



# Analyzing Visual Mappings of Traditional and Alternative Music Notation



Matthias Miller, Johannes Häußler, Matthias Kraus, Daniel Keim, and Mennatallah El-Assady

University of Konstanz, Germany

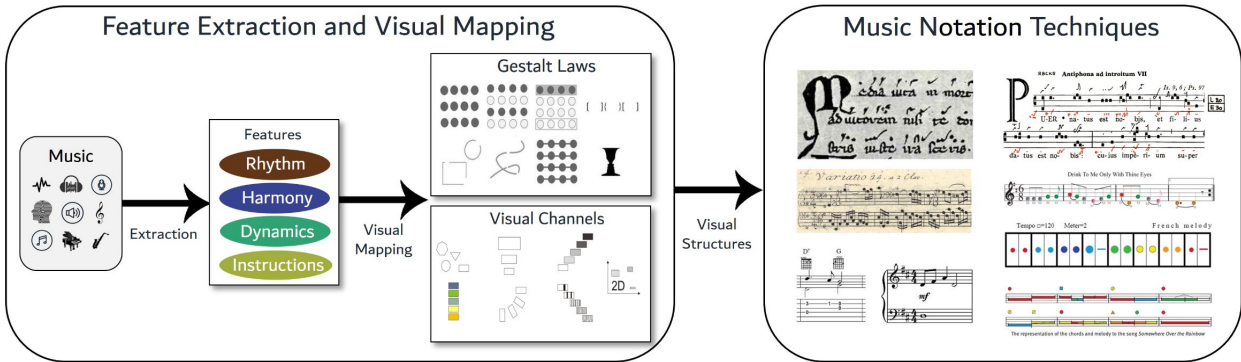


Fig. 1. Segmenting music into its basic features to design and apply task-dependent visual encodings, based on visual channels and Gestalt laws. Exploiting the whole range of the *music notation design space* enables a variety of novel music notation techniques.

**Abstract**— In this paper, we postulate that combining the domains of information visualization and music studies paves the ground for a more structured analysis of the design space of music notation, enabling the creation of alternative music notations that are tailored to different users and their tasks. Hence, we discuss the instantiation of a *design and visualization pipeline for music notation* that follows a structured approach, based on the fundamental concepts of information and data visualization. This enables practitioners and researchers of digital humanities and information visualization, alike, to conceptualize, create, and analyze novel music notation methods. Based on the analysis of relevant stakeholders and their usage of music notation as a mean of communication, we identify a set of relevant features typically encoded in different annotations and encodings, as used by interpreters, performers, and readers of music. We analyze the visual mappings of musical dimensions for varying notation methods to highlight gaps and frequent usages of encodings, visual channels, and Gestalt laws. This detailed analysis leads us to the conclusion that such an under-researched area in information visualization holds the potential for fundamental research. This paper discusses possible research opportunities, open challenges, and arguments that can be pursued in the process of analyzing, improving, or rethinking existing music notation systems and techniques.

**Index Terms**—Music Analysis, Music Notation, Visual Mapping, Visualization Pipeline, Information Visualization, Design Guidelines

## 1 INTRODUCTION

Ever since the earliest recordings of ancient cultures and societies, music has been an evident and integral part of the cultural experience and societal identity [19]. Musical instruments and tools have been discovered in archaeological sites, while paintings, scriptures, and folktale records form an indisputable trail that highlights the development of music through human history [35]. However, as evident as the human desire to express feelings and emotions through music is part of our history [18], the preservation of the melodies of our past has been a continually changing, unguided process, influenced by many factors [25].

To preserve music as part of their culture and to form a distinct identity, human societies strove to find methods that would allow them to pass such knowledge on, to later generations. Music was initially only transmitted orally [42]. However, due to the fading collective memories over centuries, there always existed a desire for a more accurate method of capturing and preserving musical creations [31]. Consequently, the

development of the first musical notations emerged and started with a simple approach; curved lines, also called neumes [43], were displayed over text to indicate the relative pitch for singers. Over time, the methods for music notation were altered and refined, depending on the purpose and objective of the music notation [39]. This serendipitous development in different cultures and times in history led to a diversity of notation systems for various application areas and instruments.

Musical notation standardizations emerged due to the predominance of some representations, which finally led to the western, *traditional* music notation that has been established as the norm we are used to all over the world. This well-known **Common Music Notation (CMN)** [37] allows experienced musicians to understand how a composition should sound, solely by reading musical expressions [20]. Such expressions are commonly represented as notes on paper that are structured in a pre-defined notation system. Thus, one central purpose of music notation is to assist musicians with the accurate communication, interpretation, and reproducibility of compositions [7]. CMN enables the capturing of musical aspects for creators and composers likewise to conserve their ideas, unambiguously. Hence, composers use music notation to communicate with performers, providing instructions on how a composition should be musically interpreted and reproduced [22]. However, the creation and standardization of a seemingly universal notation is challenging [10]. For example, depending on the instrument, musicians use different no-

E-mail: [firstname.lastname@uni-konstanz.de](mailto:firstname.lastname@uni-konstanz.de)

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: [reprints@ieee.org](mailto:reprints@ieee.org). Digital Object Identifier: xx.xxx/TVCG.201x.xxxxxxx

tations [16]. Due to the varying pitch ranges between instruments, different types of clefs exist to facilitate the discrimination of music notations between instruments. Likewise, singers require other musical representations compared to instrumentalists to understand their parts.

Due to the gradual development of notation over multiple centuries, the CMN is a result of a long-term, historical development process. For instance, one bottleneck for a wide distribution was the lack of availability of printing color at the beginning of mass printing for the reproduction of music scores on paper. Similarly, the technological progress and digitization had not yet reached the point of using interactivity or motion. From the information visualization research perspective, these historically grounded limits on the design space of music notation may have led to an established representation which does not exploit the full potential of all available techniques and encodings. For example, according to Flach et al. dyslexic individuals benefit from using an alternative notation exploiting other visual cues, enabling them to better distinguish the pitch of notes which is more difficult using the CMN [13]. Current research in the domain of information visualization provides means for a more structured approach to the design of music notation.

Hence, we postulate that bridging the domains of information visualization and music opens up space for a structured analysis of music notation and a thorough exploration of its visual design space. Such an endeavor opens up paths to novel and original research, tailoring music notation to different users and their tasks.

Considering different application fields and existing music notation techniques, this paper contributes a structured analysis of the visual design space of music notation. We define the span of the design space to integrate and analyze the state-of-the-art visualization techniques of various music notations. In doing so, we obtain means to identify benefits and drawbacks of different visual encodings. In addition, our approach enables a systematic and comparative analysis of different concepts, concerning their effectiveness by applying the Gestalt laws. Finally, these considerations reveal potential research gaps and opportunities in the domain of music notation visualization.

## 2 BACKGROUND

Depicting music in a visual form is a complex task containing several representation issues [10]. The existence of a vast variety of different music notations shows that it is overly complicated to encode all musical features into a single and consistent system because of the limited number of visual encoding channels. Designing a notation system requires one to make fundamental design decisions that depend on the target audience and the application area. Making such design decisions limits the range of possible applications which is acceptable if some use cases are well-supported even though other tasks are not. One reason why specialized notation is restricted is loss of information. For instance, tailoring a notation system to a specific instrument makes reading more difficult for musicians who are not acquainted with the instrument. A further reason is that music is subject to a continuing progress due to the development of new instruments, genres, and even rearrangements of existing works, making it impossible to take features into account that will be introduced at a later point in time. The range of application of music notation can be divided into categories (examples are given by reference), which contain but are not limited to (live) performance [15, 40], analysis [28], art [21, 32], education [45], instrument support [34], composition [3], and entertainment [14].

Dannenbergs states that the diversity between the single categories requires one to view music and its structure based on different levels of representation, since each notation design possibly contains information that is not available in other notation systems [10]. For instance, to analyze music, often abstract transformations are used to provide means of comparison that enable analysts to detect patterns and differences of musical pieces instead of focusing on single details [36]. Among others, music analysts are interested in understanding the harmonic progressions and relationship of a musical piece. Malandrino et al. propose a visualization approach to emphasize the harmonic structure of a composition by employing color to indicate tonal progressions [27]. Many approaches that propose an instrument-oriented design can also be assigned to the category 'Education' since visual metaphors that are

based on the visual appearance of the respective instrument provide high potential for learning a new instrument. For example, Dascăluș et al. utilize the design of a keyboard to create an instrument teaching platform for adult learners [11].

To summarize the broad range of music notation systems into a single framework, we first span a structured *Music Notation Design Space*.

## 3 MUSIC NOTATION DESIGN SPACE

Visually representing music requires a suitable mapping from heterogeneous input formats to visual channels. If music exists in audio format, extracting structural features is necessary before applying a visual encoding. Since the visualization or notational representation of music is ambiguous, even existing visual representations can be examined and altered to be restructured to support different situations. Music is an intricate form of art containing both structural, as harmony or rhythm, and non-structural properties like emotion and imagination. The former is mathematically formalizable. Nevertheless, there are multiple attributes of music that hardly can be communicated using formal notation. For instance, performing music often involves a specific level of expressiveness when interpreted that is difficult to formalize or to visually encode. Consequently, dealing with music as notation entails several representational issues. This problem of representation is responsible for the existing variety of different musical representations. To analyze existing music notation specifications, we necessitate extracting musical features that are commonly used to visually represent music. Due to the hierarchical structure of music, we introduce a determined level of abstraction in subdividing music into four meta-features which comprise concrete musical dimensions each of which can be subject to visual representation in musical notation systems.

### 3.1 Musical meta-features and notational dimensions

We suggest a set of meta-features that can be extracted from music each of which characterizes a unique musical attribute. Every meta-feature contains multiple dimensions that describe its specific musical part in detail. Subsequently, we consider music to be generally a composition of *rhythm*, *harmony*, *dynamics*, and *instructions* (see Step 1 in Fig. 2).

*Rhythm* describes the tempo (beats per minute) or speed of music including meter and time signatures. Pauses also belong to *rhythm*, since they influence the rhythmic movement or flow in music. *Rhythm* is the cause why music can be categorized and analyzed as time-series data and is a fundamental aspect in the design of music notation.

*Harmony* depends on how multiple tones simultaneously compose specific pitch levels. This co-occurrence of notes determines the harmonic progression of a musical piece. In music notation, one must differentiate between accidental and normal notes. Moreover, the range of a given part is defined by the octaves or height of note. We assign duration to be part of every note since varying tone lengths directly affect the harmonic behavior. Often, dynamics is used to describe the loudness or the development of intensity including the transitions between different volume levels as well as accents and abrupt changes of the musical progression.

*Dynamics* comprises volume (or intensity), articulation and phrasing since phrasing and volume are frequently combined to partition music into connected segments. Besides, articulation also shapes musical dynamics in combination with intensity and phrasing.

*Instructions* encapsulate contextual notational information such as timbre, arrangement, baseline and which finger should be used to play a specific note. 'Arrangement' includes the structure of a musical piece comprising repetitions and instrumentation. The instrumentation influences the timbre and is regarded as a separate dimension which is often implicitly represented. Depending on the instrument, the CMN uses different baselines encoded by respective clefs at the beginning of the notation indicating the pitch of the displayed notes.

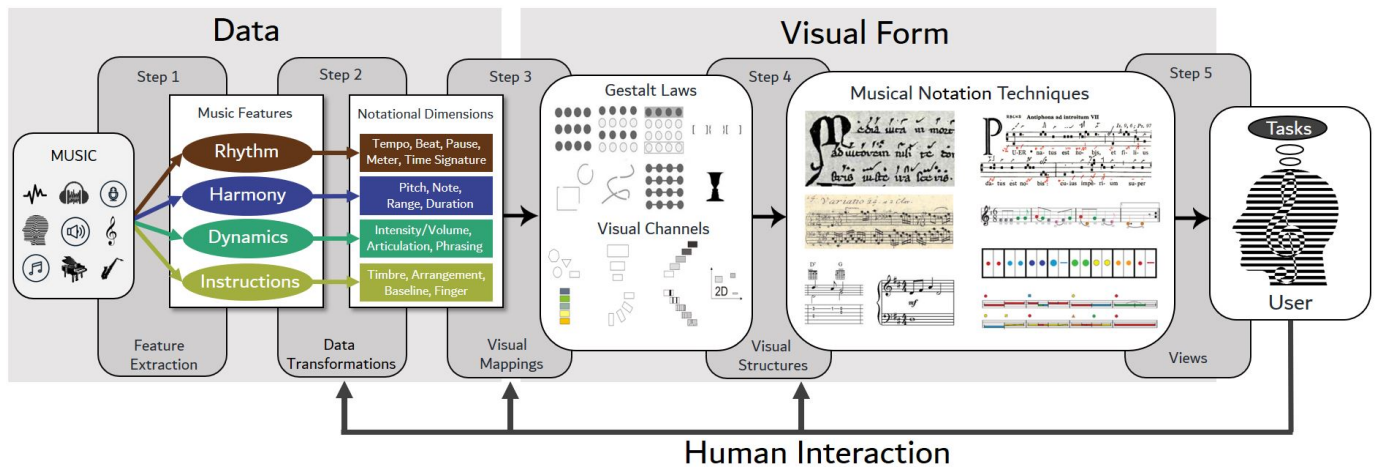


Fig. 2. Our proposed *Music Notation Visualization Pipeline* is based on Card et al.’s Information Visualization Reference Model [5]. Transforming musical data into visual music notation as a multi-step process including extraction of musical features (Step 1), data transformation (Step 2), visual mapping (Step 3) and encoding into visual structures (Step 4). Moreover, allowing users to interact with the system and changing the notation enables customization on views (Step 5) and enables notation improvement to fit the users’ tasks.

### 3.2 Users and Tasks

Different types of users need suitable music representations: music composers must be able to expressively communicate their thoughts by symbols, signs and other instructions. They achieve this by mapping musical thoughts to be structured and represented in such a way that the composed music can be reconstructed as imagined by the author. In contrast, performers should be provided with a musical notation that is easy to understand and suitable for the instrument they are playing. The notation of a musical piece can vary between different instruments to meet task-oriented requirements. Imagine a musical director, who must be aware of all instrument parts of a whole orchestra. Providing an overview of all involved instruments in this case is beneficial. On the contrary, single instrumentalists do not profit from such an orchestra notation, but could be even distracted while playing their own part. This example emphasizes the role and importance of different music notations for diverse tasks. Learning an instrument is another field of application: understanding the CMN can be a challenging task. Tailoring music notation to the user while using intuitive representations such as visual instrument metaphors supports novices during the learning process. Rather abstract representations are useful for music analysts who are more interested in patterns, progressions, and general differences between musical pieces than in specific details.

### 3.3 Visual Mapping of Musical Dimensions

Simultaneously representing multiple musical features by visual cues is substantial when it comes to providing musical notation information. During the design process of music notation, considering the *Gestalt Laws* is helpful to estimate the effectiveness of a visual cue. Since visual variables are the foundation for information visualization, which musical notation is a subset of, we take Bertin’s seven visual variables into account: *position, size, shape, value, color, orientation, and texture* [2]. Munzner extends this list by *motion, curvature, volume, and spatial region*. Munzner divides the visual channels into *magnitude channels*, which comprise ordered attributes, and *identity channels* that should be used to encode rather categorical data attributes which does not have an implicit and natural ordering [29].

It is useful to order the magnitude channels by effectiveness to reasonably apply visual channels in designing visualizations [6]. Based on Munzner’s discussion, we ordered the different visual magnitude channels from best to least starting with ‘*position on common scale*’ (top) to ‘*Volume (3D size)*’ (bottom) in Table 1. This sorting facilitates the comparison of different visual encodings by effectiveness. Moreover, readers can get a better distribution overview of how musical features are visually encoded. Applying different visual mappings between concepts avoids confusion when reading a designed music notation.

### 3.4 Music Notation Visualization Pipeline

We designed a pipeline to model the required transformation steps for the processing from musical data to a visual representation that is based on the Information Visualization Reference Model from Card et al. (see Fig. 2) [5]. In the first step, extracting musical features is required to transform the music information into a finite set of dimensions that can be potentially converted into visual form. Of course, depending on the original data format, music can contain elements such as emotions, nuances, or performance interpretation that cannot be easily visualized and conveyed to the user. During the extraction process, the loss of information should be minimized to preserve relevant information. The visual mapping and the creation of visual structures is a task- and user-oriented process to meet the users’ needs. Allowing the user to alter transformations and to influence the represented music notation provides flexibility. In some cases, users may benefit from restricted modification opportunities to maintain the quality of music representations. For example, fundamental attributes such as beat, notes, pitch, and duration should always be present. Since the traditional visualization pipeline model is designed on a rather abstract level that requires the underlying data to be homogeneous in order to process transformation and create different views, we state that music features must be extracted before applying well-known visualization techniques. Due to the abstract level it may be require additional preprocessing steps to translate musical features to be able to process them using our proposed pipeline.

## 4 TRADITIONAL AND ALTERNATIVE MUSIC NOTATIONS

Besides Common Music Notation, many different approaches have been proposed in different application domains such as research or teaching to reduce drawbacks of the CMN. These rather experimental notation concepts often use different visual channels to exploit the potential of unused visual variables. In Table 1, we provide an overview of different musical notation techniques based on categories of visual channels and Gestalt laws introduced in Sect. 3. Our objective is to indicate possible visual mappings that have not been used in a music notation system before, highlighted by empty cells having a grayed background. We point out that the given overview does not claim to be exhaustive since there are many ideas and approaches outside the world of academia (e.g., Pitch Bracket Notation [17]). In the overview table, the CMN is listed using a two notes symbol ( $\text{♩}$ ) to emphasize differences between the listed music notation approaches. Moreover, we selected the included references to be reproducible by a performer or computer instead of adding all methods that visualize any musical feature for analysis or entertainment. Frequently, music notation analysis visualizations apply abstract methods that do not take fundamental notation features into account [26, 44].

Visual Variable	Rhythm				Harmony				Dynamics		Instructions			
	Tempo / Beat	Meter / Time Signature	Pauses / Breaks	Tones (Pitch / Frequency)	Note	Range (Octaves)	Accidental / Normal	Duration	Intensity / Volume	Articulation	Phrasing	Timbre (Instrument)	Arrangement	Baseline / Clef
Text (Semantic Channel) [4]	↔, [23]	↔, [12,23,33]				↔, [12, 23]			↔, [12]	↔		↔, [9, 12]		↔, [12]
Magnitude Channels	Position on common scale	[8, 30, 38]	↔, [24, 30, 36]	↔, [12, 23, 33]	[8, 12, 38]	[1]	↔, [12, 23, 34, 45]		[9]		↔, [12]	[8, 9, 12, 38]		↔, [12, 23]
	Position on unaligned scale	[1]				↔, [12, 23]								
	Length (1D)		[45]				[24]							↔, [12, 23]
	Tilt / Angle													
	Area (2D size)													
	Depth (3D position)						[1]		[9]	[9, 24]				
	Color Luminance								[9]					
	Color Saturation		[38]						[9]					
	Texture					[8]								
Curvature					[45]								[24]	
Volume (3D size)										[38]				
Identity Channels	Spatial Region						↔							
	Color Hue					[8, 36, 41]	[8, 9, 23, 24, 45]		[23]			[12, 30, 38]		[34]
	Motion	[30, 34, 41]	[9]	[34]										
	Shape	[17]		↔, [12, 23, 24, 33]		[17]	[45]	[9]	↔, [12, 23, 24]	↔, [12, 23, 24, 33, 38]	↔, [12, 34]	[9]	↔, [12, 24]	↔, [12, 23]
Gestalt Laws	Proximity					↔, [34]	[9]	[24]		↔				↔
	Similarity	[24, 30]	[45]	↔		↔, [8, 9]	[8, 9, 23]	[9, 24, 45]	[24, 45]		[34]	[12, 30]		
	Enclosure		↔, [24, 30]			[12]								
	Closure													
	Continuity	[30]												
	Connection		[24]			[1]	↔	[12]				[34]		↔

Table 1. An overview of mapping musical notation features (Rhythm, Harmony, Dynamics, Instructions) to visual variables: magnitude channel, identity channel, and Gestalt laws. The two-notes symbol (↔) is used to indicate how the Common Music Notation (CMN) encodes music variables.

In Table 1 we classify fifteen existing music notation techniques. We emphasize that this is not representative for all notation techniques that exist in literature. It is structured to facilitate the understanding of which reference of a music representation method is using a visual variable (rows) grouped by Munzners visual channel categorization [29] and Gestalt law to encode a musical feature (columns). The columns are grouped by the characteristic musical meta-features introduced in Sect. 3.1. Some music notation concepts use different encodings for notes (a tone within an octave: A-G), ranges, and pitch. We consider pitch to be composed by note and octave. Mostly, a performer requires the exact position to precisely play a musical piece. Therefore, we decided to list them separately to highlight explicit representations of this musical dimension. Music notation often includes textual descriptions to provide information about instrumentation, volume, tempo, and meter signature. Borgo et al. subdivide all visual channels into four categories, one of which are the *Semantic Channels* containing text, number, symbols, signs, icons, and others [4]. We consider this category to be appropriate to describe the contextual music notation information (first row in the overview table). Seldomly, complete chords are directly mapped on visual variables instead of the respective single notes. For instance, Malandrino et al. enrich the CMN with a colored background to indicate the current pitch class at a particular position in the score [27]. For the sake of simplicity and clarity, we decided to omit a separate column for the chord dimension due to the scarcity of such techniques.

## 5 RESEARCH IMPLICATIONS AND OPPORTUNITIES

Our research shows how music notations can be compared regarding their visual features. To the best of our knowledge, Table 1 comprises varying music notations but is not complete and may serve as a starting point for a survey. The introduced visualization pipeline (Fig. 2) helps to both understand existing visualization techniques and develop new ones. Since the pipeline unifies the design process on a rather abstract and conceptual level, it may be required to consider certain musical dimensions in more detail. Nevertheless, we claim that any music notation visualization can be modeled using our proposed pipeline that can be extended to cover further musical dimensions that we did not consider, if necessary. In doing so, weaknesses of a specific representation, as well as its capability to visually map musical features for a given task, can be revealed, considering relevant notational dimensions. Vice versa, in the design process of new music notation visualizations, the pipeline in combination with the overview table supports the consideration of different notational dimensions.

The line-up of mappings between musical features and visual variables can also be used as inspiration to create new higher-level visualizations which also support content-based visual analysis of music.

Our research can be seen as a starting point for in-detail investigations of certain combinations of mappings and users or tasks. Specific pairs of visual variables and musical features could particularly fit certain user groups (e.g., learners, composer) or tasks (e.g., high-level analysis of a musical piece, performance). We assume that readers of the classical musical notation system are inherently biased due to early familiarization with the standard notation. Due to the familiarity, the popularity of the CMN and the historical contingency, it can be a difficult process to develop a music notation that will finally replace the CMN.

By now, we can exploit visual channels requiring technology that was not available during the development process of the CMN such as motion, color or volume (3D). Since the CMN has some disadvantages such as differentiating tone pitches, new techniques could address these drawbacks by applying visual variables in a different way. During the design process of new music visualization methods, it is necessary to take the respective application area into account, as some mappings are more intuitive in a specific situation and convey precise while others rather provide abstract information of musical features.

We argue that our design and visualization pipeline for music notation (see Fig. 2) is not only applicable to music notation but also to develop methods for music fingerprinting, to compare music regarding different epochs and styles, or to compare the visual encoding of music visualizations. For instance, a well-established mapping for some notational feature could be deployed in a higher level visualization, showing, for example, the trend of a musical feature throughout the entire musical piece. Visualization techniques as pixel visualizations, glyphs, or others could be applied to visually analyze larger amounts of musical data and enable comparison between musical pieces.

## 6 CONCLUSION

In this paper, we introduced a design and visualization pipeline for music notation based on fundamental information visualization research. This approach can be used as a foundation to compare existing music notation designs and to develop new techniques that are tailored to different users and their tasks. Thus, we bridge the research field of data visualization and the field of music representation in a structured way. An exemplary classification of fifteen notation systems indicates how musical features can be encoded. The table can be used as a starting point for a full survey of existing music notation techniques.



## REFERENCES

- [1] T. Bergstrom, K. Karahalios, and J. C. Hart. Isochords: Visualizing Structure in Music. In *Proc. of Graphics Interface 2007*, GI '07, pp. 297–304. ACM Press, 2007. doi: 10.1145/1268517.1268565
- [2] J. Bertin. *Semiology of Graphics*. University of Wisconsin Press, 1983.
- [3] L. Bigo, J. Garcia, A. Spicher, and W. E. Mackay. PaperTonnetz: Music Composition with Interactive Paper. In *Sound and Music Computing*. Copenhagen, Denmark, 2012. doi: 10.1145/2468356.2479608
- [4] R. Borgo, J. Kehler, D. H. S. Chung, E. Maguire, R. S. Laramée, H. Hauser, M. Ward, and M. Chen. Glyph-based visualization: Foundations, design guidelines, techniques and applications. In *Eurographics 2013 - State of the Art Reports, Girona, Spain, May 6-10, 2013*, pp. 39–63, 2013. doi: 10.2312/conf/EG2013/stars/039-063
- [5] S. K. Card, J. D. Mackinlay, and B. Shneiderman. *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1999.
- [6] M. S. T. Carpendale. Considering Visual Variables as a Basis for Information Visualisation. 2003. doi: 10.5072/PRISM/30495
- [7] M. Chanan. *Repeated Takes: A Short History of Recording and its Effects on Music*. Verso, 1995.
- [8] P. Ciuha, B. Klemenc, and F. Solina. Visualization of concurrent tones in music with colours. In *Proc. of the 18th Int. Conf. on Multimedia*, pp. 1677–1680. ACM, 2010. doi: 10.1145/1873951.1874320
- [9] L. Cruz, V. Rolla, J. Kestenbergh, and L. Velho. Visual Representations for Music Understanding Improvement. In *Proc. of the 13th Int. Symposium on CMMR*, pp. 319–327, 2017.
- [10] R. B. Dannenberg. Music Representation Issues, Techniques, and Systems. *Computer Music Journal*, 17(3):20–30, 1993. doi: 10.2307/3680940
- [11] M.-I. Dascălu, M. Coman, R. Postelnicu, and C. Nichifor. Learning to Play a Musical Instrument in Adulthood—Challenges and Computer-mediated Solutions. *Procedia - Social and Behavioral Sciences*, 142:311–317, 2014. doi: 10.1016/j.sbspro.2014.07.639
- [12] R. De Prisco, D. Malandrino, D. Pirozzi, G. Zaccagnino, and R. Zaccagnino. Understanding the structure of musical compositions: Is visualization an effective approach? *Information Visualization*, 16(2):139–152, 2017. doi: 10.1177/1473871616655468
- [13] N. Flach, A. Timmermans, and H. Korpershoek. Effects of the design of written music on the readability for children with dyslexia. *Int. Journal of Music Education*, 34(2):234–246, 2016. doi: 10.1177/0255761414546245
- [14] J. H. Fonteles, M. A. F. Rodrigues, and V. E. D. Basso. Creating and evaluating a particle system for music visualization. *Journal of Visual Languages & Computing*, 24(6):472–482, 2013. doi: 10.1016/j.jvlc.2013.10.002
- [15] J. Freeman. Extreme Sight-Reading, Mediated Expression, and Audience Participation: Real-Time Music Notation in Live Performance. *Computer Music Journal*, 32(3):25–41, 2008. doi: 10.1162/comj.2008.32.3.25
- [16] M. Gaare. Alternatives to Traditional Notation: Traditional notation has survived the test of time and is read by musicians around the world, but there are many musicians who desire, devise, or use alternative systems. *Music Educators Journal*, 83(5):17–23, 1997. doi: 10.2307/3399003
- [17] C. Gledhill. “Pitch Bracket Notation”. <http://pitchbracket.com/>, 2018. Accessed: 2018-07-02.
- [18] A. Goldman. The Value of Music. *The Journal of Aesthetics and Art Criticism*, 50(1):35, 1992. doi: 10.2307/431065
- [19] M. Herndon and N. McLeod. *Music as culture*. Norwood Editions, Norwood, Pa, 1979.
- [20] C. Hultberg. Approaches to Music Notation: The printed score as a mediator of meaning in Western tonal tradition. *Music Education Research*, 4(2):185–197, 2002. doi: 10.1080/1461380022000011902
- [21] M. Karttunen and A. Tenkanen. Three-Dimensional Score: Seeing Music, Hearing Sculpture. pp. 525–528. Tessellations Publishing, 2016.
- [22] R. A. Kendall and E. C. Carterette. The Communication of Musical Expression. *Music Perception: An Interdisciplinary Journal*, 8(2):129–163, 1990. doi: 10.2307/40285493
- [23] D. Kestenbaum and V. M. Hyman. Colored music notation system and method of coloring music notation, 2006. US Patent 7,148,414.
- [24] Y.-T. Kuo and M.-C. Chuang. A proposal of a color music notation system on a single melody for music beginners. *Int. Journal of Music Education*, 31(4):394–412, 2013. doi: 10.1177/0255761413489082
- [25] W. Lemberg. A survey of the history of musical notation. *TUGboat*, 37(3):284–304, 2016.
- [26] J. Li. Music Analysis Through Visualization. In *Proc. of the Int. Conf. on Technologies for Music Notation and Representation*, pp. 220–225. Anglia Ruskin University, 2016. doi: 10.5281/zenodo.924063
- [27] D. Malandrino, D. Pirozzi, G. Zaccagnino, and R. Zaccagnino. A Color-Based Visualization Approach to Understand Harmonic Structures of Musical Compositions. pp. 56–61. IEEE, 2015. doi: 10.1109/iV.2015.21
- [28] A. Mardirossian and E. Chew. Visualizing Music: Tonal Progressions and Distributions. In *ISMIR*, pp. 189–194, 2007.
- [29] T. Munzner. *Visualization Analysis & Design*. A K Peters/CRC Press, 1 ed., 2014. doi: 10.1201/b17511
- [30] T. Nakano, M. Goto, J. Ogata, and Y. Hiraga. Voice Drummer: A Music Notation Interface of Drum Sounds Using Voice Percussion Input. In *Proc. of the 18th Annual ACM Symposium on User Interface Software and Technology*, pp. 49–50, 2005.
- [31] J. Paterson. “History of Music Notation - evolution, printing, specialisation and computers”. <https://www.mfiles.co.uk/music-notation-history.htm>, 2018. Accessed: 2018-07-07.
- [32] M. Poast. Color Music: Visual Color Notation for Musical Expression. *Leonardo*, 33(3):215–221, 2000. doi: 10.1162/002409400552531
- [33] G. L. Rogers. Effect of Colored Rhythmic Notation on Music-Reading Skills of Elementary Students. *Journal of Research in Music Education*, 44(1):15–25, 1996. doi: 10.2307/3345410
- [34] K. Rogers, M. Weber, A. Rhligh, M. Weing, J. Gugenheimer, B. Knings, M. Klepsch, F. Schaub, E. Rukzio, and T. Seufert. P.I.A.N.O.: Faster Piano Learning with Interactive Projection. pp. 149–158. ACM Press, 2014. doi: 10.1145/2669485.2669514
- [35] C. Sachs. *The History of Musical Instruments*. Dover Books on Music. Courier Corporation, 2012.
- [36] C. S. Sapp. Harmonic Visualizations of Tonal Music. In *Proc. of the Int. Computer Music Conf.*, vol. 1, pp. 423–430, 2001. doi: 2027/spo.bbp2372.2001.029
- [37] B. Schottstaedt. Beyond MIDI: the handbook of musical codes. chap. Common Music Notation, pp. 217–221. MIT Press, Cambridge, MA, USA, 1997.
- [38] S. Smith and G. Williams. A visualization of music. In *Proc. Visualization '97*, pp. 499–503. IEEE, 1997. doi: 10.1109/VISUAL.1997.663931
- [39] H. Strayer. From Neumes to Notes: The Evolution of Music Notation. *Musical Offerings*, 4(1):1–14, 2013. doi: 10.15385/jmo.2013.4.1.1
- [40] R. Timmers and H. Honing. On music performance, theories, measurement and diversity. *Cognitive Processing (Int. Quarterly of Cognitive Sciences)*, 1(2):1–19, 2002.
- [41] P. Toiviainen. Visualization of tonal content with self-organizing maps and self-similarity matrices. *Computers in Entertainment*, 3(4):3, 2005. doi: 10.1145/1095534.1095543
- [42] L. Treitler. Oral, Written, and Literate Process in the Transmission of Medieval Music. *Speculum*, 56(3):471–491, 1981. doi: 10.2307/2847738
- [43] J. S. van Waesberghe. The Musical Notation of Guido of Arezzo. *Musica Disciplina*, 5:15–53, 1951.
- [44] M. Wattenberg. Arc diagrams: visualizing structure in strings. pp. 110–116. IEEE Comput. Soc, 2002. doi: 10.1109/INFVIS.2002.1173155
- [45] M. Wong and M. Danesi. Color, shape, and sound: A proposed system of music notation. *Semiotica*, 2015(204), 2015. doi: 10.1515/sem-2014-0086