This paper presents a developing Pitch Error Coding Protocol for assessing the accuracy of a musician’s performance. The protocol organized performance errors into any of three main categories, each based on an established cognitive theory of music memory and processing: (1) the Serial Distance Hypothesis (SDH); (2) the Implication Realization (I-R) model; and (3) the mental organizing principle of the Schema Theory (SCH). An elite oboist formed the basis of a detailed case study where his sight reading, practice, and performance of a challenging excerpt of music were examined. These data were used to: 1) investigate the protocol; 2) ask whether any protocol components could explain errors better than others; 3) and show where improvements after practice occurred. The results revealed that the SDH accounted for the majority of pitch errors, these originated in a three-note proximity of the target and some SDH errors overlapped with the I-R category errors. Although final counts for SDH and I-R are similar, SDH uniquely identified errors more frequently than the I-R. Future research and development of the protocol might look at combinations of pieces and performer to determine whether SDH may be a dominant source of error.

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Key words: practice, instrumental music performance, score reading, performance analysis, error analysis

Music Perception, volume 34, issue 2, pp. 132–151, ISSN 0730-7829, electronic ISSN 1533-8312. © 2016 by the Regents of the University of California all rights reserved. Please direct all requests for permission to photocopy or reproduce article content through the University of California Press’s Reprints and Permissions web page, http://www.ucpress.edu/journals.php?p=reprints. DOI: 10.1525/mp.2016.34.2.132
case study through the analysis of playing by an elite musician. Valuable precedents exist in this area of research and this paper now focuses on the music psychology literature specifically relevant to pitch error coding by Palmer and van de Sande (1993, 1995), Narmour (1990), Schellenberg (1996, 1997), Bharucha (1987, 2008), and Curtis and Bharucha (2009). The categories of pitch errors that we abstract from this literature are the Serial Distance Hypothesis, Implication-Realization Model, and Schema Theory.

Pitch Error Analysis

SERIAL DISTANCE HYPOTHESIS (SDH)
According to Palmer and van de Sande (1995), by looking directly at the data generated from an event, distinct conclusions can be drawn about the way the performer mentally organizes musical material. By measuring the distance between the location of an error against other events in the music, they found that both the structural boundaries (such as bar lines, phrase groupings, and harmonic cadences) and the structural content of musical events influenced the range of planning in music. For example, they found that most pitch errors in sight reading could be traced to pitches that existed in the vicinity of the incorrect note, to within three serial notes (on a monophonic instrument) of the source of the error. Palmer also examined which chunks of material are stored, retrieved, and simultaneously held in short term memory during a performance. Palmer and van de Sande (1993) developed a sophisticated error coding system that identified the nature of the error by classifying the different ways the source of the incorrect note could be identified in the serial vicinity of the error (see Figure 1).

At the first basic level, the errors are divided into one of two sources: 1) contextual, and 2) non-contextual errors. Based on a linguistic model of text reading, Palmer and van de Sande’s (1993) contextual errors are derived from within the context of the work. They may be related to the key of the piece in some way, as when an accidental is omitted after being indicated in another part of the same bar, or arpeggiated notes of a chord are mistakenly played in a reversed or jumbled order. During a run of notes, the player may continue in that familiar pattern and “miss” the change of direction. The error may also be influenced by the metric and structural factors. For example, if an error falls on a strong beat, that may also influence the nature of the error.

Non-contextual errors are characteristically not from any immediate source. They tend to occur interspersed throughout the piece and are not related to the score either harmonically, or as “missed/misread” occurring accidentals.

The second level of Palmer and van de Sande’s (1993) coding looks further at the derivations — or influences — that can explain the error. Errors may be placed in

![Pitch Error Coding Scheme for Single-Note Errors](image-url)
between existing notes (addition). One intruding note may be substituted for another (substitution)—this substitution can be contextual (i.e., influenced by previous or future neighbor notes in the score) or non-contextual (i.e., the error may be a random substitution of a note that is completely unrelated in any way to, or influenced by, notes from the score). A “targeted” note (i.e., the note in the score at that point in the sequence) may be shifted to a neighboring location (shift) or it may be just missed out altogether (deletion). With the exception of deletions, all these other contextual errors involve what Palmer and van de Sande call a movement (that is, the note is “moved/taken” from a forward or backward position on the score). Forward errors reflect pre-planning and show the influence of upcoming information. These are most likely to occur before a phrase boundary—as boundaries are significant events. Backward errors reflect a lack of preparation and show the influences of the preceding information. These are more likely to occur after a phrase boundary.

Applying their error coding to investigate the range of planning in music, Palmer and van de Sande (1995) found that it was influenced by two main factors: 1) the structural content of musical events (e.g., rhythmic patterns, musical phrases); and 2) the serial distance between these musical events. Palmer and van de Sande provided valuable information about what performers were thinking as they planned long sequences in musical performances.

Addition, substitution, and shift are all movement errors. Palmer and van de Sande (1995) quote Garrett’s (1980, p. 179) illustration of language processing to demonstrate movement error where a participant might say, “We completely forgot to add the list to the roof” instead of, “We completely forgot to add the roof to the list.” For this type of error to occur it is assumed that elements of the sequence must be accessible at the same time during the planning of the sequence. All the elements are familiar, but it is as if they are all lined up ready to be inserted and one just pops into the wrong place. That is, the attentional resources (Keller, 2001) required to keep the sequence order are subject to interference.

Palmer and van de Sande (1993) then wanted to identify the span of units that can be organized, held in memory and reproduced without error and in the correct serial position. They noted that planning occurred in clusters of less than 8 characters for typists (Shaffer, 1976), or 7-8 events (notes) beyond the location of the current event of the music score (Sloboda, 1974). Therefore they set up two hypotheses about distance and structure.

To test the Serial Distance Hypothesis, Palmer and van de Sande (1993) designed experiments where they varied the entry positions of the different voices in a Bach fugue. They reasoned that if memory buffer contents were structured hierarchically, then phrase changes in the test piece of music should force more errors and timing variation. There would also be an effect between the sections of the music that share the same phrase structure. More errors would be expected if there was only one phrase boundary, as more frequent phrase boundaries help to make planning easier. They expected that error type would be influenced by the nearest phrase boundary: phrase beginnings might have errors performed late while phrase endings might have anticipated errors (performed early).

The Serial Distance Hypothesis assumes that the proximity of a unit (e.g., a note within a stream of units) will influence a player’s planning, in terms of both its serial distance and its direction (i.e., coming before or arriving after the target note). If note movement errors occur (e.g., a shift “spoonerism” such as a dog barking instead of a dog barking) all elements of the sequence must be accessible at the same time during the planning of the sequence. Then as they are all lined up ready to be inserted, one or more elements slip into the wrong place. An SDH error can be assumed if the source of an error (intrusion) could be traced to a serial position from the target note that is temporally adjacent to the target note.

IMPLICATION REALIZATION (I-R) MODEL

Narmour’s (1990) theory of melodic perception and cognition hypothesized that the melodic expectations of listeners reflected innate psychological responses in addition to learned responses. Although Narmour’s (1990) research was primarily about the perception of melody by the listener, we decided to explore if it could be applied to uncover a class of pitch errors that elite musicians make. The Implication-Realization (I-R) Model offers unique insights into melodic expectations that could influence elite participants’ performance.

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1 Similar musical phrases or patterns may be easier to reproduce when reading and learning new musical material. Palmer and van de Sande (1995) stated that the importance of structural content is already evident as performers in music emphasize (harmonic) structure through changes in tone and intensity: “Elements with shared structural features may require less capacity in a memory buffer than structurally unrelated elements” (Palmer & van de Sande 1995, p. 498). Current planned events are more likely to be affected/influenced by sections that share structural features than by sections that do not share structural features. They therefore may be planned concurrently.
errors, particularly for a single line instrument such as a clarinet or oboe. Furthermore, after some exploratory work we decided to limit our investigation of I-R principles to the two broad factors of pitch proximity and pitch reversal, based on the work of Schellenberg (1997).

**Pitch proximity.** Pitch proximity is the principle that listeners perceive close intervals as originating from the same source. Deutsch (1978) also reported more efficient processing of sequences with small intervals than of sequences with large intervals. Schellenberg (1997) asserted that pitch proximity can be seen as a principle of conjunct motion—motion by scale steps in a given mode (Aldwell & Schachter, 1989)—and is relevant to harmonic voice leading as explained by Huron (2001). When a melody moves in leaps, smaller leaps become more expected than larger leaps. There is much evidence of a cross cultural predominance of small intervals in music (see, for example, Carlsen, 1981; Cuddy & Lunney, 1995; Schellenberg, 1996). Cross (2012, p. 53) writes that the principal of proximity describes that notes are "likely to be integrated into the same stream when they are close together in frequency (pitch) and time (duration)."

**Pitch reversal.** Pitch reversal describes the occurrence of listeners expecting a tone after an implicative imperative to be near the second tone and to be proximate in pitch to the tone that preceded the most recently heard note. For example, in a returning-direction three-pitch sequence, after hearing the first two tones (e.g., A4-B4), the listener expects the third pitch to either return to the original note or to return to a pitch very near it, producing a sequence: A4-B4-A4. This example fulfills both pitch proximity and pitch reversal principles.

I-R predicts that after a large interval a reversal in direction is expected. For example, C4-A4 constitutes a large leap, and so a reversal is expected. In combination with the proximity principle, the expected note would therefore be something close to G4 (close to A4, but in the descending direction since it follows a leap). Consider the pitches occurring in a simple even-rhythmic version of *Somewhere Over The Rainbow* (C4-C5-B4) as a realization of this simplified principle.

**SCHEMATAS (SCH)**

The above categories of errors infer that there are essentially innate mental processes that can explain error generation: (1) mental processing due to memory limitations and planning strategy (SDH) and (2) Gestalt principles (I-R). Narmour also considered learned responses, or top-down processing influences, that could reinforce or contradict the innate processing principles. For this reason, we needed to include a category of errors that could explain them. To explicitly investigate the "learned" kind of error, we applied Bharucha and Curtis’s (Bharucha, 2008; Curtis & Bharucha, 2009) ideas on the emergence of mental schemas through exposure to previous musical materials. This allowed our protocol to cover errors that were related to melodic expectancy, but were not otherwise covered by the SDH and I-R principles described above. Boltz's research on melodic structure (1989, 1991, 1995; Boltz & Brown, 2002) showed that familiarity with the tonal system created top-down expectations of pitch. Although the location and tonal function of a note within a melody (e.g., leading tone) was an important influence in this expectation, many of these expectations could be accounted for by exposure and the subsequent emergence of schemas that represent these underlying principles.

Meyer (1956) suggested that many forms of expectation occur swiftly and automatically, and are the result of classical conditioning. To this end Curtis and Bharucha (2009) showed that performers were influenced by recurring structures and used this to organize and process unfamiliar material. Bharucha (1987) stated that the "mind internalizes persistent structural regularities in music and recruits these internalized representations to facilitate subsequent perception" (p. 1).

One form of evidence presented by Curtis and Bharucha (2009) was to show how musical culture shapes the expectations of listeners. The authors compared participants who were culturally familiar with either the Western major mode or culturally unfamiliar with Indian *thaat* Bhairav, showing that the less familiar scale system (with a flattened 2nd and a raised 6th) was more difficult to process. Curtis and Bharucha played a test tone and asked listeners to make a timed judgment about whether the test tone had occurred in the previous series of tones. Their findings suggested that listeners’ internalized cultural knowledge drives musical expectations. A test tone that came from culturally novel material (such as the flattened 2nd would not be as common or "expected" by a musician trained in the Western culture) and was less accurately recognized than notes that were better matched with the familiar major scale.

Expectations in culturally unfamiliar Gamelan music were tested by Stevens, Tardieu, Dunbar-Hall, Best, and Tillmann (2013). Stevens et al. were interested in how "learned" cues from within the same musical piece compared to cues from one’s own musical (familiar) culture in influencing the perception of music. Manipulating the final tone of a phrase, they also manipulated the musical timbre and observed the perception by novice
listeners of the unfamiliar timbres and scale systems. They found evidence of within-session statistical learning. Listener expectations (for the initially novel materials) developed during the course of the experiment. This was in concert with Curtis and Bharucha’s (2009) finding that recurring structures encouraged the organizing and processing of unfamiliar material. Stevens et al. found that both the previously unfamiliar timbres and the proximal cues (occurring within the same sequence and over the experimental session) influenced perception of melodies from other cultural systems. Errors, therefore, could be formed by what Narmour (1990) refers to as “extraopus” intrusions that produce learned, possibly stereotyped patterns that are in conflict with the planned execution.

From a cognitive, theoretical perspective the three classes of errors were considered an adequate starting point for our interest in developing a protocol for explaining errors that musicians make.

**CASE STUDY APPLYING THE PITCH ERROR CODING PROTOCOL**

The purpose of our study was to apply the Pitch Error Coding Protocol introduced above through a case study of an elite musician. By identifying errors during the Sight Read, Practice, and Performance stages of a challenging music-performance task and applying aspects of established theories on the cognitive processing of music, we intended to go beyond the self-report and behavioral observation approaches to studying music performance learning.

**Method**

**PARTICIPANT**

One musician took part in this study. The musician was a 40-year-old oboist (with 28 years of study on the instrument) who was at the peak of an elite level career and in demand as an international soloist and chamber musician, as well as serving as principal orchestral musician of a major, national orchestra. The participant spent considerable time performing, recording, and touring. The performer also had extensive teaching experience and was, at the time of data collection (and before and after), on the faculty of a prestigious conservatory as an instrumental teacher. The identity of the oboist is not revealed due to ethical obligations and in this study the pronoun is not gender specific. We used the pseudonym ‘Bob’ when referring to the performer. While a single case study has obvious limitations, it is also important to note that finding elite musicians to do research of this nature presents several difficulties, including availability of the musician and the large amount of data that a single musician can produce. Given the exploratory nature of the protocol and the very high standard of the musician selected, the case study approach is an important step for this kind of research.

**MUSICAL MATERIALS**

A musical excerpt (shown later in Figure 8 and Figure 10 and hereafter referred to as Henderson) was selected to challenge the elite performer’s specific skills of Sight Read, Practice, and Performance to “provoke” pitch error, and to push the player beyond their comfort zone. The excerpt was taken from a larger solo work by one of Australia’s leading composers, Moya Henderson (2000), and in the experiment it was confirmed by the participant that they had never seen the music before. The notation presented many changes in pitch direction and the excerpt travels over an extreme range of pitch for the instrument. A highly chromatic, modernist excerpt with localized tonal centers, the Henderson has complex pitch combinations, but is rhythmically simple in the sense that it is comprised of a motoric 32nd-note pattern. However, the metric framework is frequently in conflict with the rhythmic groupings. For example, the repeated and variegated motifs throughout require that the performer phrase against the meter-implied conventional beam groupings of notes. This phrasing accentuates certain notes at unexpected metric locations. All of these elements make this intriguingly interesting melody unfamiliar, difficult, and awkward to play and learn in a short amount of time.

**PROCEDURE AND EQUIPMENT**

After explanation of ethical rights and responsibilities and background data collection, the elite musician was asked to sight read the test piece, practice it for eight minutes, and perform the piece. The procedure took place in a conservatorium music studio, which contained a music stand and the sheet music of the Henderson. A video recording was made of the entire session to allow documentation and analysis of the event. The technical procedure was as follows:

1) Starting with the Henderson sheet music, Bob was recorded sight reading, practicing, and performing directly into a digital video camera.

2) The audio component of the video was extracted and opened in MIDI conversion software Melodyne 3 Cre8 (Neubaecker, Gehle, Kreutzkamp, & Granzow, 2007).

3) The data processed by Melodyne was exported as a MIDI Event List (referred to as “Raw MIDI Event List”). This list was then pasted into...
Microsoft Excel spreadsheet for preparation and analysis.

4) The MIDI file was opened as Music Notation Software performance score.

5) Comparing the Sheet Music Score to the Performance Score, errors were marked and entered with the coding protocol to create the Error Coding Score (see Figure 8).

DEVELOPMENT OF THE PITCH ERROR PROTOCOL
Using the above steps to analyze sound recordings of the elite musician’s Sight Read, Practice, and Performance stages, pitch errors were identified and classified across the three categories described in the Introduction. A fourth category was created to address any errors that could not be classified into the three proposed categories. These unexplained errors are referred to as “Other” (Figure 2). Each error was classified as belonging to any category by which the error could be explained.

SOURCES OF ERRORS
SDH. The source of error was classified as SDH if it could be determined as originating from either a previously played note (that had persevered), or from a note (that was anticipated) ahead of its actual score location (see last row of right-side boxes in Figure 2). The coding system recorded the distance as a note count, as well as the direction of source of the erroneous note. The exception to any score-influenced errors in this category were deletion errors, where a note may have “fallen-off” the mental planning row. Swapped note positions (shifts) occurred when the location of the source of the error was replaced with the target at the score identified error source, as in the spoonerism example described in the introduction. The SDH error types and identifying symbols are presented in Table 1.

Table 2 shows the coding for sources of error (i.e., what influenced the errors and where they came from). These sources reflect SDH related errors of an anticipatory and perseveratory nature.

I-R. Table 3 shows the symbols used to mark I-R errors: P – pitch proximity errors were influenced by the I-R principal of pitch proximity. Pitch proximity refers to scalar continuation rather than what was required by the score. R – pitch reversal errors were coded when the played melody reversed back upon itself rather than following the notes of the original score (see Figure 3). In the present study there were no errors identified where a change in direction returned to a note other than the first note of the implicative pair. While “return to first note” occurred in all such instances of pitch reversal errors (R), further research will be required to determine whether such a singular form of reversal is too limiting for the protocol.

Figure 3 illustrates how an error (an example extracted from pilot study data) may have been from SDH and/or I-R pitch reversal (see notes n = 13 to 15 in Figure 3). SDH coding of n = 15 placed it as influenced.
from a perseveratory note originating two notes earlier at $n = 13$. I-R coding at $n = 15$ suggests the error is due to a pitch reversal (R), also influenced by $n = 13$. All sources in this example were within a three-note score distance of the error: $+1$, $-2$, $+1$, $-3$ respectively. The markings above the note beams indicate the direction (arrows ahead or behind) for the source of the error. SCH. Schematic driven errors included errors most likely driven by structural harmonic influence (for example the reference to “chromatic” marked on the score in Figure 3), and the expectation generated by learned patterns and sequences. Table 4 shows the SCH category including Harmonic (H), Unobserved accidentals (V) and the Ditto errors, which are explained further below.
An error was marked as harmonically influenced (H) if a sequence of notes played by the performer reverted to a learned pattern (such as an arpeggio, diatonic scale, or chromatic scale occurring in traditional Western music instrumental practice) rather than exactly what was required on the music score. It was fairly easy to determine the nature of the error when the surrounding notes were examined, as learned processing tended to run for several notes and “spell-out” the accessed scale pattern instead of the score-indicated notes.

Figure 3 shows an example of harmonic error: circled errors n = 14 through to 18 form a section of a chromatic sequence travelling up and down. Therefore, possible sources for the incorrect pitch at n = 14 and 17 were directly drawn from the (marked) chromatic scale (as per the annotation below the staff in the Figure). Figure 4 shows the harmonic influences in brackets beneath the score—where the notes were played as a traditional chromatic scale—filling the awkward gaps between the E and Ab, and the Ab/G# and the Bb rather than what was notated on the score. All category sources in this figure were within three-note score distance of the error (indicated by the −2 and +2 markings sitting above the direction arrows) except n = 21.1 (the decimal point refers to a note inserted, at the location of the score indicated—in this case note 21). This note was not coded as SDH because the nearest potential source for error was fourteen notes distance (+14). However, it was coded as a SCH harmonic error (chromatic influence). The chromatic scale “run” seems to have dominated the other possible error influences in this section of the score.

Errors marked as unobserved accidentals (V) reflected accidentals that were missed by the performer. They were usually missed if the courtesy accidentals were not shown beside the new note in the same bar and were mistakenly played as a “natural” (see Figure 5).

For example, a marked A# within a segment of notes in

![Figure 3. Demonstration example of coding of more than one category.](http://online.ucpress.edu/mp/article-pdf/34/2/132/191372/mp_2016_34_2_132.pdf)

### Table 4. Legend for SCH Source of Errors

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Source</th>
<th>Meaning</th>
<th>Further Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Harmonic</td>
<td>Harmonically influenced error. E...F# G</td>
<td>Implication of key encourages the adding or deleting of accidentals. A note can be accidentally replaced by another note from an (implied or actual) chord. A played ‘run’ (resembling a scale or arpeggio) is driven by its harmonic, melodic, or technical familiarity rather than by the actual score notation. This can include chromatic scale patterns, sequences and signature motifs. Three notes were sufficient in this case study to determine a harmonic influence.</td>
</tr>
<tr>
<td>S</td>
<td>Structural, Error influenced by structural source.</td>
<td>Notes on main beats have more influence as they attract the player to these tones. Bar (measure) groupings down beats and phrase boundaries can influence the notes played.</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Unobserved Accidentals Reading of a note ignores notated accidental</td>
<td>May be influenced by the recalling of a pre-existing note or simply not applying the accidental throughout the entire bar. Since the assumption of no accidental requires some learning (to play natural if no accidental is next to the note), this error is classified as being top-down.</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Ditto An error that is retained in subsequent readings of the same piece.</td>
<td>If an error occurs in one reading of the music and then occurs in a second playing (e.g., in a second run through during a period of practice, or in the performance after already occurring in the sight read) it was classified as ‘ditto’ and indicates that the error has been learnt.</td>
<td></td>
</tr>
</tbody>
</table>

Note: The error code is entered in the player score on the actual note played. The action is entered on the note position pulse on the spreadsheet.
a bar, upon occurring later on in the same bar, is played as an A natural. In this example the # was too far away—outside the range of planning—to be held in memory.

Since the note in error was played as it seemingly appeared on the score, for the purposes of this study the error of the missed accidental was coded as an unobserved accidental. The error was treated as schematic (SCH) because it suggests that the player has “slipped” into assuming a learned pattern of behavior, such as expecting to be in the key of C major or A minor, or being unconscious of key. That is, the absence of the indication of a chromatic marking was assumed to mean no chromatic needs to be played because that is what the player has learned to do (even though effectively contrary to the instructions).

An error marked as ditto (D) reflected an error that repeated itself during practice or performance. The error is treated as schematic because the player has learned the error on the first occurrence (see Table 4 for further explanation, and an example in Table 6: Performance condition, note 54.1).

Other. Some errors were found to fit more than one of the three categories of the coding protocol. Errors that did not fit within any of the three main categories were classified as Other. These typically were caused by mechanical problems, player intonation, or software recognition (e.g., where the pitch may have been “heard” too sensitively as a different harmonic but could also include otherwise inexplicable, apparently random, events). Although these ‘Other’ symbols are coded and appear on the score, only the symbols applied in the current case study are reported in the tables (see Table 5).

Results and Discussion

Table 6 lists all coded error data for Bob’s Sight Read, Practice, and Performance stages. The errors are listed as they occurred from note 1 of the score through to the final note of the score (Column B). The table indicates the type of errors played (Columns E, F, G), the source of each error played with reference to the score (Columns H-M), and the distance of the error from the source (Column D) when it was possible to ascertain. There were more sources than errors and this was because some errors could be explained by more than one category in the protocol. The category Other sources of error (that would not reasonably meet criteria for Category SDH, I-R, or SCH) are shown in Columns N-P.

The tempo of the work was marked as eighth note \( \frac{3}{4} \) at 138 bpm. It should be pointed out that the oboist sight read the work steadily at an opening tempo of eighth note \( \frac{3}{4} \) at 73 bpm. This tempo slowed to eighth note \( \frac{3}{4} \) at 50 bpm by the end of the piece.

ERROR ANALYSIS OF SIGHT READING

Twenty-nine pitch errors were identified in Bob’s sight reading. The temporal location of these errors can be seen in the Note-Time Playing Path (NTPP) shown in Figure 6. A NTPP (de Graaff & Schubert, 2010) is a timing plot of the sequence of played note onset times against the score-based predicted onset times. Incorrect
pitches (errors) are indicated, enabling the visual inspection of error location relative to score and relative performance time. Regions of relative-to-score “slowing” (rallentando) are shown to help identify the areas that may reflect temporal expressivity, or use of cognitive resources to deal with the complexities of processing and performing the piece. A reduced version of the score is shown immediately below the NTPP (Figure 6).

Of the 29 pitch errors identified some, but not all, error types in the protocol were identified. There were no deletions (missed out notes) or shifts (spoonerized notes). Bob only performed two types of errors: additional notes (15)—i.e., notes that were added to those required by the score—and substitutions (12)—i.e., where one note was “renamed” and played in the place of another. So, under stress and difficulty in predicting the patterns, Bob was more likely to add notes in-between the highly chromatic enharmonic writing, in effect “filling in” the gaps between the intervals (see Figure 4, n = 20.1, 21.1 and 22.1).

In terms of error categories, the sources of Bob’s sight reading errors were persevering (15 times) from a previously “read” note. The majority of these intrusions (10) occurred within two notes of the target. The remaining five were within five notes (distance) of the target. These were all part of the SDH category and with the “within 5 notes” criteria constituted the main influence of errors. Both SDH persevering errors and I-R pitch reversal errors (12) dominated the origins of these errors. That is, more errors can be coded as SDR than can be coded by I-R. The SCH error was identified only three times: unobserved accidentals on each occasion as illustrated in Figure 5, where the note A natural is played instead of an A#.

The SDH error codes both the direction and the distance between the error and its source, giving information about the player’s processing of the material. It is interesting to note that in Bob’s case, the majority of the errors during sight reading were perseveratory (a total of 15 out of 29 errors) and most (11 of these 15) were within three notes from their source (Column H, Table 6): Three errors were within one note from the source (i.e., a repeat); nine errors were within two notes, one was within three notes, three notes were within four notes, and one was within five notes from its source. Two other anticipatory notes (n = 72 and 174) registered within five notes from their source, (i.e., read ahead and anticipated from a note in the future) and did not persevere. All of these errors fell into SDH category of the protocol and indicated that the score influenced Bob’s note-reading errors.

Again, a small number of errors could be attributed to sources more than three notes away from the target. Interestingly, the intrusions that could be attributed to notes more than five away from the target (n = 55, 66, 67.1, 67.2, 138, 140, 162, 163, 163.2, 165.1, and 165.2) were all perseverations. Nevertheless, these errors would be better attributed to one of the other categories of the protocol, should that be possible. For example, note 55 (illustrated in Figure 5) was coded as SCH (as an unobserved accidental note), meaning that Bob read the note (without the accidental #) as an A natural. He seemed to “forget” or not notice that the sharp applied to this A; the marked accidental had, by then, slipped five notes.

### Table 5. Legend for ‘Other’ Source of Errors

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Source</th>
<th>Meaning</th>
<th>Further Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>hel</td>
<td>Held</td>
<td>A note sustained to assist processing</td>
<td>The source did not include notes sustained for expressive purposes.</td>
</tr>
<tr>
<td>mech</td>
<td>Mechanical</td>
<td>Error driven by mechanical fault, or physical problem.</td>
<td>Awkward fingering stumbles, squeaks, undesired overtones, and all types of mechanical and instrumental problems were tagged as Mechanical errors.</td>
</tr>
<tr>
<td>O</td>
<td>None</td>
<td>No recognizable source of error.</td>
<td>Where there was no other reasonable explanation found for the source of an error, it was coded as O.</td>
</tr>
<tr>
<td>O</td>
<td>MIDI</td>
<td>A note/pitch/timbre ‘misheard’ by the note recognition software</td>
<td>Misheard sounds by software include overtones and other non-pitched sounds (such as pencil taps, talking, chair movement and metronome). “Extreme use of expressive timing and unexpected interpretations of ornaments may also cause a matcher to misinterpret correct performance events as errors’ (Heijink, Desain, Honing, &amp; Windsor, 2000, p. 44). Misheard notes are marked by the researcher usually during the error coding preparation, for correction on Performance score and NTPP.</td>
</tr>
</tbody>
</table>
## Table 6. Pitch Error Types and Sources

<table>
<thead>
<tr>
<th>Condition</th>
<th>Note # from start</th>
<th>Source # of note error</th>
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Notes: P = Practice, SR = Sight Read, Perf = Performance, ad = additional, sub = substitution, per = perseveratory, ant = anticipatory, PR = pitch reversal, dit = Ditto, i.e., done before and retained, har = harmonic error marked as chromatic or as a diatonic scale in the chart, un = unobserved accidental, hel = sustained note ('held'), mec = mechanical, O = none. Three digits separated by slashes at the bottom row indicate tally of errors in each error source for SR/P/Perf conditions respectively. The error sources: shift, and pitch proximity (IR), are not displayed because such errors were not identified in any of the three conditions.

Dark grey shading in Column D indicates notes within 3 notes distance from source of error. Mid grey in Column D indicates notes less than 5 notes distance from error source. No shading in Column D indicates SDH was greater than a 5 note proximity of an error source.

*Distance of error note from source note: e.g. 2- means source is 2 notes to the left of the error; 2+ means source is 2 notes to the right of the error, etc. Light Grey rows with bold text indicate errors duplicated in more than one condition.
back from the target note. It seemed that it was no longer held in his immediate working memory. Thus, both SDH and SCH could explain the error, but SCH was in this case a more parsimonious explanation.

Similarly, note 66 (Table 6 Column B) was six notes from its previous source (outside the five note distance) and coded the same as $n = 55$, i.e., was not deemed an SDH but as an SCH unobserved accidental error. Both $n = 67.1$ and 67.2 were additional notes, where Bob held on to the pitch in order to prepare his next foray. Notes $n = 138$ and 140 exhibited the same SCH unobserved accidental behavior as note 55, i.e., “forgetting” to continue with and apply the accidental from the previous raised C#. Another possible explanation for avoiding these accidentals is that there is a convention in atonal or contemporary music that the notes can be taken as exact representation, i.e., all accidentals are stated for every application. In Bob’s case, his post-practice performance corrected notes $n = 55, 138$, and 140. This indicated that he had not in fact intended to interpret the notes literally, but had indeed misread them in the earlier sight reading. The remaining outliers were categorized as Other mechanical errors (mis-sounded notes/squeaks) and occurred at $n = 162, 163, 163.2$, and $n-165.1$. Note 107 was a breath where no breath was

FIGURE 6. Bob’s sight read and performance data as combined NTPPs. a) NTPP: The x-axis shows note pulses as the percentage of score time elapsed. The negative y-axis illustrates the player time and unfolds down the page throughout the performance. The larger size dotted (lower) line is Bob’s Sight Read and the smaller dotted (upper) line is his Performance after 8 mins Practice. The steadier tempo of the Performance, fewer errors and observance of the required rallentando (emphatic and slower required on the score at bars 3 and 6) can be observed - in comparison to the Sight Read. Errors are shown in Sight Read (clusters of – crosses at A, B, C) and in Performance as four △ triangles.

FIGURE 7. Example of the most frequent source of I-R error Pitch Reversal PR (R on the score). Here Bob reverted to playing the previous note, rather than adjusting pitch for the new note. The top line of music represents the actual notes played by Bob, while the bottom line shows the actual score.

The full error coded score for Bob’s sight reading is shown in Figure 8. The top line of music represents the notes played by Bob (oboe), while the bottom line shows the score. The note number is represented with the italic numbers within the staves. The majority of errors coded in this condition are the R pitch reversal ($n = 15, 27, 69.1, 69.2, 70$, etc.)
FIGURE 8. Bob’s error coded Sight Read score.
The top line of music represents the actual notes played by Bob (oboe), while the bottom line shows the actual score. Errors are marked as discussed for the coding protocol.
ERROR ANALYSIS OF PRACTICE

Out of 891 notes played during Bob’s Practice stage, only 17 were identified as errors. Bob mainly made SDH additional error types, which were largely perseveratory in source (influenced by previous notes on the score), and exhibited a prevalence for I-R pitch reversal. This perseverance of errors continued to influence Bob’s practice, although he stopped and corrected each of these errors as they occurred. SDH deletions did occur in the Practice stage, although they had not occurred in either the Sight Read or Performance stages.

The main characteristics of Bob’s Practice stage (Figure 9) were the many repetitive segments, seen unfolding across the NTPP page, travelling through the piece from the first note to the last. The Practice NTPP was in contrast to both his Sight Read and Performance NTPPs, where the black dotted lines travelled down the page as time unfolded. The “working-over” of smaller groups of notes and in segments gave the Practice NTPP a distinctive practice signature. Bob’s “signature” revealed whether he used longer segments of notes (appearing as lines of 22, 23 notes in Figure 9b - NTPP), or worked in shorter groupings (clusters of 2, 3, 4, or 5 notes), or combined all of these. The NTPP indicated if he played continuously, or rather stopped to work things out (shown as solid horizontal bands), varied tempo to control the learning (marked by an oval where the dotted line dipped or curved) or made mistakes (indicated as a plus sign). Bob’s Error Coded Practice Score similarly shows segments of notes as they occurred in time, and any periods of No-play in between, with many rests. When these data are placed together they give a picture of his practice moving back and forth across the page, through the music.

Column D of Table 6 shows that within Bob’s Practice condition (P) most notes are on or within a two-note distance from the origin of the error. Columns E and F show that within the SDH type of errors, additional (9 out of 17 errors) and substitution (6) dominated the results. All but three of these SDH errors in Column H were perseveratory (14; influenced from the previously seen/played notes). Column J shows pitch reversal (8) errors from I-R and while all of these eight coincided with the perseveratory source for the SDH coding, I-R did not account for every error coded in the Practice stage. In total there were only eight occurrences of I-R pitch reversal errors in Bob’s Practice stage.

ERROR ANALYSIS OF PERFORMANCE

The number of errors in Bob’s Performance stage (see Table 6, and the smaller dotted—upper—line NTPP Figure 6) were small in comparison to the Sight Read condition, and revealed that the predominant errors were not only SDH perseveratory (4 out of 4 errors in total) but also I-R pitch reversal (3 out of 4), with one harmonic and one unobserved accidental. Thus, in addition to demonstrating Bob’s improvement as a result of practice, we were also able to identify which kinds of errors impact the final performance (namely persevering SDH errors which are substitutions). A more detailed comparison of the conditions is reported in the following section.

COMPARING ERRORS BETWEEN THE PERFORMANCE AND SIGHT READ CONDITIONS

Figure 6 combines data from Bob’s Sight Read and Performance conditions in a NTPP. Error reduction, increased speed, and more stable tempo are evident. The error coded score (NTPP Figure 6) shows that Bob’s Performance stage improved from his Sight Read stage in the following ways: 1) a much shorter play time overall, reduced by nearly half the time to 32 seconds; 2) continual unstopped or slowed play (no large gaps between any consecutive points); and 3) reduced errors of only four triangles (from the previous 29 crosses in the Sight Read condition). Table 6 confirms that while Bob had 17 additional SDH errors in the Sight Read condition, he had none in the Performance condition and only four SDH substitutions (13 were in the Sight Read condition), so additional errors disappeared and substitution errors remained (and greatly reduced in number).

Table 6 shows the sources of Bob’s Performance stage errors in comparison with his Sight Read stage. Fewer sources (as well as fewer types) are evident. In terms of the sources of errors remaining after the Practice stage into Bob’s performance, he still produced SDH perseveratory (3), PR (2), and I-R harmonic (only 1) errors, and again in reduced numbers compared to the Sight Read stage. The categories of SDH anticipatory, SCH unobserved accidentals, and Other mechanical did not occur at all in the Performance condition.

COMPARING ERROR CODED SIGHT READ, PRACTICE, AND PERFORMANCE STAGES

Influence of the score. Marking Bob’s errors onto a fresh score and then observing the “hot spots” (repeat errors occurring in more than one of Bob’s playing condition) revealed the location of the errors (Table 6) on the score for the Sight Read and Performance conditions (Figure 10).

Six hotspots were found in the Henderson (Figure 10, marked with light grey square frames and solid grey four-point stars, and Table 6 shown as notes 132 and 171). These spots revealed that while phrase boundaries
FIGURE 9. Bob’s Practice of the Henderson as NTPP.

a) The NTPP x-axis shows note pulses as the percentage of score time elapsed. The negative y-axis illustrates the player time and unfolds down the page throughout the performance. Crosses indicate pitch errors. Circles show areas of interest with temporal deviation such as slowing or uneven tempo. Shaded bands illustrate periods of No-play. See Figure 8 for Bob’s Coded Practice Score of Henderson. b) Score of the Henderson aligned with the x-axis of the NTPP.
FIGURE 10. Pitch Error Types and Sources collapsed on Henderson score for Sight Read and Performance.

- = error in either Sight Read or Performance, + = additional note error in either Sight Read or Performance, ■ = same error in both Sight Read and Performance, □ = three note grouping indicating a Pitch Reversal error, □□□ = multiple note error clusters of leaps and pitch reversal/proximity.
(bar lines or note groupings) did not cause any more or less difficulty than any other sections, a particular combination of notes did cause more error. Looking firstly from the I-R perspective, pitch reversal (PR) seemed to attracted errors and difficulty for both the Sight Read and Performance conditions (see dark grey square frames in Figure 10 and Column J [PR] in Table 6). PR occurred where one note moved to a different pitch on the score and returned, but did not return to the “expected” or anticipated note as set-up by the prior pattern.

From the SDH perspective, four note areas showed errors from sources, excluding I-R PR and PP, and were simply marked as an error (light grey outlined four-point stars) or specifically as an additional note (or additional breath—these errors are classified as a SDH in Table 1), as indicated by dark grey outlined four-point stars. These four stars appear on the marked-up score, outside the dark grey square frames. As Table 6 confirmed more SDH errors than I-R, it is interesting to see that these occur in very similar areas of the score on Figure 10.

One broader area of the score did cause difficulty for Bob, requiring a steep climb out-of-range in the last section of the excerpt (from n = 153 onwards, marked with a dark grey square frame). The out of range section required the player to make a decision as to how to deal with the problem. In this case the player decided to play the section down an octave, bringing the pitches back into the range of the instrument for that section of the piece. This decision was not coded as an error. Instead, multiple note error clusters were caused in this area by leaps, pitch reversal, and pitch proximity, filling in non-conjunct steps with SCH errors (chromatic, harmonic, additional) and Other (mechanical) errors in ranges extending beyond the comfort range of playing.

Fifteen notes from a total of 50 note errors (unshaded rows in Column D Table 6) were non-SDH across the three conditions. If these errors were SDH intrusions, their source would have been further than a three-note proximity and therefore most likely to have been influenced from sources other than SDH. Also of interest was that the elite player repeated four errors across conditions (see Table 6 light grey rows with bold text, n = 27, 104, 132, 171). Within the Sight Read and Performance tests highlighted by Figure 10 he only repeated errors in both conditions in two places (n = 131/132 and 171, see Table 6 and Figure 10). However other errors were played alongside these errors throughout the different conditions, which perhaps suggests that there are different influences at play—at the same places on the score—at different occasions for the same player.

Conclusion

In this paper we reported the development of a Pitch Error Coding Protocol to help understand the cognitive processing that explains errors. By combining into one protocol the Serial Distance Hypothesis (Palmer & van de Sande, 1993, 1995), the Implication-Realization (I-R) Model (Narmour, 1990; Schellenberg, 1996, 1997), and Schema Theory (Bharucha, 1987, 2008; Curtis & Bharucha, 2009), we were able to classify a large majority of errors and provide insights into the cognitive foundations of those errors. The emphasis of our model is that when an error is made, there may be multiple and non-exclusive explanations for the error. However, we were able to determine which of the models best explain the mental processing at work. Specifically, the Serial Distance Hypothesis explained the majority of errors. Furthermore, after a short period of practice, the elite musician was able to reduce the number of errors from 29 to 4 in the Sight Read and Performance conditions, respectively. The innovation of the present study is that we were able to identify the nature of the errors, since each was persevering, indicating that notes in the recent past are able to continue to intrude into memory even after practice. It should, however, be noted that anticipatory SDH errors were proportionally smaller overall, and so the perseveratory nature of the errors appears to be a general malaise under the present conditions, not necessarily restricted to Performance conditions only. Pitch reversal from the I-R category also appears to be an area where errors persist. Each of these kinds of errors could therefore be targeted to help the musicians further improve their practice strategies. However, this study is exploratory and focuses on a single case study, and so applications and generalizations at this stage must be made with caution.

Further research is required to determine how elite musicians deal with different kinds of music, and how musicians of different levels of competence and different musical instruments produce errors. Above all, the intention of this detailed case study is to stimulate further debate on identifying the nature or errors by taking a cognitive perspective on the act of performing music. The near absence of schematic errors suggests that the highly skilled musician is able to override any errors that occur as a result of inappropriate application of learned patterns not required in the score. We speculate that less experienced players will be proportionally more prone to such errors because they have not learned to inhibit and override their desire to automate recently learnt patterns (scales, arpeggios, portions from other pieces). The SDH and I-R categories of the
protocol ensure that one category of error is not simply counted without consideration for other kinds of errors, making the development of the protocol a valuable tool in understanding performance cognition and eventually for generating hypotheses about the kinds of errors that might be expected. One important product of this research is that it can inform music practice in the teaching and learning of students. If the sources of errors are better understood, music students can be taught to predict likely “hot spots” and self-regulate their behavior to avoid the pitfalls generated by the score, and to learn more accurately and efficiently.

Further research will also be required to determine whether SDH is the primary source of error explanation in sight reading in general, or whether the nature of the error is dependent on the level of expertise and the nature of the music played. For example, research is recommended in coding student performances of music scores that (for the students’ level) cover a range of difficulties, and that these difficulties entail a variety of parameters, such as pitch and rhythm related. The present study focused primarily on pitch errors.

Our analysis did not reveal errors that could be attributed to fingering or hand position problems. Profession musicians have developed motor skills to override limitations of unnatural hand positions (Ericsson, 2007; Lehmann & Gruber, 2006, pp. 464-467; Miller, Peck, Brain, & Watson, 2003) and so it seems reasonable that no specific errors could be attributed to biomechanical limitations. However if seeking to explain errors in less experienced players the “mech” errors could be modified to allow differentiation between biomechanically generated errors versus mechanical problems of the non-vocal instrument itself.

The error coding protocol is intended to be used by musicians and researchers to better understand the nature of learning music from a cognitive perspective. The decision to present the protocol through the analysis of an elite musician working on a complex task was a considered one to uncover and then harness best-practice approaches to learning. The protocol will require further investigation and possibly revision as more musicians and repertoire are tested and as different sources of error are identified and refined. As discussed, we speculate that error categories I-R (e.g., reversal) and Other (e.g., mech) will be further developed. Future iterations of the protocol will also need to account for the structural content of the music (Palmer and van de Sande, 1995), particularly for pieces that have elements of large scale similarity and segmentation in comparison to the test piece used in the present study.

Identification of the source of errors using the protocol could also be wed with more conventional methods of performance analysis, such as think-alouds and other qualitative approaches to provide a richer understanding of how musicians cognitively organize material. Our research program focuses on elite performers because we believe there is still much we can learn from them that can be applied to less experienced musicians. This paper presents a challenge to see whether SDH remains a significant explanation for these younger players.

Author Note

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