for examination of error locations in the piece—both with respect to the score and to the (clock) time at which the error was made. Revised

versions of the NTPP are being developed that will be able to represent performances of rhythmically more complex pieces, where score-indicated gaps between consecutive note onsets are not isochronous. One way of displaying events is to present the score-predicted timings (on the *y*-axis) as a percentage of time elapsed from the beginning of the piece. This approach allows easy interfacing of the MIDI output while retaining interpretability.

Using the NTPP, one can compare the various regularities and idiosyncrasies of performances with performance outcomes, so that highly specific underlying practice strategies, leading to effective performance strategies, may then be identified. Comparisons can be made between players of different levels of expertise. Graphs generated can be used to identify tempo fluctuation and stability, with slower or faster tempi and less or more accuracy (Fig. 8a and c, and more directly Fig. 10, provide ‘before’ and ‘after’ examples of such a comparison, made by the same player under different conditions). Figures 10, 11, and 12 illustrate how NTPP graphs can show direct comparisons between different playing sessions by the same player or by different players on one graph.

The Note-Time Playing Path may also be useful for investigating tempo expression. We have compared the played notes with the score-generated output. Fluctuations from a straight diagonal line in the NTPP may thus be indicative of expressive timing variations, in addition to tempo regulation for the purpose of practice. Although pitch and tempo analyses were the main focus of the present examples—because the musical example used lent itself to such analysis—the NTPP can also be used to represent other kinds of parameters, such as rhythm errors.

Conclusions

In the research reported here, we have developed a technique that can provide new insights into music performance through visual inspection of low-level note timings taken directly from a sound recording of a playing musician. Recordings of elite musicians were used under three conditions (sight read, practice, and performance) of a short, difficult piece of music. We described how we developed our technique and gave the results of analyses of the musicians as examples of possible applications of the new tool. We couched this in terms of six explicit aims of the study; here, we report the conclusions related to each of these aims.

1. The NTPP method described here offers a semiautomated approach to analysing performance. However, some elements of this method, such as error coding, are time consuming, and further work is required to increase the degree to which the sound-recording-to-NTPP plotting can be more fully automated.
2. Recent advances in audio-to-MIDI conversion have allowed fast and high-precision conversion of note timings and pitches to be identified. The present NTPP application demonstrates that this technology can be adapted to provide new insights into understanding music performance. Specifically, graphs of performance, generated from the coding of low-level note timings extracted from actual sound recordings, provide a highly objective approach that requires no mediation from either player or researcher.
3. The emergent visualisation from the low-level features enables investigation of high-level musical information such as segmenting during practice sessions and tempo fluctuations. We found that our approach also complements the high-level performance cue identification found in Chaffin’s SYMP system.
4. Note-Time Playing Paths provide an entry point for other coding systems. In the present application of the NTPP, we were able to incorporate pitch errors that were played to provide a more detailed understanding of playing behaviours. However, the criterion for error coding needs to be specified and further developed, because the present version of the NTPP makes a rather general assumption of what constitutes a pitch error (± 0.5 of a semitone), which is a limitation of the audio-to-MIDI software used. Future work will allow microtonal and intonation issues to be captured by the system and processed as required. There is much potential in further expanding the system to identify and analyse other aspects of music performance of research interest.
5. Data obtained in our study are comparable to other traditional techniques of analysis. In the examples presented, we reported some interview data collected from the musicians to better understand some aspects of the NTPP that were ambiguous or not immediately clear. For example, in periods of no play (discussed in reference to the practice session shown in Fig. 8b), we were able to use interview data to examine whether or not that was a period of on-task thinking. We therefore propose that it would be ideal to use both more objective tools, such as the NTPP, and more introspective, self-report approaches found in more conventional analyses of music performance.
6. The NTPP lent itself to comparisons of compatible playing (such as two performances by different players or a sight read and a performance by the same player). The overlaying of two (or more) NTPPs provides vast potential for comparing how an individual learns and how individuals differ from one another in music performance and practice.

In this article, we have demonstrated that the NTPP provides an objective technique for practice and performance research. The data presented here demonstrated how strategies used by a performer were observed without any self-reported interpretations. Using audio analysis technology to collect precise data and then presenting these in a visually detailed way have allowed us to make comparisons within performances, between performances, and between performers themselves. The combination of the Note-Time Playing Path analysis with such traditional research techniques as video coding, interview, and think-alouds will provide new potential for a richer combination of data. This technique is already being harnessed for research into music performance and practice, and it should provide important new information for the study of music education and psychology.

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