ABSTRACT
We present an analysis of change-points in the loudness time series of audio recordings of Chopin’s Mazurkas. The change-point positions are derived using the PELT algorithm and a heuristic is introduced for the automatic extraction of change points of multiple recordings of the same piece. We map the change points to the corresponding score position for analysis. The results show that significant dynamic score markings do indeed correspond to change points; and, evidence suggests that change points in score positions without dynamic markings correspond to structurally salient events or events based on temporal changes.

1. INTRODUCTION
Researchers have shown that expressive parameters, such as timing and loudness changes, serve to highlight and delineate important music structures [1,4,7]. Building on [7], we will focus on performed loudness in recorded music audio, to analyse the meaning of dynamic changes in a large-scale corpus.

2. METHOD
The data comprises of loudness time series derived from 2000 audio recordings of forty-four Chopin Mazurkas obtained from the Mazurka Project 1. We extract the loudness time series in sones using the \textit{ma_sone} function from MA toolbox 2 and we align it to score beats using the score edition of Paderewski, Bronarsi and Turczynski [9].

For each time series we extract the change points by implementing the methods Pruned Exact Linear Time (PELT) [6] and CROPS [3] from the \textit{R} package “changepoint” [5], using the “meanvar” function and we set the penalty values according to the heuristic described in [8], where the second derivative of the cost function introduced needs to be greater than a given threshold $S$.

For the $n^{th}$ recording of an $m^{th}$ Mazurka having a frame sequence $(A_{mn})$ and length $|A_{mn}|$, the threshold value is calculated using the formula:

$$S = k \cdot |(A_{mn})| \cdot \log |(A_{mn})|,$$

where $k$ is defined for each Mazurka as shown in Table 1.

3. RESULTS
Example results for Mazurkas Op. 6 No. 3 and Op. 63 No. 3 are shown in Figure 1. The bar charts show the popularity of change points across score-time (measured in beats).

![Change-point popularity charts for Mazurka Op. 6 No. 3 (top) and Op. 63 No. 3 (bottom).](image)

Figure 1: Change-point popularity charts for Mazurka Op. 6 No. 3 (top) and Op. 63 No. 3 (bottom).

We consider a change-point position to be popular if it was present in more than 40% of the recordings. Figure 2...
Table 1: The value of the parameter \( k \) in the threshold formula that has been used for all the recordings per Mazurka. Mazurkas are indexed as “M<opus>-<number>.”

<table>
<thead>
<tr>
<th>Mazurka</th>
<th>M06-1</th>
<th>M06-2</th>
<th>M06-3</th>
<th>M06-4</th>
<th>M07-1</th>
<th>M07-2</th>
<th>M07-3</th>
<th>M17-1</th>
<th>M17-2</th>
<th>M17-3</th>
<th>M17-4</th>
<th>M24-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>7 \times 10^{-7}</td>
<td>9 \times 10^{-7}</td>
<td>1 \times 10^{-6}</td>
<td>3 \times 10^{-7}</td>
<td>5 \times 10^{-6}</td>
<td>1 \times 10^{-7}</td>
<td>2 \times 10^{-7}</td>
<td>9 \times 10^{-7}</td>
<td>9 \times 10^{-7}</td>
<td>4 \times 10^{-6}</td>
<td>8 \times 10^{-7}</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The value of the parameter \( k \) in the threshold formula that has been used for all the recordings per Mazurka. Mazurkas are indexed as “M<opus>-<number>.”

![Pie chart showing score marking types corresponding to popular change-point positions.](image1.png)

**Figure 2:** Distribution of score marking corresponding to popular change-point positions.

This suggests that a change point is likely the most popular response to dynamic markings, \{pp, p, mf, f, ff\}, followed by boundaries of crescendo or diminuendo signs, then accents, \{sf, fermata\}, tempo markings, \{rallentando, ritenuto, tenuto, a tempo, Tempo I, rubato, slentando\}, or expression markings, \{calando, con fora, dolce, perpindosi, expressivo, sotto voce, poco piu vivo\}. The "other" category comprises of unmarked positions but, importantly, points corresponding to phrase or motif boundaries (see, for example, Figure 3).

![Phrase-boundary (top) and motif-boundary (bottom) change points in Mazurka Op. 33 No. 2 and Mazurka Op. 30 no. 1, respectively.](image2.png)

**Figure 3:** Phrase-boundary (top) and motif-boundary (bottom) change points in Mazurka Op. 33 No. 2 and Mazurka Op. 30 no. 1, respectively.

4. DISCUSSION

We introduce a systematic way of detecting change points in loudness time series of music audio recordings. When tested on a Chopin Mazurka dataset, the most popular change-point positions cover score positions having a dynamic marking. They also correspond to structurally salient score features such as crescendo and diminuendo signs, accent, tempo, and expression markings, and phrase and motivic boundaries. As in any studies of musical expression, we need to bear in mind that expressions chosen in response to score markings vary between performers, between performances, and within the same performance [10].

Our results suggest that change points in loudness information can provide important input for music structure boundary detection. Further work could also determine the connections between tempo and dynamics, for example, in studies of musical tipping points [2].

5. REFERENCES


