The Mensural Scoring-up Tool

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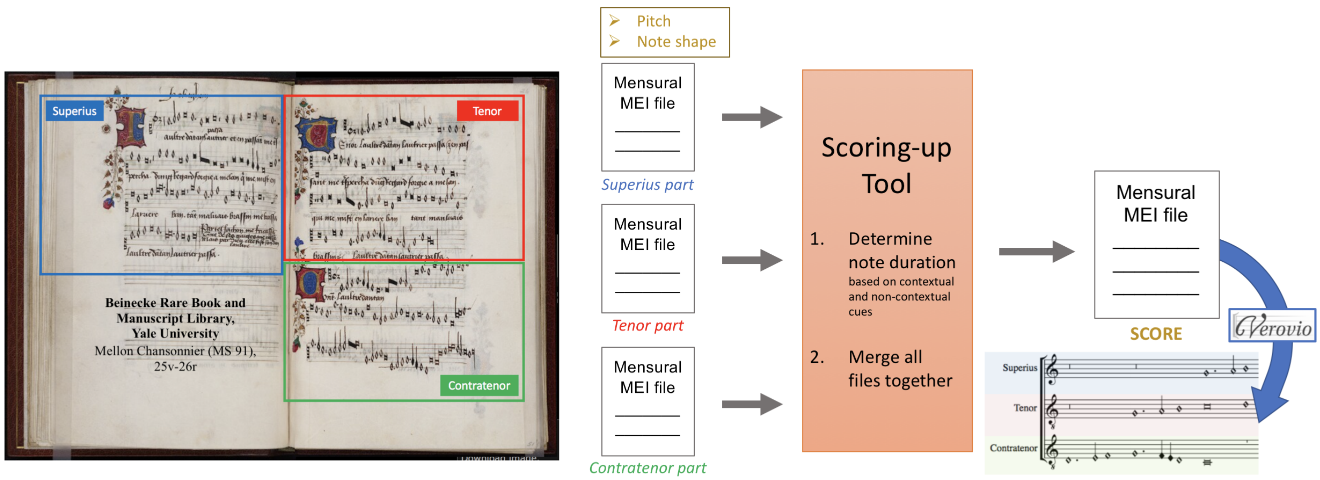

Figure 1: Mensural music is commonly written in separate parts. The Mensural Scoring-up Tool outputs a single file that, when rendered, presents the music as a score with the notes aligned vertically.

ABSTRACT

Vocal polyphonic music from 1280 to 1600 is written in mensural notation and it is typically presented in a layout with separate parts. In this paper, we introduce the *Mensural Scoring-up Tool*, a set of scripts designed to automatically transform the separate-parts representation of the music into a score by dealing with the context-dependent nature of the notation through the implementation of the principles of imperfection and alteration, outlined by Franco of Cologne (ca. 1280). This tool exhibits 97% accuracy in a corpus of fourteenth- and fifteenth-century pieces, including both black and white mensural notation. The new encoding generated by the Scoring-up Tool could be useful for digital libraries that have digitized their collections of mensural music documents since the symbolic score could accompany the digital images providing a representation that makes the music accessible to a larger audience—since these symbolic scores can easily allow for a conversion into modern values and for playback—and that facilitates music analysis for the experts.

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CCS CONCEPTS

• **Applied computing** → **Sound and music computing**; *Extensible Markup Language (XML)*; *Format and notation*; Digital libraries and archives; • **Information systems** → *Document representation*.

KEYWORDS

mensural notation, parts to score transformation, automatic transcription, encoding, Mensural MEI

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1 INTRODUCTION

The processes of digitization and optical music recognition (OMR) are useful to encode the musical content of music sources into machine-readable symbolic music files. Digital libraries conduct these processes to provide access to their music collections and make them searchable both by their metadata and musical content. In the case of music written in common Western music notation (CWMN), images and symbolic files usually provide enough information for a modern musician to understand the piece. But this is not true when the music is written in notational systems unfamiliar to modern musicians.

Vocal polyphonic music from 1280 to 1600—unless transcribed into modern notation—is performable only by the experts familiar with mensural notation. In mensural notation, the duration of the notes is not absolute but rather depends on the context (i.e., on the notes preceding or following a given note). To disambiguate the duration of the notes, the performer must be familiar with the principles of *imperfection* and *alteration* that describe how the duration of a note is affected by the context. Moreover, most mensural compositions keep their voices in separate areas of the page or book opening (e.g., the choirbook format) or even in different books (i.e., partbooks). This separate-parts layout obscures the visualization of the vertical sonorities which are evident when the music is represented as a score (see Figure 1).

In the case of mensural sources, digitization and OMR processes are not enough to provide a "performable" representation of the music. OMR can return information about the note's pitch and category (e.g., long, breve, and semibreve), but it is not designed to interpret the duration of the note. In this paper, we present a tool that interprets the duration of a mensural note based on a series of principles and rules. The *Mensural Scoring-Up Tool* deals with the context-dependence issue of mensural notation by implementing the principles of imperfection and alteration (section 3.1). It also handles other mensural notation specificities such as distinguishing between a *dot of division* and a *dot of augmentation* despite their identical appearance (section 3.2) and assigning the correct duration for groups of notes in *hemiola coloration* (section 3.3).

The Mensural Scoring-up Tool can be used at the end of an OMR workflow so that the music content retrieved by the OMR system can be further processed to encode the duration of each note. There are several OMR technologies that have already been used with mensural music—including Aruspix [13], a pair of convolutional neural networks for symbol and position classification [11], and a multi-modal symbol classifier [3]—and others that can be adapted to work with this repertoire—this includes the Gamera recognition framework [4, 7, 10] and a holistic staff recognition method using convolutional recurrent neural networks [2]. Once the music content is retrieved by the OMR system and the part corresponding to each voice has been encoded into a symbolic file, the Mensural Scoring-up Tool takes these files and returns a single one containing the information of all the voices plus the durational value of each of their notes. The symbolic files involved in the scoring-up process (both input and output) are to be encoded in the MEI format [9, 16] since this is one of the very few formats that allows for encoding mensural note values through its Mensural MEI module [17].[1] The resulting Mensural MEI file can be rendered using Verovio [14] to display the encoded score. In a digital archive, the image of the music document could be accompanied by this score, providing a representation of the music that can be understood by musicologists and performers without expertise in mensural notation. Potentially, since the result is a symbolic file, audio generated from the encoded score could also accompany the image, making the music accessible to non-musicians as well. The symbolic file itself could be used for counterpoint studies and other computational musicological analyses.

[1]Therefore, any intermediate representation returned by the OMR software must be transformed into Mensural MEI.

2 MENSURAL NOTATION

Mensural notation is the predecessor of the Common Western Music Notation (CWMN) system. When mensural notation started, there was already a way to explicitly notate pitch—through the use of staff lines and clefs. Mensural notation introduced the idea of using different note shapes to represent different note values. But the note shape by itself was not enough to explicitly convey the duration of the largest notes: maxima, long, breve, and semibreve. The relative duration values of these notes have two possibilities: a ternary value called *perfect* or a binary value called *imperfect* (see Table 1).

Table 1: The different relative durations of the four longest mensural notes.

Notes		Values				
Name	Shape	Perfect (3)			Imperfect (2)	
Maxima						
Long						
Breve						
Semibreve						

The actual duration of these four notes depends on two additional factors: mensuration and context. *Mensuration* establishes the relation between a note and that of the next smaller degree [1]. The mensuration at each of the largest four note levels is known as *maximodus* (for the maxima-long relation), *modus* (for the long-breve relation), *tempus* (for the breve-semibreve), and *prolation* (for the semibreve-minim). To give an example, if a section is in imperfect maximodus, perfect modus, imperfect tempus, and major prolation that means that **by default** the maximas and breves are imperfect and the longs and semibreves are perfect.

In imperfect mensuration, the note shape explicitly indicates a binary value (similar to CWMN). However, when there is perfect mensuration at any of these four note levels, the note shape is not enough to calculate the duration. In perfect mensurations, the duration of the individual note symbols is not absolute but rather depends on the *context*. The context refers to the notes preceding or following a particular note that can modify its default durational value (i.e., the value given by the mensuration). There are two main types of modifications due to context:

- *Imperfection*, when a perfect note becomes imperfect. It can be caused by the following (*imperfection a.p.p. = a parte post*) or the preceding (*imperfection a.p.a. = a parte ante*) notes.
- *Alteration*, when the duration of a note—either perfect or imperfect by default—is doubled.

The *principles of imperfection and alteration* describe the different scenarios in which these modifications must be applied. These principles are enumerated in Franco of Cologne's *Ars cantus mensurabilis* (ca. 1280) [18]. In Franco, the principles are written in terms of the long and the breve (i.e., at the long-breve level) but they were extended to the other three note-levels during the fourteenth century. According to Parrish [12], "the logic behind these principles is that the underlying movement of the music is by a series of perfections, each of which is three breves long [also referring to the long-breve level]" (see Figure 2). In other words, the principles are driven by the idea of applying modifications (imperfection and alteration) to keep the structure of the music in triple meter (i.e., perfect mensuration). The implementation of these principles in the Mensural Scoring-up Tool follows this idea (see section 3.1).

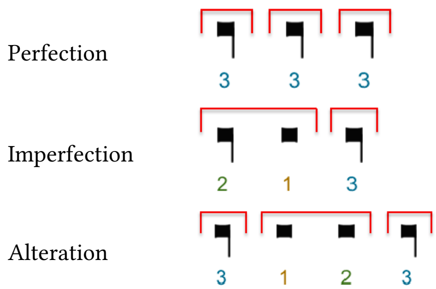

Figure 2: Examples of the different principles. The numbers below the notes indicate the durational values in terms of the breve while the brackets above mark the groups of notes that form a perfection. These brackets illustrate the use of the principles of imperfection and alteration as a way to keep the structure of the music in triple meter.

The *dot of division* is used to indicate a different grouping of perfections. For this reason, it can only be used in perfect mensurations. The rearrangement of the perfect groupings results in a different interpretation of the sequence of notes (see Figure 3).

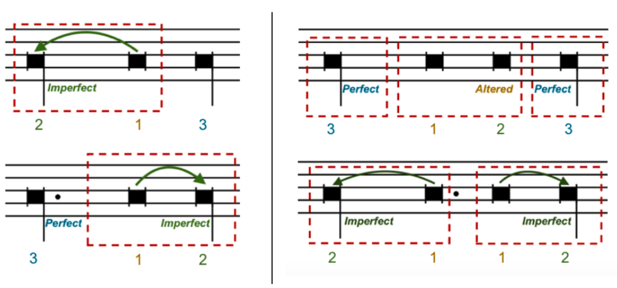

Figure 3: Change in the interpretation and perfect groupings (dotted red boxes) of the sequences in Figure 2 (middle and bottom) by the use of a dot of division.

There are other non-context-related features that can modify the durational value given to a note by the mensuration; these are dots of augmentation and coloration. A *dot of augmentation* is applied to imperfect notes and—similar to a dotted note in CWMN—it increments a note by half of its value, making it perfect. While the effect of the dots of division and augmentation is distinct, both of them are identical in appearance. The issue of identifying a dot as a dot of division or a dot of augmentation is addressed by the Scoring-up Tool (see section 3.2). On the other hand, *coloration* consists of writing a group of notes on a different ink color to momentarily modify their relative values. Since we are focusing on perfect mensurations, the case of coloration considered in this work is *hemiola coloration*, named after the 3:2 relation between colored and uncolored notes. Hemiola coloration is applied at a particular note level. All colored notes are imperfect, which causes colored notes at a level higher than or equal to the hemiola-coloration level to be reduced to two-thirds of their uncolored value, while those at a lower level have the same value as their uncolored counterparts. An example for *hemiola temporis* (where the hemiola-coloration level corresponds to the breve) is shown in Figure 4.

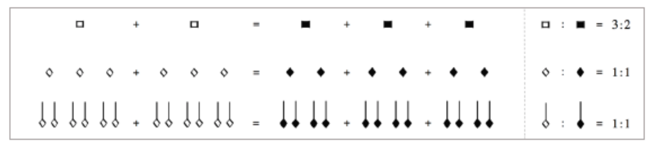

Figure 4: In hemiola temporis, 3 colored breves take the place of 2 uncolored ones (first equation). When substituting the breves by semibreves, since the colored breves are imperfect and the uncolored breves are perfect, the total of colored and uncolored semibreves is the same in both sides of the equation. The relation between colored and uncolored semibreves (and other smaller note values) in hemiola temporis is 1:1.

3 THE SCORING-UP TOOL

The Mensural Scoring-up Tool is implemented as a set of Python scripts.[2] For each piece, the Scoring-up Tool takes as input a set of Mensural MEI files encoding each of the voices of the piece. These input files contain information about the voice's mensuration and the pitch and note-shape of each of its notes. The output of the Scoring-up Tool consists of a single Mensural MEI file that contains all the information about the notes provided in the input files plus the durational value of each of these notes. When this Mensural MEI file is rendered in Verovio, the piece is displayed as a score with its notes vertically aligned (see Figure 1).

The Scoring-up Tool has two modules needed for producing this output file: one for determining the duration of the notes based on contextual and non-contextual cues, and another to merge all input files together. These modules can be applied in any order. While merging the input files is a trivial process (see Appendix C), finding the notes' duration involves the application of the principles of imperfection and alteration (to deal with the context-related features), the distinction between the dots of division and dots of augmentation, and the handling of hemiola coloration. The following sections will expand on each of these issues and how they are implemented within the Scoring-up Tool.

3.1 Implementation of the Principles of Imperfection and Alteration

Franco's principles regarding the interpretation of the long and the breve are written in terms of the number of breves between two consecutive longs. Therefore, to implement these principles

[2]https://github.com/ELVIS-Project/scoring-up

to correctly interpret a voice in triple meter we will: (1) divide the musical content of the voice into this type of sequences and (2) compute the number of notes between the boundaries of each sequence—in terms of breves (for perfect modus), semibreves (for perfect tempus), or minims (for major prolation)—to determine the note (or notes) to modify.

3.1.1 Delimitation of Subsequences. The first step in dividing the musical content M of a voice into subsequences is to determine the note used as *delimiter* for these sequences. The delimiter note is the note that is in perfect mensuration (e.g., in perfect modus the delimiter note is the long). Once the delimiter note is set, a *delimited* (or *bounded*) *sequence* of notes may be defined. A delimited sequence $S = (s_i)_{i=1}^{k}$ is defined as a subsequence of consecutive elements (notes and rests) of M such that s_1 and s_k are either uncolored notes (or rests) with a note value higher or equal to the delimiter note or colored notes with any value, and $s_2, \ldots, s_{k-1}$ are uncolored elements (notes or rests) with a value lower than the value of the delimiter note. The start note s_1 and the end note s_k of the sequence are called the *boundaries* (or *boundary notes*) of the sequence, and the notes between these boundaries are the *middle notes* of the sequence. Table 2 shows the notes used as delimiters and the notes used as boundaries for the different types of perfect mensuration.

As an example of how to locate the delimited sequences S that divide a voice, let us consider $M = (m_1, \ldots, m_{15})$ to be the first fifteen elements (notes and rests) of a voice written in perfect modus, as shown in Figure 5. Given the mensuration, the long is used as the delimiter note to define the delimited sequences S to divide M. This means that the sequences $(s_i)_{i=1}^{k}$ can have either an uncolored long or maxima, or any colored note at the s_1 and s_k boundaries, but the notes $s_2, \ldots, s_{k-1}$ must be uncolored notes shorter than a long (i.e., uncolored breves, semibreves, minims, etc.). Thus, the musical content M of the voice is divided into the following sequences delimited by the long: (m_1, m_2, m_3), $(m_3, m_4, m_5, m_6, m_7, m_8)$, (m_8, m_9), (m_9, m_{10}, m_{11}), (m_{11}, m_{12}), (m_{12}, m_{13}), and (m_{13}, m_{14}, m_{15}).

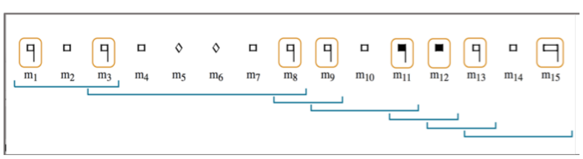

Figure 5: Example of a fifteen-note excerpt divided into sequences delimited by longs. The brown boxes indicate the notes that act as boundaries for each of the delimited sequences, and the blue brackets encompass all the notes that are part of each of these delimited sequences.

In two special cases the start note or the end note of a delimited sequence is assigned a value of *None*; the first case is when the first note m_1 of a voice is a note (or rest) that has a value lower than the delimiter (see Figure 6), and the second case is in the presence of a dot of division (see Figure 7).

3.1.2 Application of Modifications. The principles outlined by Franco take a sequence of notes delimited by longs and then perform the following actions:

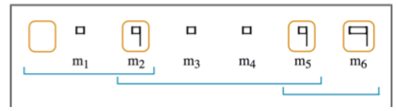

Figure 6: Example of a six-note excerpt that begins with a note shorter than the note used as delimiter (the long). The yellow boxes indicate the notes that act as boundaries for the delimited sequences, and the blue lines encompass all the notes that are part of each of these sequences, the first one being $(None, m_1, m_2)$.

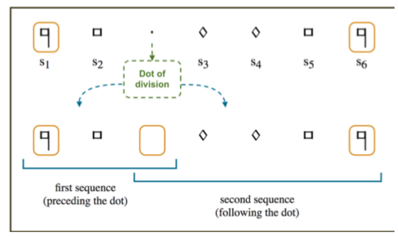

Figure 7: Example of the division of a sequence delimited by longs into two subsequences (also delimited by longs) due to the presence of a dot of division. The start note of the first subsequence is the same as the start note of the larger sequence, but its end note is now set to *None*. The start note of the second subsequence is *None*, and its end note coincides with the end note of the larger sequence.

(1) Arrange the notes into perfect groupings (i.e., groups of three breves).
(2) Determine the number of notes left out of these groupings.
(3) And, based on this number, modify the durational value of a note (or notes) by either imperfecting one or both of the longs at the boundaries of the sequence or altering the last breve.

Thus, we reformulated these principles in terms of a *modulo 3* operation as shown in Table 3. Even though the table is written for the case of perfect modus, the same applies to the other perfect mensurations. Thus, the variables n and p refer to the semibreves in perfect tempus, and to the minims in major prolation.

The Scoring-up Tool follows the "general interpretation" in Table 3 unless there are conditions that force an "alternative interpretation" of the sequence by forbidding one of the aspects of the general interpretation—this is, by forbidding either one of the two forms of imperfection, forbidding alteration, or even not allowing a note to keep its perfect durational value. The most common conditions include the use of a dot of division or that the note to be modified is actually a rest or has been substituted by smaller note values. The complete list of these conditions and the notes in the sequence $(s_i)_{i=1}^{k}$ they refer to are shown in Table 4.

So far, these two operations—delimitation of subsequences and application of modifications—have been described in terms of perfect mensuration at one note level. When perfect mensuration is

Table 2: Delimiter and boundary notes to define the delimited sequences for the different types of perfect mensuration.

Mensuration	Delimiter note	Boundary notes
Perfect modus	Long	Uncolored longs and maximas or any colored note
Perfect tempus	Breve	Uncolored breves, longs, and maximas or any colored note
Major prolation	Semibreve	Uncolored semibreves, breves, longs and maximas or any colored note

Table 3: Implementation of Franco's rules regarding the interpretation of longs and breves as a modulo 3 operation.

Number of breves between the boundaries (n)	Number of perfect groups of breves (p)	General Interpretation	Alternative Interpretation
$n = 3p + 1$	$p \geq 0$	Imperfection a.p.p.	Imperfection a.p.a.
$n = 3p + 2$	$p = 0$	Alteration	Imperfection a.p.p. & Imperfection a.p.a.
	$p > 0$	Imperfection a.p.p. & Imperfection a.p.a.	Alteration
$n = 3p$	$p = 0$	Start note remains perfect	
	$p = 1$	Start note remains perfect	Imperfection a.p.p & Alteration
	$p > 1$	Imperfection a.p.p. & Alteration	Start note remains perfect

present at multiple note levels in a voice, the Scoring-up Tool defines and processes the sequences delimited by short notes first, and then proceeds to sequences delimited by larger notes.

3.2 Distinction of the Dot Functionality

The distinction of the dot's functionality between augmentation and division is based on four premises. The first two are based on how Franco describes the use of a dot of division at the long-breve level:[3]

(1) A dot of perfection comes directly after the start note of a delimited sequence. That is, it is zero units away from s_1.
(2) A dot of imperfection is one unit away from the start note s_1, where the unit is a breve in the case of perfect modus, a semibreve in the case of perfect tempus, and a minim in the case of major prolation.

The other two premises correspond to our own hypotheses, based on examples,[4] regarding the case where a delimited sequence contains more than one dot:

(3) There can only be one dot of division (or perfection) in a delimited sequence.[5]
(4) The first dot is the only candidate for being a dot of division (or perfection).

[3]In [18, p. 120–2], he places the dot either after the start note, where it would forbid an imperfection a.p.p. (behaving as a dot of perfection), or one breve away from the start note, where it would imply an imperfection a.p.p.
[4]We looked at 20 songs in Duffin's edition [8] of the GB-Ob MS for examples of delimited sequences with multiple dots. Although these examples were not numerous, in the vast majority of them all the dots were dots of augmentation. There was only one piece in which this was not the case: the first dot of the sequence was a dot of division which was followed by dots of augmentation.
[5]This is true since we are not dealing with *Ars antiqua* repertoire, where sequences can have more than one dot of division.

Following these four premises, for each delimited sequence $(s_i)_{i=1}^{k}$, the Scoring-up Tool determines the functionality of the first dot by computing the distance between the start note s_1 and this dot. Any following dots in the sequence are considered to be dots of augmentation (or dots of perfection acting at a smaller note level). Regarding the distance between the first dot and s_1, the following three scenarios are considered:

- The distance $d = 0$. Then the dot is classified as a dot of perfection.
- The distance is $0 < d < 1$ or $d > 1$. Then the dot is classified as a dot of augmentation.
- The distance is $d = 1$. This dot could be either a dot of division or a dot of augmentation. Therefore, to determine the functionality of the dot, the Scoring-up Tool looks at the second part of the sequence (i.e., the one following the dot). Let us consider that the dot lies between the notes s_j and s_{j+1}. Thus, the middle notes of the sequence can then be divided into two parts: the subsequence $(s_2, \ldots, s_j)$ of notes preceding the dot and the subsequence $(s_{j+1}, \ldots, s_{k-1})$ of notes following the dot. It has been established that the $\sum_{i=2}^{j} s_i$ is equal to one breve. On the other hand, the sum of the notes after the dot $\sum_{i=j+1}^{k-1} s_i$ has two possibilities: being an integer or not. If it is an integer, then the dot is considered a dot of division since it is dividing the sequence $(s_i)_{i=1}^{k}$ into two parts with an integer number of breves, each of which would have an effect on each of the boundary notes. On the other hand, if it is not an integer, the dot is considered an augmentation dot and the fractional part of the sum $\sum_{i=j+1}^{k-1} s_i$ would be completed by the additional $\frac{s_j}{2}$ value generated by this augmentation dot.

Table 4: Conditions that prevent imperfection, either of the start note (imperfection a.p.p.) or of the end note (imperfection a.p.a.) of the sequence, alteration, or that do not allow the start note to keep its perfect durational value.

Interpretation	Conditions that prevent a given interpretation	
	Related to the note	Condition of the note
Imperfection a.p.p.	Start note (s_1)	It has a value of *None*
		It is a rest
		It has a value higher than that of the delimiter note (e.g., in perfect modus, this happens when s_1 is a maxima rather than a long)
		It has a dot (i.e., dot of perfection)
		It has already been modified by the previous notes (i.e., imperfection a.p.a.)
Imperfection a.p.a.	End note (s_k)	It has a value of *None*
		It is a rest
		It has a value higher than that of the delimiter note
		It has a dot (i.e., dot of perfection)
		It is followed by a note of the same type (e.g., in perfect modus, this happens when a long is followed by another long, then the first long must be perfect)
Alteration	Last middle note (s_{k-1})	It is a rest
		It is smaller than supposed to (e.g., in perfect modus, this happens when the last breve is substituted by smaller note values such as two semibreves)
Remain perfect	Start note (s_1)	There is a dot of division
		It has already been modified by the previous notes

In the case of a dot of division, the delimited sequence $(s_i)_{i=1}^{k}$ is separated into two sequences of the form $(s_1, \ldots, s_j, None)$ and $(None, s_{j+1}, \ldots, s_k)$, given that the dot is placed between the s_j and s_{j+1} notes (see Figure 7). Each of these two sequences is processed separately according to the procedures presented in Section 3.1.

3.3 Hemiola Coloration

In the Scoring-up Tool, the level of hemiola coloration is defined as the largest colored note whose uncolored durational value, according to the mensuration, would be perfect. After determining the level of the hemiola coloration, all colored notes at a level higher than or equal to the hemiola-coloration level are reduced to two-thirds of their uncolored value, while the value of the ones on a lower level is kept unchanged.

3.4 Encoding of the Features

Imperfection, alteration, augmentation (due to the presence of a dot of augmentation), the nature of the dot (division or augmentation), and the effect of coloration are encoded within the Mensural MEI file returned by the Scoring-up Tool. Table 5 shows the MEI attributes and elements used to encode these features.

4 EXPERIMENT

4.1 Corpus and Metric

We tested the performance of the Mensural Scoring-up Tool in a set of fourteenth- and fifteenth-century pieces, all of which included perfect mensuration at least at one note level (Appendix A: Dataset). We compared the Mensural MEI file resulting from the scoring up against a ground-truth Mensural MEI score, which encoded the correct durational values for each of the notes. At the beginning of this work, not only there was no existing repertoire encoded in Mensural MEI but also there was no way to encode the dataset into Mensural MEI files other than hand-coding them. Concurrently, Martha Thomae was working with Desmond on the Measuring Polyphony Project [5, 6] and developed a tool for transforming annotated modern transcriptions (encoded in CMN MEI) of mensural pieces back into mensural notation (encoded in Mensural MEI). We used this tool, the Mensural MEI Translator,[6] to build our corpus. The Translator can only work if the modern transcription has been annotated to account for mensural notation specificities that are not part of regular modern transcriptions (e.g., markings for alterations and dots of division). So, even though the time for encoding the Mensural MEI files of our dataset was reduced greatly using this tool, the annotation of the modern transcriptions and the verification of their consistency with the originals only allowed for creating a small dataset of nineteen pieces: 8 from the fourteenth century and 11 from the fifteenth. The modern transcriptions used to create the Mensural MEI ground truth and input files were obtained from the Choral Public Domain Library (CPDL),[7] the Josquin Research Project (JRP),[8] and the Measuring Polyphony Project.[9] This workaround of using annotated modern transcriptions to encode the pieces in Mensural MEI was needed to avoid the time-consuming task of encoding the Mensural MEI files by hand. Current developments in Humdrum have introduced another option. The ***mens* format has been designed as a way to simplify the writing of Mensural MEI [15].

Regarding the metric used to evaluate the performance of the Scoring-up Tool, we determined the tool's accuracy in identifying

[6] https://github.com/DDMAL/CMN-MEI_to_MensuralMEI_Translator
[7] http://www.cpdl.org/wiki/
[8] http://josquin.stanford.edu
[9] https://measuringpolyphony.org

Table 5: MEI attributes, and their corresponding elements, used to encode note-value modifications and dot functionality.

Feature	MEI Attributes	MEI Elements
Imperfection	@num="3" @numbase="2"	<note>
Alteration	@num="1" @numbase="2"	<note>
Augmentation	@num="2" @numbase="3"	<note> <rest>
Dot of division	@form = "div"	<dot>
Dot of augmentation	@form = "aug"	<dot>
Hemiola effect	@num="3" @numbase="2"	<note>

which note values should or should not be modified (from their default value given by the mensuration) from the set of all modifiable notes in a piece (see Table 6).

4.2 Results and Discussion

The accuracy results for each piece were high, ranging from 90.6% to 100% and the vast majority being above 97%. The quality of the notes (this is, their label as perfect, imperfect, or altered) was incorrect for only 55 out of a total of 2866 modifiable notes in the corpus (see Table 7). The largest source of error by far is the lack of a dot of division in sequences that, according to the ground truth, are supposed to follow the "alternative interpretation". A missing dot of division can cause the misinterpretation of either 2 or 3 notes (for $n = 3p$ and $n = 3p + 2$ sequences, respectively). In this case, its absence in 11 instances caused 25 notes to be misclassified as perfect/imperfect/altered. The second most common mistake was that the Scoring-up Tool assigned the wrong duration to the last note of the voices in some pieces. This is because the tool is designed to interpret the value of these notes according to the mensuration. But, in the contemporaneous musical practice, the last long at the end of each voice on a piece was not meant to have a fixed duration.

There were other two types of errors related to dots. First, in the Scoring-up Tool, we did not consider adding support for *dots of alteration*. These are dots of division that are used close to the end of a delimited sequence to indicate that the penultimate note (s_{k-1}) should be altered. Franco did not provide examples of dots of alteration and, moreover, alteration can result from the rearrangement of the perfect groupings of notes due to the presence of a dot of perfection or imperfection. This is the reason why dots of perfection and imperfection were the only two types of dots of division implemented in the Scoring-up Tool. The dot of alteration is mentioned by Willi Apel [1], but the examples he provides are dots that also fall into the categories of either a dot of perfection or imperfection (see Figure 8). This experiment provided the opportunity to verify that dots of alteration are actually used and although an alteration can be a "secondary" effect of a dot of perfection or imperfection, the dot of alteration stresses that this is the modification to be made. The second type of error consisted of one instance where a dot of perfection was placed in a position other than following the start note (s_1), for which the Scoring-up Tool automatically classified it as a dot of augmentation due to the premises outlined in Section 3.2. Apparently, at least in this dataset, the idea that there is only one dot of division per delimited sequence is correct, but the assumptions about its placement will have to be modified to account for dots of alteration and for dots of division that are farther from the beginning of the sequence. Although there were very few dots of alteration compared to dots of perfection and imperfection, we have to evaluate both ends of the delimited sequence to be comprehensive in our search for dots of division. We also need to allow for the dot to be at values other than $d = 0$ (for a dot of perfection) or $d = 1$ (for a dot of imperfection). As long as the distance d is an integer, the dot is a candidate for being a dot of division. After locating the dot of division, all the following dots (in the case of a dot of perfection or imperfection) or all the preceding dots (in the case of a dot of alteration) can be considered as dots of augmentation.

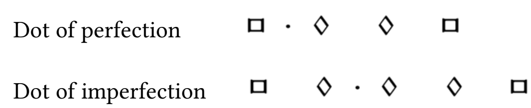

Figure 8: These dots of perfection and imperfection are also dots of alteration since they are placed two-semibreves away from the end, stressing the alteration of the last semibreve.

We must also consider the position of the semibreve rests within the staff. Whether two consecutive semibreve rests lie on the same staff line has an effect on the perfect groupings and, therefore, on the notes which are modified by the context. This issue is both an error in our dataset, which does not encode the position of the semibreve rests, and in our tool. We should also consider that sometimes the groups of notes that are supposed to be in hemiola coloration are not completely colored. The most interesting source of error is that two of the pieces from the mid-fifteenth century did not follow Franco's rules for imperfection and alteration. In these two pieces, we can see evidence of the transition towards sixteenth-century mensural notation where the principle of alteration falls into disuse and where local context gains precedence over global context. For more details and examples of each source of error, see [19].

5 CONCLUSIONS

In this paper, we presented the first approach to the automatic scoring up of mensural music written after the thirteenth century. Mensural music is typically characterized by the presentation of the sources in separate parts and by the context-dependent nature of the durational value of its notes. The Mensural Scoring-up Tool takes a set of Mensural MEI files that encode the mensuration, the pitch, and the note-shape information of each of the voices of a mensural piece; it determines the durational value of each note

Table 6: Categories of modifiable notes on a mensural piece.

Categories of Modifiable Notes (M.N.)		Requirements for belonging to a M. N. category	Quality of a note in a M. N. category
Notes subject to modification by context	Notes subject to imperfection (perfect notes)	Non-colored note	Perfect OR Imperfect
	Notes subject to alteration	Penultimate note in a sequence that has either $3p + 2$ (with $p \geq 0$) or $3p$ (with $p \geq 1$) notes between the boundaries AND not substituted by smaller note values	Regular OR Altered
Notes subject to augmentation		Notes followed by a dot, except for perfect notes	Regular OR Augmented
Colored notes		Being colored	Same as OR 2/3 of uncolored note durational value

Table 7: Type of errors in the scoring-up output.

Types of Error		No. of errors	Mislabeled notes per instance	Total of mislabeled notes
Errors in the sources	Missing dot of division	8	2	16
		3	3	9
	Mistakenly colored note	1	1	1
	Incomplete hemiola group	1	2	2
Errors in the experiment	Dot of alteration	3	2	6
	Dot misplacement	1	1	1
	Last note's undetermined duration	7	1	7
	Semibreve rest lines	2	2	4
Transition to XVI c. mensural notation		5	2 in 4 instances	8
			1 in another	1

based on the context and the given mensuration; and, finally, it produces a single Mensural MEI file that, when rendered, shows the piece with the voices lined up in score format.

The Scoring-up Tool deals with the context-dependency issue by implementing the principles of imperfection and alteration found in [1, 18]. In addition to these principles, the implementation also considers hemiola coloration and dots of division and augmentation. This tool can handle pieces with voices written in different mensurations, as well as voices with perfect meter at multiple note levels (e.g., a voice in *perfect* modus, imperfect tempus, and *major* prolation). This first approach towards the automatic scoring up of mensural music, which only considers the horizontal dimension of the music, is already showing promising results. The accuracy of the tool in determining the correct duration of a note whose value was subject to modification—either by the context, the presence of a dot, or coloration—was approximately 97% on average. Some further improvement might be obtained by also including the vertical dimension (i.e., taking a look at counterpoint). Future work also includes adding support for handling the sources of error discussed in Section 4.2 as well as expanding the tool to work with pieces that lie in the transition between fifteenth and sixteenth centuries, adding support for partial imperfection (i.e., the imperfection of part of a note), and minor coloration.

The integration of the Scoring-up Tool into an Optical Music Recognition (OMR) workflow will allow for the automatic encoding of mensural music into scores with minimal human intervention—since a prior OMR stage will eliminate the need to hand-code the input files. Digital libraries will be able to display the score alongside the digitized original, providing a more familiar layout for modern musicians. Moreover, because the score is encoded as a symbolic file, it will allow for playback, which will make the music accessible to an even wider audience. For the expert, the score will provide information about the vertical sonorities—obscured in the separate-parts layout of the originals—which are useful in counterpoint studies. The symbolic files themselves could also be used for computational-musicological analysis.

ACKNOWLEDGMENTS

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A DATASET

The process of annotating the modern scores to represent mensural notation specificities (e.g., dots of division and alteration) was conducted in Sibelius following the guidelines given at the Measuring Polyphony Project website.[10] The annotated modern score can then be exported into a CMN MEI file using Sibelius' SibMEI plugin.[11] These annotated CMN MEI files are converted into Mensural MEI files by using the Mensural MEI Translator (mentioned in section 4.1). The resulting Mensural MEI files encode the mensural pieces in the original notation and with the correct durational value for all their notes. This three-stage process (Figure 9) was used to obtain the ground truth and, by further processing, the input data for this work.

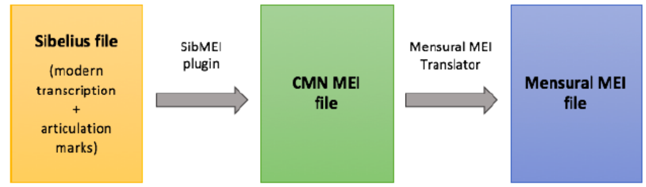

Figure 9: Three-stage process that takes modern transcriptions of mensural pieces and translates them back into mensural values encoded within a Mensural MEI file.

For the fourteenth century, we chose pieces from the *Ars nova* repertoire of the Measuring Polyphony Project, which are all motets. The motets chosen were the ones that, at the current stage of the project, had been double-checked against a manuscript source and included all the corresponding articulation marks. These eight pieces were already encoded as Mensural MEI files, so no preprocessing was needed.

For the fifteenth century, the Mensural MEI files were obtained by converting modern transcriptions of the pieces back into mensural notation using the process outlined in Figure 9. For this purpose, we obtained modern transcriptions in MusicXML and MIDI formats from the Josquin Research Project (JRP) and the Choral Public Domain Library (CPDL); these file formats were imported into Sibelius and checked against the manuscript for further editing (i.e., the addition of the articulation marks).[12] Given the amount of time invested in the transcriptions, and because some of them needed more than just the addition of the articulation marks to be fully faithful to their manuscript sources, we only used chansons, since these are short compositions. We chose triple meter chansons by Du Fay and Ockeghem to represent the beginning and middle of the fifteenth-century music, respectively.

The dataset of fourteenth- and fifteenth-century pieces is shown in Table 8 and their mensurations are found in Table 9. A few pieces included partial imperfection; since this feature is currently out of the scope of the scoring-up tool, the notes that were partially imperfected were substituted by either an imperfect or perfect note (depending on the case) for the purpose of this experiment.[13]

[10] The articulation marks used to represent mensural notation features can be found at the "Encoding Process" section in https://measuringpolyphony.org

[11] https://github.com/music-encoding/sibmei

[12] The Du Fay chansons were checked against a clean and error-free edition of the original manuscript source [8], while Ockeghem's were checked against the original manuscripts. For the most part, the manuscript sources used for Ockeghem pieces were error-free, except for an extra note in the cantus of *Ock3008*, a repeated group of notes in the cantus of *Ock3012*, and two notes missed in the cantus of *Ock3027*. These errors were removed so that both Ockeghem's and Du Fay's pieces are based on sources of the same quality.

[13] There are four instances of partial imperfection in the motetus of Iv004, one in the tenor of Duf22518, and one in the contra voice of Duf3025.

Table 8: Fourteenth- and fifteenth-century pieces used in the dataset.

<table>
<tr><th>Piece Code</th><th>Short Title</th><th>Composer</th><th>Source of the Modern Transcription</th><th>Source of the Mensural Piece</th></tr>
<tr><td>Iv001</td><td>Bona condit</td><td>Vitry</td><td rowspan="8">Measuring Polyphony Project</td><td rowspan="8">I-IV</td></tr>
<tr><td>Iv002</td><td>Cum venerint</td><td>Anonymous</td></tr>
<tr><td>Iv003</td><td>Decens</td><td>Vitry</td></tr>
<tr><td>Iv004</td><td>De touz</td><td>Machaut</td></tr>
<tr><td>Iv005</td><td>Diex</td><td>Anonymous</td></tr>
<tr><td>Iv006</td><td>Durement</td><td>Vitry</td></tr>
<tr><td>Iv007</td><td>Hugo</td><td>Vitry</td></tr>
<tr><td>Iv008</td><td>Post misse</td><td>Anonymous</td></tr>
<tr><td>Duf16002</td><td>Ce moys de may</td><td>Du Fay</td><td>CPDL*</td><td rowspan="5">Edition of Du Fay Chansons from GB-Ob in original notation by Ross W. Duffin [8]</td></tr>
<tr><td>Duf22518</td><td>Je ne suy plus</td><td>Du Fay</td><td>CPDL**</td></tr>
<tr><td>Duf3007.2</td><td>Craindre vous vueil</td><td>Du Fay</td><td>JRP</td></tr>
<tr><td>Duf3025</td><td>Bon jour, bon mois</td><td>Du Fay</td><td>JRP</td></tr>
<tr><td>Duf3069</td><td>Resvelons nous</td><td>Du Fay</td><td>JRP</td></tr>
<tr><td>Ock3008</td><td>La despourveue</td><td>Ockeghem</td><td>JRP</td><td>US-Wc</td></tr>
<tr><td>Ock3009_Dijon</td><td>L'autre d'antan</td><td>Ockeghem</td><td>JRP</td><td>F-Dm</td></tr>
<tr><td>Ock3009_Mellon</td><td>L'autre d'antan</td><td>Ockeghem</td><td>JRP</td><td>US-NHub</td></tr>
<tr><td>Ock3012</td><td>Ma maistresse (first part)</td><td>Ockeghem</td><td>JRP</td><td>D-W</td></tr>
<tr><td>Ock3016</td><td>Presque transi</td><td>Ockeghem</td><td>JRP</td><td>US-Wc</td></tr>
<tr><td>Ock3027</td><td>Permanent vierge</td><td>Ockeghem</td><td>JRP</td><td>F-Dm</td></tr>
</table>

* CPDL #16002: Edited by Brian Russell (submitted 2008-02-15).
** CPDL #22518: Edited by Renato Calcaterra (submitted 2010-10-27).
Key: JRP = Josquin Research Project, CPDL = Choral Public Domain Library

Table 9: Mensuration values for each voice of the pieces in Table 8. The numbers in the columns labeled as "L", "B", and "Sb" represent the perfect ("3") or imperfect ("2") mensuration at the level of the long, breve, and semibreve, respectively. The dash in the "Sb" column of some voices indicates that there are no semibreves or minims in that voice and, thus, the definition of the mensuration at the level of the semibreve is not applicable.

<table>
<tr><th rowspan="2">Piece Code</th><th colspan="3">Voice 1</th><th colspan="3">Voice 2</th><th colspan="3">Voice 3</th><th colspan="3">Voice 4</th></tr>
<tr><th>L</th><th>B</th><th>Sb</th><th>L</th><th>B</th><th>Sb</th><th>L</th><th>B</th><th>Sb</th><th>L</th><th>B</th><th>Sb</th></tr>
<tr><td>Iv001</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td>3</td><td>2</td><td>2</td><td>-</td><td colspan="3">—</td></tr>
<tr><td>Iv002</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td>-</td><td colspan="3">—</td></tr>
<tr><td>Iv003</td><td>3</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td colspan="3">—</td></tr>
<tr><td>Iv004</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>-</td><td>2</td><td>2</td><td>-</td></tr>
<tr><td>Iv005</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>-</td><td colspan="3">—</td></tr>
<tr><td>Iv006</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>-</td><td colspan="3">—</td></tr>
<tr><td>Iv007</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td>3</td><td>3</td><td>2</td><td>-</td><td colspan="3">—</td></tr>
<tr><td>Iv008</td><td>2</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td><td>3</td><td>2</td><td>2</td></tr>
<tr><td>Duf16002</td><td rowspan="2">2</td><td rowspan="2">2</td><td rowspan="2">3</td><td rowspan="2">2</td><td rowspan="2">2</td><td rowspan="2">3</td><td rowspan="2">2</td><td rowspan="2">2</td><td rowspan="2">3</td><td rowspan="2" colspan="3">—</td></tr>
<tr><td>Duf22518</td></tr>
<tr><td>Duf3007.2</td><td rowspan="9">2</td><td rowspan="9">3</td><td rowspan="9">2</td><td rowspan="9">2</td><td rowspan="9">3</td><td rowspan="9">2</td><td rowspan="9">2</td><td rowspan="9">3</td><td rowspan="9">2</td><td rowspan="9" colspan="3">—</td></tr>
<tr><td>Duf3025</td></tr>
<tr><td>Duf3069</td></tr>
<tr><td>Ock3008</td></tr>
<tr><td>Ock3009_Dijon</td></tr>
<tr><td>Ock3009_Mellon</td></tr>
<tr><td>Ock3012</td></tr>
<tr><td>Ock3016</td></tr>
<tr><td>Ock3027</td></tr>
</table>

B MANUSCRIPT ABBREVIATIONS

I-IV: Ivrea, Biblioteca Capitolare d'Ivrea 115 (Ivrea Codex).
D-W: Wolfenbüttel, Herzog August Bibliothek 287 (Wolfenbüttel Chansonnier).
F-Dm: Dijon, Bibliotèque Municipale 517 (Dijon Chansonnier).
GB-Ob: Oxford, Bodleian Library MS. Canon. Misc. 213.
US-NHub: New Haven, Beinecke Rare Book and Manuscript Library 91 (Mellon Chansonnier).
US-Wc: Washington, DC, Library of Congress, Music Division M2.1 L25 Case (Laborde Chansonnier).

C THE MERGE MODULE

The merge module merely takes the MEI elements corresponding to the voice metadata (`<staffDef>`) and its music content (`<staff>`) from each of the input Mensural MEI files and places them within the appropriate MEI elements of the output Mensural MEI file (Figures 10 and 11).

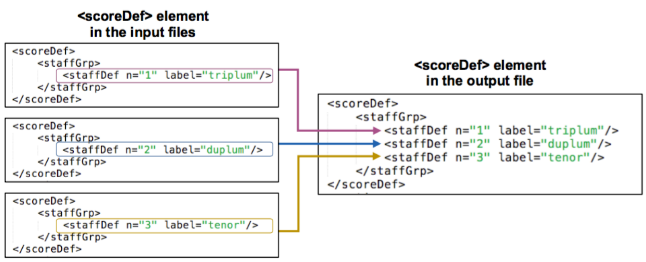

Figure 10: Example of how the merge module deals with the metadata of each voice for a three-voice piece. The metadata of each voice is encoded within the `<staffDef>` element of each input file (for simplicity, only the `@n` and `@label` attributes of the voice are shown). The merge module adds each of these `<staffDef>` elements as a child of the `<staffGrp>` element within the `<scoreDef>` (score metadata) element in the output file.

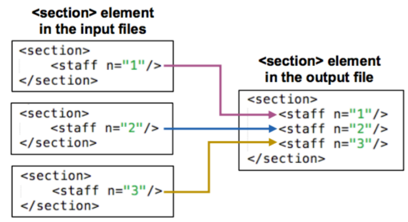

Figure 11: Example of how the merge module deals with the musical content of each voice for a three-voice piece. The musical content (i.e., notes and rests) of each voice is encoded within the `<staff>` element of each input file. The merge module adds each of these `<staff>` elements as a child of the `<section>` element in the output file.

The application of the merge module alone would produce a file that, when rendered in Verovio, would show the voices stacked up without any vertical alignment. Let us call this a "quasi-score" representation. Since no duration modifiers (`@num` and `@numbase` attributes) are encoded within this quasi-score, Verovio will show how the notes would be interpreted if all of them are given the default duration implied by the mensuration. Therefore, a comparison between the quasi-score—obtained through the merge module—and the score—obtained through both the merge and duration-finder modules—can show which are the notes whose duration gets changed by contextual or non-contextual queues. If one wants to obtain the actual score for either a piece in imperfect or perfect mensuration, both modules should be used.[14]

[14]The merge module is not enough for interpreting a piece that is entirely written in imperfect mensuration. This is because the effect of a dot of augmentation would not be encoded unless the duration-finder module is ran.