Measuring the musical skills of a prodigy: A case study

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ABSTRACT

While there is a strong interest in and fascination with music prodigies, very few measurements have been conducted on this rare phenomenon and very little empirical data exist. We document the case of LN, an 11-year-old music prodigy. We tested him on his cognitive skills (non-verbal reasoning and working memory), rhythm and melody discrimination skills, sight reading, improvisation, pitch accuracy, and musical memory. The data were then compared to various controls: a group of music students of the same age group (for cognitive and discrimination skills); three university music students with perfect pitch (for pitch accuracy and musical memory); and a music prodigy of similar age who was tested almost one hundred years ago (for pitch accuracy and musical memory). This is the first study that compares the test results of a contemporary music prodigy with the rare data of a prodigy studied in the early 20th century; the results are remarkably similar. LN's results on cognitive skills confirm the exceptional working memory often associated with prodigies. Most interestingly, musical ability results revealed a phenomenal level of melody discrimination, pitch accuracy and musical memory (skills related to auditory pitch memory), but just average rhythm skills, below average sight reading ability and he was not able to improvise. This suggests the potentially important role of exceptional auditory pitch memory in the development of musical prodigies.

1. Introduction

In recent years we have seen a great deal of interest in exceptional young music performers. Music prodigies are regularly featured in the media, from television appearances on popular programs such as *60 Minutes* and *The Ellen DeGeneres Show* to the more than 13,000 results generated from a search for "music prodigy" on *YouTube*, or to over 3000 videos resulting from a more specific search for "child prodigy piano" on *Google*. Less prevalent, however, is scientific research on the specific abilities of these music prodigies, and case studies with empirical data are quite rare.

Although rare, published reports of music prodigies are not new. Barrington (1770) authored a descriptive account of Mozart at eight years old, which included tests for sight reading and improvisation. Barrington's study of Mozart was outlined years later in a science magazine where the author noted the lack of knowledge about the study despite its value: "for it is a rare thing: a scientist's study of an artist" (Tolansky, 1959). However, it is not until the 20th century that investigation, in the tradition of psychological experimental study, on prodigies began. Such is the case with a 1924 report of a young girl whom musical critics called "youthful Paganini," in which Stedman was investigating the most effective method to train prodigies. Much later,

Feldman and Goldsmith (1986) followed six prodigies for a period of nearly 10 years through interviews conducted with the young prodigies, their parents, and their teachers.

More recently, McPherson (2007) investigated, over a 3-year period, a talented young pianist who was first interviewed when she was 7. So far, almost all case studies have been descriptive in nature, and papers with quantitative measurements and empirical data are rare. Two early German case studies were among the first psychological studies to look into the prodigy phenomena: Baumgarten (1930) examined nine prodigies including two pianists, two violinists, and one orchestra conductor; Révész (1916/2007) observed and tested the young prodigy Erwin Nyiregyházi from 1910 to 1914 (starting when the boy was 7 years old) and reported his findings in *The Psychology of a Musical Prodigy* (initially published in German in 1916 and translated into English by the author in 1925). We then have to move to the 21st century to find more empirical studies on prodigies. In 2003, Ruthsatz and Detterman (2003) used "a summation approach to investigate the cognitive, musical and practice elements involved in becoming an extraordinary performer" (p. 509) and in 2012, Ruthsatz and Urbach (2012) examined the cognitive and developmental profiles of eight prodigies. Besides the results reported in these recent studies, we have little empirical data on the abilities that characterise music prodigies;

while we know they have a good mastery of their musical instrument and are outstanding performers, we have few documented measures on their other skills, those usually referred to as musicianship skills. This paper presents a case study based on observable musical tasks performed under controlled test conditions.

The subject of this paper is LN, an 11-year-old Canadian pianist who is known as a prodigy because of his achievements in various prestigious competitions and his performances with major orchestras. In this study, we investigate how LN performs on specific cognitive tests, on rhythm and melody discrimination, sight reading, improvisation, pitch accuracy, and on music memory tasks. These areas of expertise have been associated with music prodigies in previous descriptive studies (Geake, 1996; Howe, Davidson, Moore, & Sloboda, 1995; McPherson, 2007; Vandervert, 2009), but, according to Ruthsatz & Detterman (2003) have rarely been measured. In order to better understand LN's performance on these skills, we compared his results with various controls. First, LN's cognitive results, and rhythm and melody discrimination results were compared with a group of 40 regular music students in the same age group (10 to 12 years old) and another group of 25 regular music students with the same number of years of piano lessons (4–6 years). Both groups had gone through the same testing procedure. Secondly, LN's pitch accuracy results and music memory results were compared with three university music students with absolute pitch, who completed the same tests. Thirdly, LN's results for pitch accuracy and music memory were compared with a rare set of empirical assessment data available on another music prodigy in the early 1900s, Erwin Nyiregyházi (Révész, 1916/2007). We do not know if music prodigies are alike in the musical skills they possess, so this gave us the opportunity to compare two music prodigies who lived almost 100 years apart.

This paper is important as it provides another good example of a prodigy's very high measures on working memory supporting the idea of dissociation between working memory and other measures of intelligence. This study also suggests another type of dissociation noticeable with prodigies, this one within the different subskills related to the specific domain in which a prodigy excels. As our results will show, music prodigies are not exceptional in every skill associated with music expertise. In this particular case, LN shows outstanding results in skills specifically related to auditory pitch memory while being average or below average in some other musical skills. These findings might indicate the important role that exceptional auditory pitch memory plays in the development of musical prodigies.

1.1. General intelligence and working memory

When looking at the literature on general intelligence and prodigies, we find that superior intelligence (Ruthsatz & Detterman, 2003; Simonton, 1994) or good intelligence (Vandervert, 2009) is a common feature. Following their investigations of six young prodigies, Feldman and Goldsmith (1986) concluded that contrary to an academic genius who shows extremely high IQ and can perform well in many domains, prodigy's talent is domain specific and requires above average cognitive abilities but not extreme intelligence. Ruthsatz and Urbach (2012) who investigated the cognitive profiles of eight prodigies, four of which were music prodigies, also observed that while prodigies had at least a moderately elevated level of intelligence, their full scale IQ scores were not consistently on the extreme end of the spectrum. However, exceptional working memory has been identified as a characteristic for all music prodigies for whom we have relevant data (Révész, 1916/2007; Ruthsatz & Detterman, 2003; Ruthsatz & Urbach, 2012; Stedman, 1924). LN's case study provides another example of an apparent dissociation between working memory, which always seems to be high in prodigies, and other measures of intelligence that are (in LN's case) average to above average.

1.2. Musical skills and auditory pitch memory

Feldman and Goldsmith (1986) described prodigies as highly specialized children in one particular domain. Since then it has become fairly common to view prodigies as being domain specific (Ruthsatz & Detterman, 2003; Ruthsatz, Ruthsatz, and Ruthsatz-Stephens, 2014). However, while children's outstanding performances might be domain specific, there is a possibility that a prodigy may not be exceptional in all of the sub-skills associated with a particular domain. Equally revealing are the musical abilities that musical prodigies are not consistently displaying. LN's case study shows amazing scores on sub-skills related to auditory pitch memory, but average or even low scores on other musical skills not dependant so much on auditory memory.

2. Case history

Through written correspondence and transcribed interviews with both LN's mother and his current piano teacher, as well as an interview with LN, we were able to develop his case history. LN was born in 2005 to highly educated parents and is the second of four children. His parents are academics and have no musical background; however, two of his three siblings play the piano (the youngest, at only two years old, was still too young for music lessons at the time of this study). When LN was one year old, his older brother provided an early source of music exposure with his daily practice on the family electronic keyboard (they later acquired a grand piano). As a toddler, LN showed early expression of music, humming melodies before he was able to talk. When he was three years old, his elementary school music teacher recognized his absolute pitch ability and suggested to his mother that he study music, so at age four, he began a program of group lessons for children and their parents. LN appears to have already been motivated to learn music. His mother writes: "He naturally feels music. When he was 4 years old, he could take a music book, sight read and play through page-by-page for hours." (LN's mother, personal communication, March 15, 2015). After two years in the program, LN started formal piano lessons and briefly studied with one teacher before transferring to his current piano teacher when he was eight years old. From then on, his rate of progress was very impressive and matched a group of 16 prodigies that we studied previously (Comeau, Vuvan, Picard-Deland, and Peretz, in press). When compared to a sample of 277 piano students, we found that this group of 16 prodigies progressed through the grade levels almost three times more quickly than regular students (2.08 vs 0.73 grades per year). LN's rate of progress was 2.75 grades per year.

LN mentioned in his interview that he likes to play the piano and loves his piano lessons, although he sometimes struggles with practice. This is supported by his mother who acknowledges that in the past, practice was hard and boring for him, especially slow practice. She encourages LN by providing him with organization and reminders, adding that he would otherwise only practise 1 h a day. LN's teacher (Dr. M.) also talked about the difficulty encountered with the frustration and boredom LN sometimes experiences in practice. Dr. M. has worked to overcome this issue. The teacher would share stories with LN and bribe him with the promise of practicing together over Skype as practice buddies. While practice is sometimes a challenge for LN, he understands the importance of willpower, and knows that learning music requires effort, persistence, and practice. During the interview, LN indicated more than once that his success is the result of a lot of practice and hard work.

LN also recognises the importance of a good teacher and his mother is very appreciative of his current piano teacher. "Even though LN is gifted, he could not win any music competition before he met his current piano teacher, Dr. M. Great teaching makes a huge difference." (LN's mother, personal communication, March 15, 2015). Dr. M., who has worked with other gifted students, talks of LN with great affection as he describes his humour, personal charm, healthy childish love of climbing trees and monkey bars, as well as his connection with Russian

composers (both LN and Dr. M. are of Russian descent), remarkable memory ability, natural sense of timing, effective use of rubato, and quick learning. Dr. M. works many hours a week with LN, reporting that the shortest time they spend in lessons is 4 h/week (LN's piano teacher, personal communication, April 10, 2015).

In terms of his cognitive development, LN was late to talk but his mother taught him letters and phonics. He began to read by age three, but preferred logic puzzles to stories. His strong interest and facility for logic and math may influence his musical ability. Dr. M. describes how LN learns new repertoire using memory skills, but also using numbers to make connections between the notes and intervals. LN's mother also offered insight into his general intelligence: "He is very good at math and science. He spent lots of time reading math books (including calculus) when he was 6–8 yrs. In large part, he is self-taught and he is now finishing high school math curriculum. Sometimes he would think about math problems day and night, even hiding a math book under his pillow. I remember when he was a second grader, he explained grade 11 chemistry topics to his friend in the school playground" (LN's mother, personal communication, March 15, 2015). LN continues to show his strong interest in mathematics and chemistry by reading books on mathematics and memorizing the elements of the periodic table. He has also won several prizes for his mathematical ability. LN's two siblings have both been identified as gifted in intelligence testing and have also won mathematics competitions.

As for as the home environment, all children are home schooled to accommodate LN's music commitments. Even though LN's parents have no musical background, they support his musical talent development in many ways. They are involved with transporting him to lessons, sitting in on lessons, helping with practice and attending concerts and recitals. Since LN began working with his current teacher, his parents make a three-hour drive to another city and stay half a day at the teacher's apartment for LN's lesson. LN's parents are also providing a practice environment with a grand piano and an additional piano for the three children to practice. His parents also support his musical talent by having him attend master classes and workshops.

At the time of the study, LN had already won numerous awards for performance, twice winning a major national competition with a score of 99%, the highest mark ever awarded. He has also competed internationally and won important prizes. LN has performed with several Canadian orchestras, including the Toronto Symphony Orchestra and the Orchestre Symphonique de Montréal. He has shown talent in music composition, performing his work publicly in recitals and winning national and international composition competitions. His older brother has also won music performance and composition awards.

LN's testing for this study was administered over a two-day period on April 10 and 11, 2015 at the Laboratory for Brain, Music, and Sound Research (BRAMS) in Montreal, Canada.

3. Cognitive abilities

Measurements: We chose to test LN with three specific subtests of the Wechsler Intelligence Scale for Children, fourth edition (WISC-IV; Wechsler, 2003), based on the exceptional working memory scores that have been displayed by prodigies in other studies (Ruthsatz &

Detterman, 2003; Ruthsatz & Urbach, 2012; Stedman, 1924). Our decision was also influenced by the work done at the Laboratory for Motor Learning and Neural Plasticity (Bailey & Penhune, 2010; Ireland, 2014). The Matrix Reasoning subtest (MR) measures non-verbal reasoning and visual pattern recognition. The Digit Span and Letter-Number Sequencing subtests measure working memory. The Letter-Number Sequencing test is cognitively more demanding due to additional sequencing demands. Participants' raw scores were converted to scaled scores based on age-based norms for all three subtests. Further, Digit Span and Letter-Number Sequencing scaled scores were added to produce a Working Memory Index (WMI) scaled score. These subtests have been found to have high test-retest reliability and internal consistency (Wechsler, 2003).

3.1. Test description

For the Matrix Reasoning subtest, participants must identify the missing portion of an incomplete visual matrix from one of five response options. For the Digit Span test, participants are asked to repeat progressively longer number sequences backwards and forwards. For Letter-Number Sequencing, the participant first hears a mixed sequence of numbers and letters and is then required to repeat numbers first (in numerical order), and then letters (in alphabetical order) (Wechsler, 2003). Tasks were cued by a visual display presented on a computer monitor. After participants were familiarized with each task, auditory stimuli were presented binaurally via Sony MDRZX100B headphones adjusted to a comfortable sound level. All cognitive tasks (Digit Span, Letter-Number Sequencing, Matrix Reasoning) were administered in the order in which they appear in the original assessment battery and all subtests were administered according to standardized procedures.

3.2. Results

LN's cognitive scores were calculated and compared to children of his exact age (within 3 months) in the standardization sample for the WISC-IV. The population-based mean for subtest scaled scores on the WISC-IV is 10, with a standard deviation 3 (Wechsler, 2003). Results for LN's nonverbal analytical reasoning ability are shown in Table 1. According to the standardization sample for the WISC-IV, his score of 15 is above average range for his age group. The results of the working memory tests are shown in the same table. LN's score of 17 in the digit span test is in the superior, or exceptional strength category. His result in the letter-number sequencing test is above average. The Digit Span and Letter-Number Sequencing test scores are added to produce a Working Memory Index scaled score. For this composite, LN's score of 30 is in the 97th percentile for his age. LN appears to have an exceptional working memory.

Several studies (Forgeard, Winner, Norton, & Schlaug, 2008; Ho, Cheung, & Chan, 2003; Nutley, Darki, & Klingberg, 2013) have shown that musical training is associated with cognitive abilities and musically trained children outperform their age-matched counterparts with no musical training. So we decided to compare LN's scores with a control of 40 music students in the same age group (10 to 12 years old), since the standardization sample for the WISC-IV does not specifically reflect the

Table 1
Results of general intelligence assessment using Wechsler intelligence scale for children (4th edition).

| Test | Music student group[*] | | | LN | | |
	Mean score	SD	Descriptive classification	Score	Percentile	Descriptive classification
MR (matrix reasoning)	11.3	2.63	Average	15	85	Above Average
DS (digit span)	11.3	2.07	Average	17	95	Superior, or exceptional strength
LNS (letter-number sequencing)	11.1	3.19	Average	13	75	Above average
Working memory composite (DS & LNS)	22.4	3.92	Average	30	95	Superior, or exceptional strength

[*] Mean score for the group of 40 regular music students (ages 10 to 12).

results of a group of music students. This group of young musicians were recruited through private music lessons and Suzuki music camps in Montreal, Waterloo, and Ottawa, and all had gone through the same testing procedure (Ireland, 2014). Table 1 shows LN's score compared with the group of 40 music students close to the same age. The mean scores for the music-student group for all tests are in the average range according to the standardization sample for the WISC-IV. LN's scores were higher, and sometimes much higher, than the music-student group mean for all tests.

4. Rhythm and melody discrimination

4.1. Measurements

For testing LN's rhythm synchronization and melody discrimination skills, we used a computer-based test initially developed for adults (Chen, Penhune, & Zatorre, 2008) and later adapted for children (Hyde et al., 2009); it is this second version that was used in our study. LN's rhythm and melody discrimination results were analysed, then compared with two control groups, both subsets of music students recruited from private music lessons, and Suzuki music camps in Montreal, Waterloo, and Ottawa who had performed the same tests (Ireland, 2014); one group was of similar age to LN (ages 10 to 12, *N* = 40), and another group had similar years of piano lessons (4 to 6 years; *N* = 25).

4.2. Rhythm synchronization

4.2.1. Test description

The rhythm synchronization task (RST) is a measure of auditory-motor synchronization, in which participants tap in synchrony with a series of musical rhythms presented via headphones. The test comprises three levels of difficulty with two rhythms per level: two easy (rhythms with a strong beat and repeating patterns), two metric simple (rhythms with a strong beat but no repetition), and two metric complex (rhythms with a syncopated beat). Each rhythm lasted 6 s and was composed of 11 woodblock notes. The participant is instructed to listen to the rhythm, and then to listen once again while tapping in synchrony on the button of a computer mouse. Each rhythm was presented three times in counterbalanced order, and each trial had two phases: listen; listen and tap. Five practice trials with feedback from the experimenter were conducted. Performance on the test was measured by inter-tap interval (ITI) deviation, a measure of synchronization. The timing of all taps made by the participants was aligned with the timing of the six rhythms. To calculate the ITI deviation, only the taps that fell within half the interval surrounding each rhythm were retained. The ITI deviation was calculated by dividing the interval between each pair of taps by the actual interval between the corresponding pair of woodblock notes in the rhythm, and then subtracting from the number one. Lower ITI deviation indicated better synchronization or less deviation from the overall structure of the rhythm.

4.2.2. Results

LN's results for the rhythm discrimination tasks are shown in Table 2. His results are compared to two groups of regular music students (one of similar age, the other with similar years of music lessons). For the easy task, LN attained a similar score to that of his peers. For the metric simple and complex tasks, his score was superior to the mean score for both comparison groups (always over the 70th percentile). We might have expected LN's scores to be among the best compared to other children, but a number of participants from both comparison groups had superior scores as more than a quarter of children with similar years of lessons scored equal to or better on the metric complex task.

Table 2
Rhythmic discrimination test results: LN compared with sample of child musicians.

Task	Mean ITI deviation[*]			LN percentile		Participants with scores equal to or better than LN	
	LN	Ages 10 to 12	4 to 6 yrs of lessons	Ages 10 to 12	4 to 6 yrs of lessons	Ages 10 to 12	4 to 6 yrs of lessons
Easy	0.22	0.19	0.23	23	46	31/40	14/25
Metric simple	0.29	0.35	0.39	74	86	11/40	4/25
Metric complex	0.31	0.37	0.38	80	73	8/40	7/25

[*] Lower ITI deviation indicates better synchronization or less deviation from the overall structure of the rhythm.

4.3. Melody discrimination

4.3.1. Test description

For the melody discrimination task, we assessed the ability to discriminate melodies differing by a single note. There were two phases to this task: simple and transposed. For the simple task, participants were asked to listen to two melodies of equal duration and then choose *same* or *different* response by clicking the right or left button of a computer mouse. Melodies varied in length from 5 to 11 notes and were all in major tonalities. The task includes two blocks of 15 trials. In 16 of the 30 trials (the "different" trials), the pitch of a single note anywhere in the melody was shifted up or down by up to five semitones. The key and contour (overall pattern of upward and downward movement) of the original melody were maintained despite the shift in pitch. Performance was measured by the proportion of correct responses. The second phase (transposed) was the same as the simple task, however the second melody was transposed upwards by four semitones. In some of the trials, the melody was exactly the same (albeit transposed), while in other trials, the pitch of a single note was shifted up or down by one semitone to alter the melody.

4.3.2. Results

Results are shown as the percentage of correct responses; i.e. what percentage of the melodies were correctly identify as *same* or *different*. (Table 3). LN's scores are high on these tests with 90% correct answers for both the simple and transposed melody tasks. These results are high compared to both groups of young music students, especially on the more difficult transposed melody task, where he is in the 99th percentile of other music students of the same age, and 100th percentile of those with the same number of years of music lessons. The last two columns of Table 3 show that several comparison-group participants did score equal to or better than LN on the simple task. However, only one child from his age group and no children with similar years of lessons scored better on the transposed task.

Table 3
Melody discrimination test results: LN compared with sample of child musicians.

Task	Percentage of correct responses			LN percentile		Participants with scores equal to or better than LN	
	LN	Ages 10 to 12	4 to 6 yrs of lessons	Ages 10 to 12	4 to 6 yrs of lessons	Ages 10 to 12	4 to 6 yrs of lessons
Simple	90	80	78	72	83	12/40	5/25
Transposed	90	63	63	99	100	1/40	0/25

5. Sight reading and improvisation

5.1. Test description

LN's sight reading skills were evaluated using two pieces from the Associated Board exam requirements for grade 8 using a preparation workbook for examinations "Improve Your Sight reading" for piano by Harris (1993), Page 27 ("Scherzando") and Page 33 ("Delicato"). He was given 30 s to preview each piece, and then asked to perform them. The performances were audio and MIDI recorded for evaluation using two methods. First we asked a senior examiner from the Royal Conservatory of Music (RCM) to provide an evaluation using the RCM guidelines. She graded the performances as she would for a student at the ARCT level, since LN performs pieces at this level. She provided two grades: an overall grade based on accuracy of notes, rhythm, fluency and musicality, as well as a grade based on rhythmic accuracy only. For the second method we evaluated the performance in a more objective way as follows: the MIDI recordings were transferred to *GarageBand* software for transcription to a musical score. Performance accuracy was then determined using the Music Reading Scale (a music-reading assessment guide developed by the Piano Pedagogy Research Laboratory). An evaluator listened to the audio recording and determined the number of pitch and rhythm errors committed. Rhythm errors were identified as wrong note value or hesitation on a note-by-note basis if the duration of a note or rest is noticeably different than written in the score. Pitch errors were allocated to the following categories: inserted notes, wrong notes, omitted notes, restriking (a single note) and re-playing (a group of notes). The *GarageBand* transcription was used as an aid to confirm pitch and rhythm errors when the evaluator was uncertain using the audio recording alone. His performance accuracy was compared to three university level piano students who sight read the same two pieces.

LN's improvising skills were assessed by asking him to play a well-known tune, followed by improvisations on that tune in various styles. The first tune he was asked to play was Happy Birthday, followed by improvisations in the style of funeral march, a minuet, and a lullaby. The second tune he was asked to play was Mary Had a Little Lamb. LN responded that he did not know that song. After some discussion about children's songs he was a familiar with, he was asked to play Jingle Bells, followed by improvisations in the style of Debussy, then Mozart.

5.2. Results

The RCM examiner's scores for LN's sight reading performances (out of ten) were as follows: 6.5 (overall) and 7.5 (rhythm only) for piece 1, and 7 (overall) and 6 (rhythm only) for piece 2. LN's marks were below average, and not much higher than a passing grade (in the RCM grading system, a passing mark is 6, and an average mark is 8). These results were in agreement with the second evaluation method (using the Music Reading Scale), in which we found that LN's sight reading performances consisted of several errors including many hesitations resulting in performances without a consistent metre established that did not sound confident or convincing. In the first piece ("Scherzando") consisting of 101 notes, LN had 13 pitch errors and 37 rhythm errors. In the second piece ("Delicato") consisting of 145 notes, he had 16 pitch errors and 18 rhythm errors. In comparison, all three university level piano students committed fewer errors, as shown in Table 4.

LN was not enthusiastic about the improvising task, stating that he was "horrible at it". Indeed, he did not improvise as such, but simply harmonized by adding a left hand accompaniment while making some small adjustments appropriate for the style of improvisation that was requested. He played in a minor key for the funeral march, played slowly and quietly for the lullaby, and added an Alberti bass for Jingle Bells in the style of Mozart, but in all cases he did very little to improvise on the themes. He did not attempt to play Jingle Bells in the style of Debussy, stating "I have never played any Debussy".

Table 4
Comparison LN's sight reading errors with three university student pianists.

Piece	Error type	LN	JB	GW	ND
Piece 1	Pitch error	13	7	5	16
	Rhythm error	37	11	0	6
	Total	50	18	5	22
Piece 2	Pitch error	16	8	2	12
	Rhythm error	18	9	1	10
	Total errors	34	17	3	22

6. Pitch accuracy and musical memory

6.1. Measurement

To assess LN's pitch perception and musical memory, we used measures developed by German philosopher and psychologist Carl Stumpf in the early 20th century for his studies of music prodigies. Although known simply as an amateur musician, Stumpf had showed precocious musical talent as a child, learning the violin by the age of 7. By age 10, he had learned five other instruments and written his first musical composition. It is therefore not surprising that he became interested in psychometric testing of music prodigies. We chose this specific series of tests to be able to compare LN's results with the rare empirical assessment data available on another music prodigy, Nyiregyházi, who was tested by psychologist Géza Révész, (1916/2007) almost a century ago. To get information on these tests and to become familiar with the studies conducted in the early twentieth century by Carl Stumpf (1883, 1890) and Géza Révész (1916/2007), publications by both authors were consulted. The information and excerpts provided by Révész proved to be very useful; when selecting the tasks for pitch perception and musical memory, the tests and exercises were taken directly from these earlier studies.

To assess pitch accuracy, four tests were administered: frequency adjustment, singing, identification of a single note and identification of the notes of a complex chord. For the measurement of the first two pitch accuracy tests, we used the built-in microphone of a *Sony HDR-XR100* video camera and the audio-analysis tool *Wave Candy*. The frequency of the note produced was compared to the frequency of the target note. The difference between frequencies was converted to cents using an online conversion tool (available at: http://www.sengpielaudio.com/calculator-centsratio.htm). The measurement in cents was then converted to a fraction of a tone. Any result greater than a whole tone away from the target was reported according to its intervallic distance (minor third, perfect fourth etc.). For the two identification tasks, the names of the notes given by the participant were recorded and then analysed to find the number of correctly identified notes.

To assess musical memory, three tests were administered: listen and play from memory, practise with score and play from memory, and study the score and play from memory. For all three musical memory tests, both an audio and a MIDI recording were produced. The MIDI recording was then transferred to *GarageBand* software for transcription to a musical score. Performance accuracy was then determined using the Music Reading Scale (as described in Section 5). In addition to pitch and rhythm errors, the total number of notes played, total number of correct notes played, and total number of correct harmonies played were determined. Scoring identifying harmonies allowed the evaluator to give credit to a participant who might have identified a correct chord with an incorrect voicing or inversion. The result in this case would be a correct harmony with the possibility of having incorrect notes in the melody. One piece did not have clearly defined accompanying harmonies because of its contrapuntal nature; as such, the only measurement employed in the evaluation of that particular piece was correct notes. In some cases, the number of notes played by the participant exceeded the number of actual notes in the piece. This can occur when the participant 'brushes' up against a wrong note, begins a phrase and

then goes back to repeat it in order to correct a wrong or missed note, fills in a harmony with too many notes, or plays extra notes while experimenting or searching for the correct ones.

LN's pitch accuracy and musical memory were then compared to a prodigy from the early 1900s, Erwin Nyiregyházi (1903–1987), who was a Hungarian-born American composer and pianist. He started piano at around age 3 and began formal lessons at age 4 at the National Hungarian Royal Academy of Music with teachers Istvàn Thomàn and Arnold Szèkely. Nyiregyházi was said to have displayed his gift of perfect pitch before the age of three by reproducing melodies he heard with a mouth organ.

LN's results were first compared with three university music students with absolute pitch who completed the same pitch and memory tests. SM started lessons at age 6, had completed her ARCT (Associate of The Royal Conservatory of Toronto) level and had perfect pitch. She was 22 years old and an undergraduate student at the time of the testing. YL's starting age is unknown; she had completed her ARCT level, had perfect pitch and had completed a BA in piano performance and an MA in music. She was 31 years old at the time of the testing. JP started lessons at the age of 3, had completed her ARCT level and had perfect pitch. She was 34 years old at the time of the testing and was currently enrolled in an MA in music. They were all tested by the Piano Pedagogy Research Laboratory at the University of Ottawa, Canada. The piano used was a 7′6″ acoustic Yamaha piano with optical sensors and integrated MIDI operating system (Disklavier). All of the tests were video-recorded for reference.

6.2. Pitch accuracy – frequency adjustment

6.2.1. Test description

The equipment used for this task included a 'pitch slider' (Hutchins & Peretz, 2012) which is an electronic device that produces a sine wave that can be adjusted by sliding one's finger across a flat rectangular plane. This device was connected directly to a computer to record the exact frequency participants would respond with. The pitch slider is a modern version of the Stern Variator, which was a device constructed in the early twentieth century for the prodigy test trials of Stumpf and Révész. Participants were asked to find the given notes on the pitch slider. This task did not involve the presentation of any notes, but simply provided the name of the notes with an indication as being within an octave above or below C4 (middle C on the piano) which gave a potential range of two octaves (A3–A5). There was no time limit to find the pitches and participants were given one attempt per pitch. Notes given as targets are as follows: A4 (440 Hz), E3♭ (156 Hz), D4♯ (311 Hz), F4♯ (370 Hz), B4 (494 Hz), E4♭ (311 Hz), G4♭ (370 Hz). One note (E3♭) was not within the slider's range, but was included to see if participants would realize that.

6.2.2. Results

LN's frequency adjustment results with the slider were compared with three university students with perfect pitch. The accuracy of each participant in finding the given pitch is represented in Fig. 1. Note that the lighter columns indicate responses that were off by approximately one octave. In those cases, the error was calculated based on the note one octave higher or lower than the target note. When we look at the pitch production results for all seven notes, LN's results were consistently good and better than other students. Only once does his production result vary slightly more than 1/4 tone from the correct tone value. The results were further summarized in Fig. 2, showing the mean, minimum and maximum errors (using the absolute value of the errors). On average, LN's responses were off by 0.14 tones, compared to an average of 0.31 tones for the controls.

LN's results with the slider were also compared to Nyiregyházi's results on the Stern variator (Révész, 1916, 2007). When given a target note of A4, Nyiregyházi produced a frequency of 448 Hz. For the same target note LN produced a note on the slider with a frequency of

432 Hz. Both results are very close to the target note; LN was 5/32 of a tone (or 0.16 tones) below, and Nyiregyházi was the same distance above the target. However, this comparison assumes the frequency of A4 to be today's standard of 440 Hz. During the time when Nyiregyházi did this test, there was more tuning variability, so we cannot be sure of the exact frequency Nyiregyházi was accustomed to hearing for each note.

6.3. Pitch accuracy – singing

6.3.1. Test description

The second pitch production test required participants to sing, in a comfortable register, several notes named one at a time by the examiner: A – Eb – B – D♯ - Gb – F♯. Range or octave did not matter as the range was dependent on the participant's voice. They had one attempt for each note.

6.3.2. Results

LN's results in singing were compared with three university students with perfect pitch. The accuracy of each participant in finding the given pitch is represented in Fig. 3. The results are further summarized in Fig. 4, showing the mean, minimum and maximum errors (using the absolute value of the errors). LN's pitch production was very accurate: his least precise response was 1/8 of a tone distance from the exact note frequency. LN's results for this task were better than the comparison group where several responses were off by a full tone or more. On average, LN's responses were off by 1/16 of a tone, compared to an average of 1.1 tones for the control group.

6.4. Pitch accuracy – identification of a single note

6.4.1. Test description

Participants were asked to name a note that was played on a standard grand piano by the examiner. There was one attempt for each note played. Once the note was named, the examiner would play a quick chromatic scale in an attempt to erase any intervallic references the participant might use before quickly playing the next note. Notes: Low: A2b – A2b – D1 – A1b – E3 – C1♯ - B0; Middle: D4 – C5♯; High: C6♯ - C7♯ - C7♯ - F7♯. The names of the notes given by the participant were recorded and compared to the notes that were played by the examiner. We also looked for trends with respect to the register (low, middle, high) of each note.

6.4.2. Results

LN was able to correctly identify all notes in all registers (7 low; 2 middle; 4 high for a total of 13 notes). In a similar test conducted by Révész, Nyiregyházi's pitch identification results were 5% lower than LN's perfect score (Table 5). However, it should be noted that the test conducted by Révész included more notes in all registers (13 low; 13 middle; 13 high for a total of 39 notes) and Nyiregyházi answered only two notes (low register: specific notes were not stated) incorrectly (Révész, 1916/2007, p. 67).

LN's results were compared with three university students with perfect pitch. The accuracy of each participant in finding the given pitch is represented in Fig. 5. We observe that none of the university students' scores come close to LN's perfect score. When we evaluate the percentage of correct notes based on register, it shows in Fig. 5b that the middle register was the easiest register for the participants and the more extreme registers (low and high) were more difficult.

6.5. Pitch accuracy – identification of the notes of a complex chord

6.5.1. Test description

A series of chords ranging from four notes to six notes from Stumpf's (1883) initial study were played and the participant was asked to name the notes of each chord. The chords were dissonant 7th-type chords or
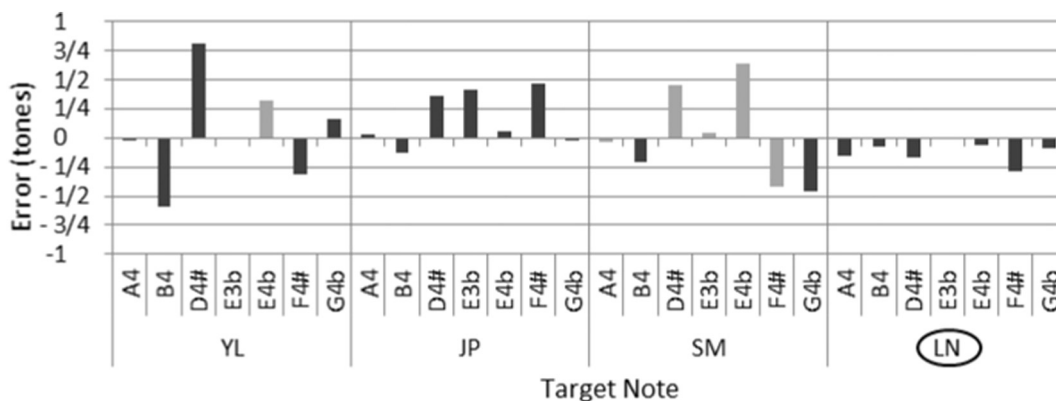
Fig. 1. Slider results - grey columns indicate responses that were off by approximately 1 octave.
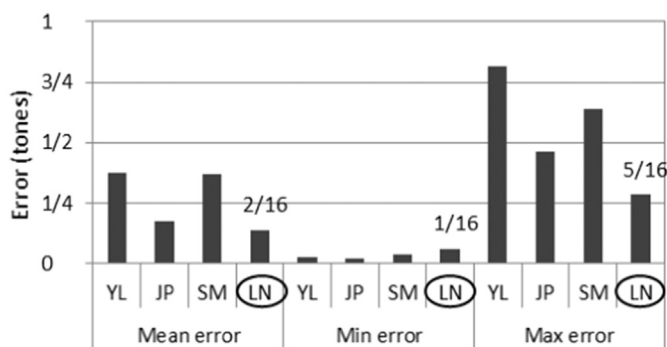

Fig. 2. Slider results (adjusted for wrong octave): the mean, minimum and maximum errors.
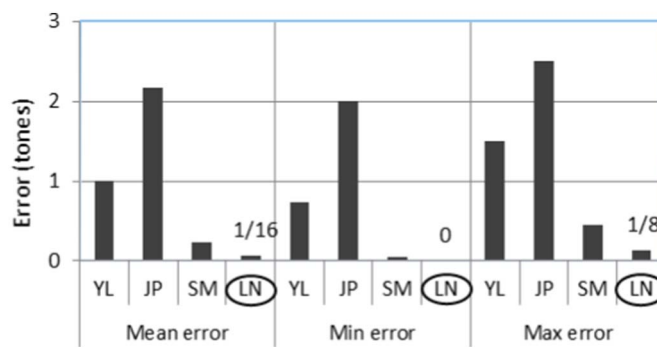

Fig. 4. Singing results: Mean error was calculated using the absolute value of the errors. Minimum and maximum errors are the absolute value of the actual errors.

cluster chords and were all played harmonically. Révész (1916/2007) described the manner of playing the chords for his testing of Nyiregyházi as follows: "… the chords were struck once, sharply." Thus, each chord was played for a very short duration, almost like a staccato, to be consistent with the testing by Révész. Fig. 6 illustrates the chords used for this test. Due to an examiner's error, chord 8 was omitted from the test. For the chord identification exercise, the total number of notes in each chord was calculated along with the number of correctly identified notes to determine a percentage of correct answers.

6.5.2. Results

LN correctly identified all chord notes in four of the eight examples (Fig. 7a) and almost 80% of correct notes in total (Fig. 7b). LN's results are impressive, but Nyiregyházi's results were even better (Révész, 1916/2007). He was able to correctly identify 97% of the chord notes, in comparison to LN, who identified 79% of the notes correctly.

Table 5
Comparison of Nyiregyházi's and LN's note identification results.

	Low notes	Middle notes	High notes	Total correct	Total notes	Percent correct
EN	11 out of 13	13 out of 13	13 out of 13	37	39	95%
LN	7 out of 7	2 out of 2	4 out of 4	13	13	100%

LN's results were compared with three university students with absolute pitch. Fig. 7a displays the number of chords perfectly identified and Fig. 7b displays the overall percentage of correct notes identified for all chords by LN and the comparaison group. LN's result of 79% of correct notes identified is significantly better than the comparison group, which range from no correctly identified notes to 20%.

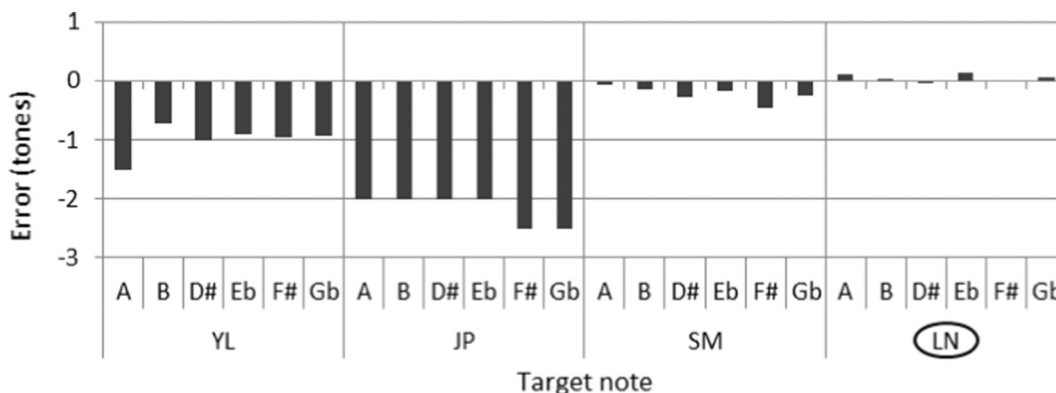A final comparison of the results for the single-note and chord

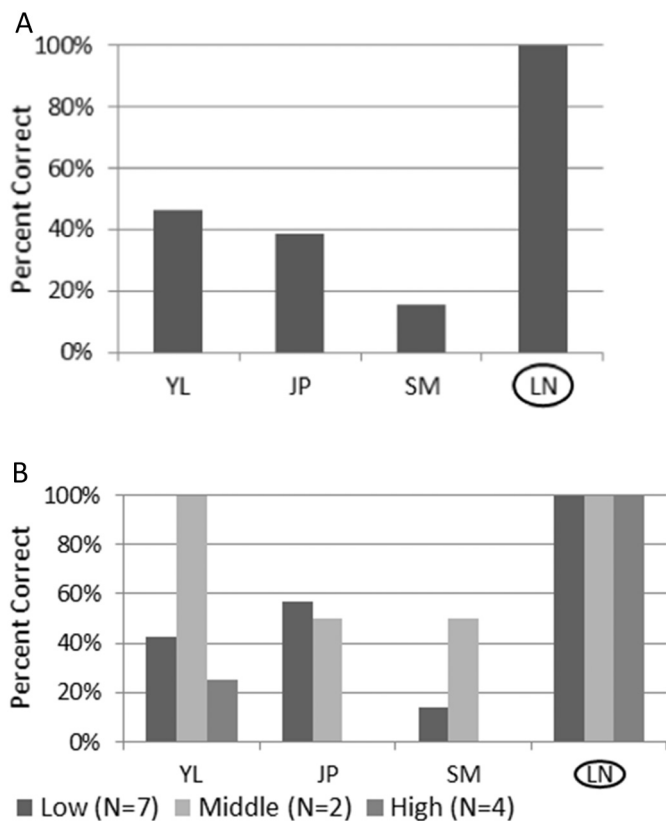Fig. 3. Singing results (adjusted for wrong octave).

Fig. 5. a. Single-note detection results. Percent correct indicates percentage of notes that were correctly identified. b. Single-note detection results divided by register (low, middle, high). Percent correct indicates percentage of notes that were correctly identified.
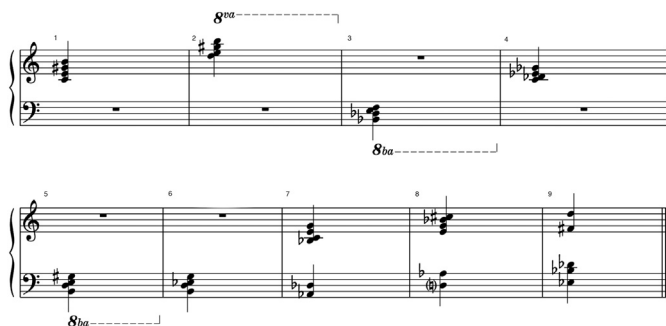

Fig. 6. Chords played in the chord identification test (Stumpf, 1890, pp. 369–370), and used in Révész, (1916/2007).
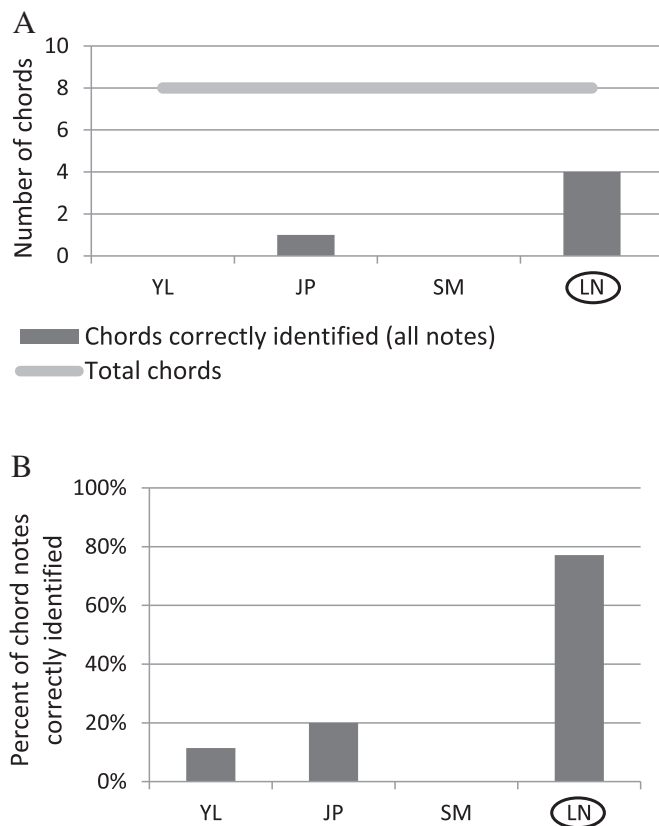

Fig. 7. a. Chord identification results: number of chords correctly identified for LN and three university students with absolute pitch. b. Chord identification results: percent of notes correctly identified for LN and three university students with absolute pitch.
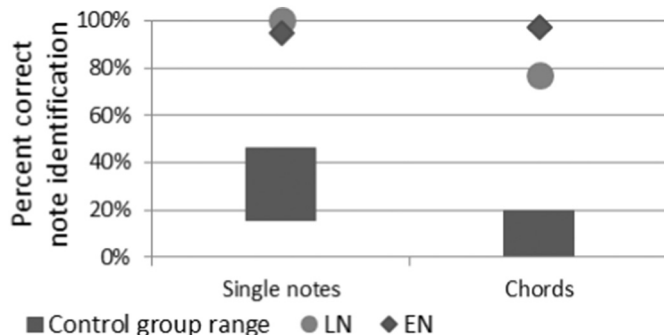

Fig. 8. Summary of results for the single note and chord identification tests.

identification tasks has been plotted in Fig. 8. The comparison of results for the single-note exercise shows that Nyiregyházi's results were slightly under LN's, and both were far better then control. The results from the chord identification test can be more accurately compared as the same set of chords was used in both tests. Nyiregyházi performed better than LN in the chord identification test, and both performed much better than the control group.

6.6. Musical memory – listen and play by ear

6.6.1. Test description

In this test, participants were asked to listen to a recording of two musical excerpts, each of 8 bars in length (Fig. 9a and b) and attempt to play them back. The tempo and style of each piece were contrasting, as well as the harmonic complexity. In order to track any potential improvement, three trials were taken by each participant for both pieces. Participants were first instructed to listen to the excerpt then attempt to

play it back as accurately as possible. After the first attempt, they listened a second time after which they would try to play it again, and finally the whole process was repeated a third time. The same procedure was followed for the second piece.

6.6.2. Results

LN's results are shown in Fig. 10. For Piece 1, LN asked to hear the piece an additional two times before attempting to play it back. For this reason, an additional attempt (trial 4) was included. For Piece 2, he attempted to play back the excerpt after the first listening. For the first attempt at both pieces, LN's accuracy is only slightly better than that of the 3 university students he was compared to. However, in the second attempt he improved significantly in comparison. With the second piece he made considerable improvement in trial 3 as he included the repeat. LN also played with very accurate rhythm. In his final trials, only 11% (10/87) of note durations were noticeably incorrect for piece 1 and 5% (13/267) were incorrect for piece 2. By comparison, the controls were
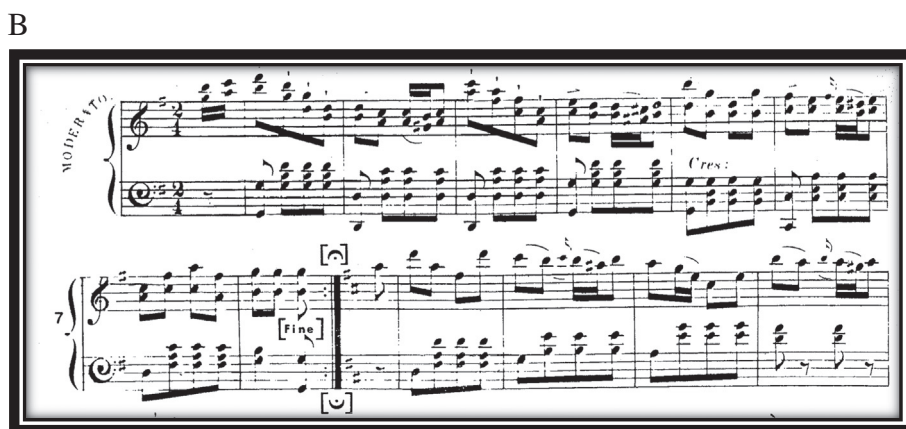
A

B

not able to play with accurate rhythm as they appeared to be primarily concerned with finding the correct notes in a trial and error manner. Consequently, none of them established a regular metre that could enable evaluators to determine the number of notes with correct or incorrect durations. This was consistent for the control group for the other two musical memory tests as well.

For LN, the number of correctly identified harmonies increased with each trial for piece 1. The other three university students did not show any improvement with respect to harmony identification through all trials of piece 1 (Fig. 11). LN and JP were able to consistently identify more harmonies with each trial in piece 2. LN performed best, correctly identifying all harmonies in piece 1 and 2 by the second trial and third trial respectively.

Révész 1916/2007 tested Nyiregyházi in a similar manner for musical memory, but a direct comparison with LN cannot be made because different pieces were used. Nyiregyházi was presented with pieces that were considerably simpler: the first listen-and-play piece consisted of one melodic line (that could be played in one hand) containing a total

of 13 notes. Nyiregyházi played this piece accurately on the third attempt. The second piece was more complex (containing notes in both hands, with two melodic lines in the right hand), but it was considerably shorter and less difficult than the pieces presented to LN.

6.7. Musical memory – practice the score and play

6.7.1. Task description

Participants were given 50 s to look at a short 2-bar excerpt (Fig. 12); then they played it through once with the score and once without the score. Then all participants repeated this process. This resulted in two practice trials and two memory trials.

6.7.2. Results

For his first attempt, LN played the first measure correctly and overall played 14 of the total 36 notes correctly. In his second trial, he played 34 correct notes out of 36, with most of the second bar as written. When LN was compared with the three university students with
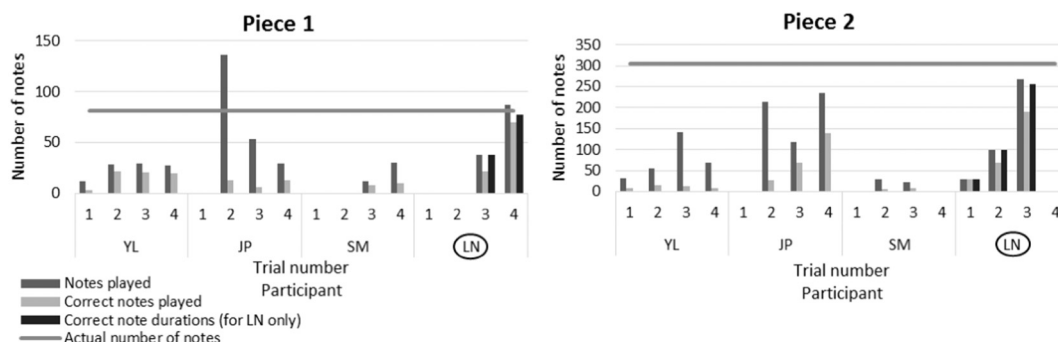

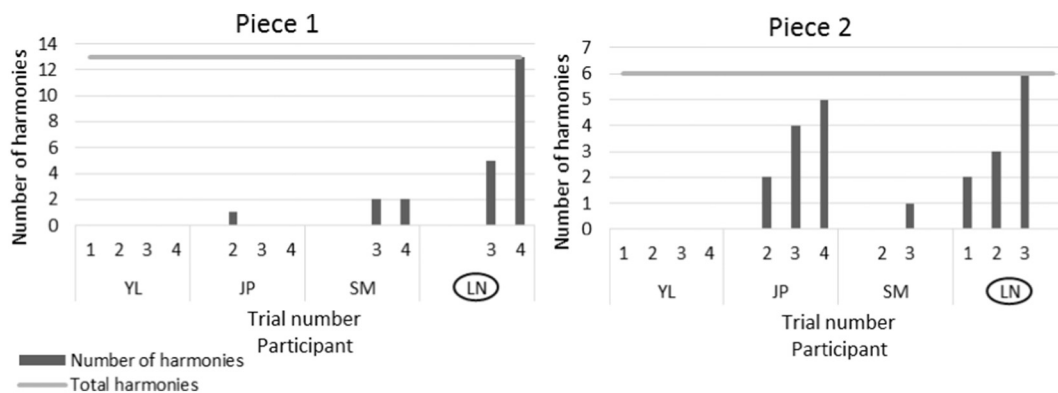**Fig. 10.** Total and correct number of notes played for each piece.

Fig. 11. Correctly played harmonies. Trial numbers are shown only when an attempt was made to play back.

Fig. 12. Theme presented for the practice a score and play from memory test. This musical excerpt is the same as used by Révész (1916/2007, p. 91) with Nyiregyházi.

perfect pitch, he performed significantly better (Fig. 13). His rhythm accuracy was very good in this test. By his last attempt he played all but one note with correct duration, whereas the controls' rhythm was played so inaccurately that it was not measurable, as explained above.

Nyiregyházi was also tested using the same musical excerpt. He was granted six trials when the experiment by Révész was originally conducted in 1910. Révész noted that after playing the piece for the first

time, no reproduction was possible on the first memory trial. During the second trial, the piece was also wrongly reproduced. Not until the third trial did Nyiregyházi reproduce the first bar correctly. Up until the sixth trial, the second bar could not be reproduced and the experiment was broken off (Révész, 1916/2007, p. 91). It is evident that LN was considerably more successful here.

6.8. Musical memory – study the score and play

6.8.1. Test description

Participants read through (without playing) a short 4-bar except (Fig. 14a) and 2-bar excerpt (Fig. 14b) and then played that excerpt from memory without the score. There was no time limit for looking at the score of the first piece, but there was a 60-second limit for the second piece. Participants were allowed two trials (studying the score and playing) for each piece.

6.8.2. Results

For this task, correct notes played and the type of errors were measured (Fig. 15). In his first attempt at piece 1, LN played approximately two thirds of the piece accurately, but could not continue from that point, leaving several notes of the fourth measure unplayed. His second attempt at piece 1 was nearly perfect as he succeeded in
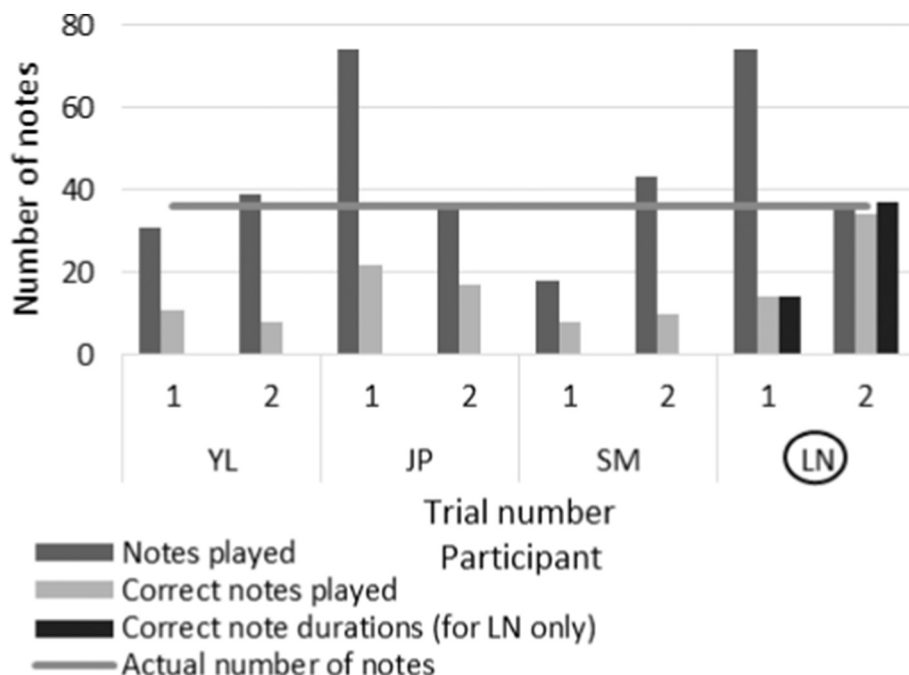
Fig. 13. Practice a score, then play from memory: total and correct number of notes played from memory.

A

Fig. 14. a. Theme 1 presented for the study score and play from memory test. This musical excerpt is the same as the one used by Révész, 1916/2007, p. 92) with Nyiregyházi. b. Theme 2 presented for the study score and play from memory test. This musical excerpt is the same as the one used by Révész (1916/2007, p. 94) with Nyiregyházi.

B

performing 42 correct notes out of 47. LN did even better with piece 2, getting almost all the correct notes with only one attempt. When LN was compared with three university students, he performed significantly better on both pieces. For piece 1, two of the university students did not improve the total number of notes played correctly. For piece 2, all participants showed an increase in the number of correct notes played in their second attempts, but none came close to LN's performance in his first attempt. Similarly, LN played with much more accurate rhythm than the controls. For piece 1 (trial 2), 6% (3/47) of note durations were incorrect. For piece 2 (only trial), 12% (4/34) of notes durations were incorrect.

The first musical excerpt had also been used to test the musical memory of Nyiregyházi. He was reported to have both hummed the score and pretended to play it while silently absorbing it. Because of this, Révész thought the task for testing Nyiregyházi's optical memory was compromised. It should be noted that Nyiregyházi reportedly took 6 min and 30 s and 8–9 read-throughs to memorize the score. In the first

trial, the first three bars were reported to be faultless and the fourth and final bars contained a few mistakes in the lower parts. The second trial contained no mistakes (Révész, 1916/2007, pg. 92–93). LN did neither the humming nor mimicking actions when absorbing the score; he sat at the piano quietly contemplating the music. When the score was removed, he played the first three bars successfully but stopped at the fourth bar. After studying the score for a second time, LN played the score without error. It should be noted that LN took only 2 min for the first attempt and 40 s for the second, even though he was instructed to take as much time as needed. The second piece was not used by Révész in the same way as it was used with LN, therefore a comparison cannot be made.
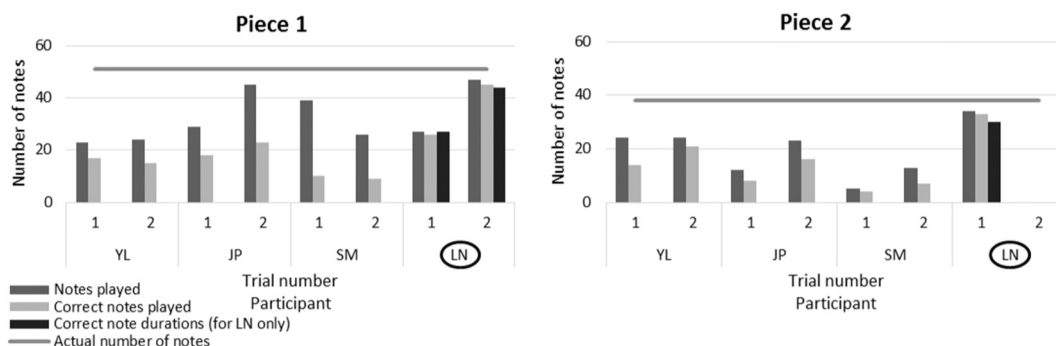

Fig. 15. Total and correct number of notes played for each piece.

7. General discussion

7.1. Background information

Interviews with LN, his mother, and his current teacher gave us specific information to build up an interesting case history. LN's situation is consistent with what is reported in other accounts of music prodigies: evidence of music talent or early signs of auditory skills prior to any training in music; access to an excellent teacher; sustained efforts of at least one parent willing to be totally devoted to the development of the child's talent; family environment that values and encourages the development of musical skills even when neither parent has had any previous formal musical training (Feldman, 1993; Feldman & Goldsmith, 1986; Feldman & Morelock, 2011; Jenkins, 2005; McPherson, 2007; Simonton, 1994).

Then empirical data collected through various tests of general intelligence and musical skills contributed specific information about LN's extraordinary qualities.

7.2. Working memory

As expected, LN's working memory was found to be excellent, in the rank between the 95 and 99 percentile, thus in line with other studies that identified exceptional working memory as a characteristic for all music prodigies for whom we have relevant data (Révész, 1916/2007; Ruthsatz & Detterman, 2003; Ruthsatz & Urbach, 2012; Stedman, 1924). It confirms the apparent dissociation observed in prodigies between their extraordinary working memory and their average or above average scores on other psychometric measures. The importance that working memory plays in the development of exceptional abilities has still not been explained. However, our study of LN indicates that a similar kind of dissociation might be observed within domain specific skills and here too, memory might play an important role.

7.3. Musical abilities

This case study provided the opportunity to examine a music prodigy who meets the criteria researchers commonly assigned to such children (i.e. young individuals who perform on their musical instrument at the same level as highly trained professionals). LN's playing performances make him a "young individual who, in record time, has moved to the most advanced levels of performance" (Feldman & Goldsmith, 1986, p. 79) and he clearly shows signs of "precocity, rapid learning, and quick ascent to a high performance level" (Howard, 2008, p. 117). He can "perform culturally relevant tasks at a level that is rare even among highly trained professional adults in their field" (Ruthsatz & Detterman, 2003, p. 510). However, it is important to point out that the common conception of a music prodigy relies essentially on evidence of extremely good performance skills (performing pieces on a musical instrument). In fact, proof of good musical aptitude or evidence of proficiency in other musical skills besides performance are not being considered in the criteria of that definition of a music prodigy. While related musical skills like sight reading, improvisation or ear training might be mentioned, they have not been measured in recent studies on music prodigies. It could be related to the mythical image of the young Mozart displaying exceptionality on so many different musical tasks. Some might assume that by observing evidence of phenomenal performing skills in young children, these prodigies must surely have outstanding musical aptitude on every musical parameter or exceptional abilities on any musical skills. However, when investigating LN's abilities in specific musical sub-skills, we found that this prodigy excels in tasks relying specifically on auditory pitch memory, but was average or below average on other tasks that are not associated so much to auditory memory.

7.4. Pitch accuracy

The skills showed by LN on the pitch accuracy tests appeared to be quite phenomenal. When compared with university students, LN consistently outperformed them in all exercises, often by a huge margin, even if the participants of the control group also had perfect pitch, were much older, were highly trained and were known as musically-gifted individuals. LN's score were also congruent with early 20th century studies of Nyiregyházi. Both prodigies showed outstanding skills in pitch accuracy and they outperformed highly trained musicians with perfect pitch. These results are interesting since this is, to our knowledge, the first study to investigate a contemporary prodigy and compare his score with empirical data from a prodigy of another era. The strong similarities in pitch accuracy between the two prodigies are remarkable.

Absolute pitch (also known as perfect pitch) is the ability to name or produce the note of a given pitch in the absence of a reference note. People who have absolute pitch can identify and name musical notes easily and rapidly, similar to the way most people name colors (Deutsch, 2013). It has been documented however that not all subjects who have been identified as having absolute pitch perform at the same level of accuracy (Bermudez and Zatorre, 2009a). LN and Nyiregyházi did obtain scores of 100% in the most common absolute pitch tasks (identifying single notes) while control groups did not perform as well. But the real difference was revealed when we tested for pitch discrimination using the tests that were administered to Erwin Nyiregyházi (Révész, 1916/2007). It became apparent that these tests were difficult enough to reveal the exceptional level of pitch discrimination skills displayed by the two prodigies (LN and Nyiregyházi) when compared to other high-level musicians. These exercises clearly establish their pitch discrimination 'superiority' by consistently showing an extremely high level of accuracy while other participants with absolute pitch obtained scores between 0 and 20%.

There is much evidence that people with absolute pitch have a particular brain structure circuitry that involves regions associated with pitch perception and memory (Bermudez & Zatorre, 2009b; Loui, Li, Hohmann, & Schlaug, 2011; Oechslin, Meyer, & Jäncke, 2010; Ohnishi et al., 2001; Schulze, Gaab, & Schlaug, 2009; Wilson, Lusher, Wan, Dudgeon, & Reutens, 2009). In a study researching the neuronal basis of absolute pitch, Elmer et al. (2015) identified a functional link between the auditory cortex (the brain regions that control early perception functions) and the dorsal frontal cortex (the brain regions involved in late memory functions). They believe that this coupling enables efficient exchange of information between the two areas; in other words, auditory and memory information can be quickly exchanged. The researchers explain that in absolute pitch possessors, auditory perception most likely depends on a strong link between the auditory cortex and the brain structures that process memory information.

Interesting differences have also been found between participants with and without perfect pitch in a study by Schulze et al. (2009). They believe that for possessors of absolute pitch, an early encoding phase of tones into specific pitch categories results in less reliance on working memory. The possibility that musicians with absolute pitch rely less on working memory for pitch processing can be an important factor contributing in the development of exceptional musical ability. It could 'free' the working memory from pitch processing and allow more resources for performance.

7.5. Melody discrimination

On melody discrimination, when compared with children of his age group, LN's melody results are just above average on the original melodies (64th percentile), but clearly outperformed the control group on the more difficult transposed melodies (99th percentile). The low results on the original melodies are most likely due to the fact that this melody discrimination test is not difficult enough to show the

exceptional level of melody discrimination skills that prodigies normally display. The melody discrimination task is another example of LN's proficiency on a skill that relies on auditory perception and memory functions.

7.6. Musical memory

Superior music memory – identified by the ability to remember large segments of music following very little exposure – is highly prevalent among music prodigies and is widely supported in the literature (Haroutounian, 2002; Ruthsatz & Detterman, 2003; Winner & Martino, 2000). There are numerous reports by music prodigy's parents that their child began to play by reproducing from memory pieces that they had heard (Ruthsatz, Ruthsatz, & Ruthsatz-Stephens, 2014; Kopiez & Lehmann, 2016). In the few rare occasions in which the musical memory of prodigies was tested, results confirmed the reports of the descriptive studies. For instance, when Révész (1916/2007) studied the 7-year-old Nyiregyhazi, a series of memory tests were administered and showed a short-term musical memory "almost equal to that of an adult musician tested. That is, [Nyiregyhazi] performed as well as the musician when asked to listen to pieces of music, commit them to memory, and play them back." (Winner & Martino, 1993, p. 268). When Ruthsatz and Detterman (2003) did a case study of a 6-year-old pianist, they mentioned that the most striking aspect of their investigation was his general and specific music memory capabilities. Exceptional memories have been reported consistently in case studies, both by descriptive accounts and empirical studies of musical prodigies.

Interestingly, LN performed extremely well on a task where he was required to study a score (by looking at the notes without playing) and to play it afterwards (without access to the score) while he did poorly on a sight reading task, when the procedure of both tests have many similarities. But LN explained that he finds it hard to read notes and play it at sight, but in the 'study a score and play' task, he was able to "look at the notes and hear the music in his head and memorise the sounds", then all he had to do was to "play the music he had memorised in his head". The ability to memorize and replay musical melodies with limited exposure, often better than older and well-trained music experts is most likely related to an exceptional pitch memory. This is again, an indication that superior memory ability may be a factor that helps to accelerate musical learning and should be looked at more closely in further studies.

7.7. Rhythm discrimination

LN's test results on rhythm synchronization are particularly interesting. When compared to a group of music students of the same age or to a group of music students with the same number of years of training, LN's results were slightly below average for the easy rhythm task and good, but not outstanding, for the two complex rhythm tasks (67 percentile for the metric simple and 83 percentile for the metric complex). If we compare LN's score with a group of young adult musicians (between 18 and 34 years old) who did the adult version of this test in a study by Bailey and Penhune (2010), LN is below average, an indication that he has not reached the rhythm skill level of young adult musicians. Rhythm synchronization is clearly not a skill that differentiates LN from other music students. Interestingly, rhythm abilities are rarely, if ever, discussed in reports on music prodigies and we have no empirical data on the rhythm skills of prodigies to which we could compare our findings. This is obviously an area that requires more investigation.

7.8. Sight reading and improvisation

LN did not do well on these two skills. This might not be too surprising as many professional musicians never reach expertise level in sight reading and improvisation. But what is particularly interesting in the context of this study is that LN performed extremely well on skills that depend on auditory pitch memory and not as well on other skills where this particular type of memory does not appear to be as central. In sight reading, a musician is involved with "perception (decoding note patterns), kinesthetic (executing motor programs), memory (recognizing patterns) and problem-solving skills (improvising and guessing)" (Lehmann & McArthur, 2002, p. 135). While sight reading is sometimes related to auditory skills (Sloboda, 1985), auditory pitch memory is usually not considered a subskill of sight reading (Lehmann & McArthur, 2002).

With improvisation, a performer is believed to rely on previously learned "musical material and excerpts, repertoire, sub skills, perceptual strategies, problem-solving routines, hierarchical memory structures and schemas, generalize motor programmes" (Pressing, 1998, p. 53). Kenny and Gellrich (2002) have identified eight cognitive processes at work during improvisation including anticipation, recall (of music that has just been played) and feedback processes. Improvisers often refer to their knowledge of musical structure and rely on "plans and strategies" (Lehmann, Sloboda, & Woody, 2007, p. 134) to explain the process of improvising. However, strong auditory pitch memory is rarely discussed in the literature on music improvisation and there are many musicians with amazing skills in improvisation who do not have absolute pitch; improvisation does not require the same cognitive process that we observed while testing LN.

8. Conclusion

By typically performing on their instrument at an adult level of competence while still young, "musical prodigies demonstrate above-age talent development" (Geake, 2008, p. 192). It is important to note however that the skills that prodigies displayed on their musical instruments will decline in degree of exceptionality over time (Humphreys, 1985; Jackson, 2000; Mills & Jackson, 1990) as other less precocious musicians will reach similar levels of performance (Bamberger, 1986). Interestingly, this study also investigated whether the "extreme precocity" (Morelock & Feldman, 2003) observed in performing music repertoire extend to pitch accuracy and musical memory, two skills related to auditory pitch memory. On these particular skills, LN's results show sign of precocity, "an earlier-than-expected, domain-specific development" (Edmunds & Noel, 2003, p. 185), but LN's pitch accuracy and musical memory could also be extraordinary abilities that even highly trained individuals will never reach. The highly trained university students with absolute pitch that we tested displayed auditory skills much below then LN's scores. Therefore, the outstanding auditory skills displayed by prodigies might not be so much a sign of precocious development as a set of skills that have developed far beyond the limits of many musicians who have had considerable training and have become experts in the field. While performance skills will decline in degree of exceptionality, it is possible that prodigies continue to display consistent superiority in their pitch accuracy and musical memory throughout their life, an indication that phenomenal auditory pitch memory is an important component to better understand and explain phenomenal musical talent.

While the focus of this case study was the collection and analysis of quantitative data from one particular music prodigy, and the comparison of this data with one historical prodigy and three control groups (regular music students of the same age, regular music students with the same number of years of music training and graduate university students with perfect pitch), a future project could compare a number of contemporary music prodigies in the same study to see how uniform they are in their musical skills. Another possibility would be to conduct empirical testing on a group of prodigies and a group of professional musicians, including professionals who were identified as prodigies and professionals who were never recognized as musically gifted in early childhood. This could potentially yield interesting insights into the characteristics of prodigies.

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