MEASURING AND MODELLING DYNAMICAL PHENOMENA OF MUSIC PERCEPTION

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ABSTRACT

Perception of music is an active dynamic process: while music unfolds in time, we constantly form expectations about its possible continuations. These expectations operate on several levels of music, such as melodic, harmonic, rhythmic, and tonal. Music in many styles is organized around one or more stable reference tones. In Western music, this phenomenon is referred to as tonality. As music unfolds in time, the tonality percept often changes. For instance, the clarity of tonality can change over time. Furthermore, the particular piece of music may contain modulations from one key to another. These changes in perceived tonality may be important in the creation of expectancies, tension, and even emotions. The article discusses methods for measuring the dynamics of music perception, in particular the perception of tonality, by means of listening experiments. Furthermore, it discusses a dynamic model of this process based on a short-term memory model and a self-organizing map (SOM). The output of the model is shown to converge with the perceived tonality, as measured in listening experiments. The model allows for dynamic visualization of perceived tonal context, making it possible to examine the clarity and locus of tonality at any given point of time.

1. INTRODUCTION

In the field of perception, Cognitive Psychology of Music studies the perception of basic musical features, such as pitch, timbre, and pulse, as well as higher-level musical features, such as tonality, meter, and form. Studies on the production of music focus mainly on processes involved in performance, improvisation, and composition. Further areas of inquiry include musical development, skill, memory, emotions, and cross-cultural studies. To tackle these questions, Cognitive Psychology of Music utilizes empirical methods, such as psychological experiments (rating, production, priming) and brain measurements (neuropsychology of music) to gather experimental evidence about musical processes on both behavioral and neurophysiological level.

In the development of theories about these processes, computational modeling plays an important role. In this context, the computer models can be understood as theories about music cognition that has been formalized in a way that they can be implemented as computer programs. Computational modeling of cognitive processes can help us understand the problem under investigation in various ways. First, the development of the model may help us learn about the particular musical process by forcing us to define a description of how the musical task may be achieved and what the underlying mechanism may be. Second, simulations carried out with a model, and comparison of its output with empirical data, can be used to test the validity of the theory it represents. Third, a valid computational model can be used to produce hypotheses that can be used in the design of empirical experiments (i.e. psychological experiments and brain measurements). Finally, computational models of music cognition can be used in various practical applications. These include, for instance, interactive music systems that can be used in music performance and education.

An essential feature of music and music perception is its temporal, dynamic nature. Listening to music is an active process: while music unfolds in time, we constantly form expectations about its possible continuations. These expectations consider various aspects of music, such as melodic, harmonic, rhythmic, and tonal structure. As proposed by Meyer [1], the fulfillment or violation of these expectations may be the source some of the emotions evoked by music. Undeniably, emotions are a central reason for why we listen to music in the first place. Therefore, understanding the dynamic processes behind music perception in general and musical expectancy in particular is crucial for understanding music appreciation.

This paper presents a method for measuring the dynamics of music perception, in particular the perception of tonality, by means of listening experiments. Moreover, it presents a dynamic model of this process based on a short-term memory model and a self-organizing map (SOM). The output of the model has been shown to converge with the perceived tonality, as measured in listening experiments. The model allows for dynamic visualization of perceived tonal context, making it possible to examine the clarity and locus of tonality at any given point of time.

2. PERCEPTION OF TONALITY

Music in many styles is organized around one or more stable reference tones (the tonic, in Western tonal music). This is reflected in Western music theory by the key of music. Krumhansl and Shepard [2] introduced the probe-tone technique to investigate one aspect of how a tonal context influences the perception of pitch, in particular the perceived stability of each pitch within a tonal context. The results of these studies were in line with music-theoretic predictions, with the tonic highest in the hierarchy, followed by the third and fifth scale tones, followed by the remaining scale tones, and finally the non-diatonic tones. The obtained profiles are depicted in Fig. 1.

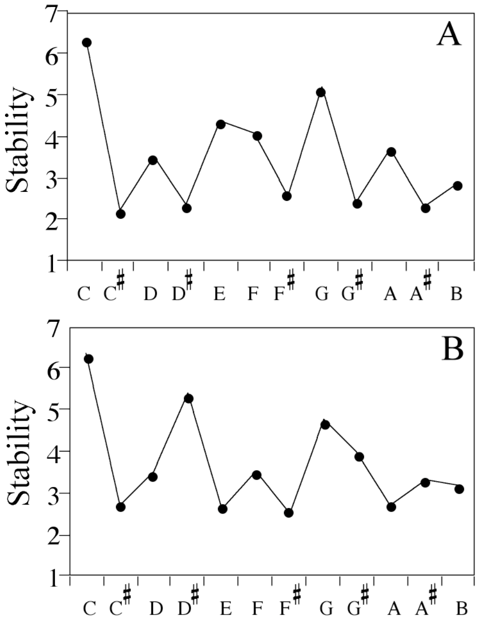


Fig. 1. Listeners ratings of stability of each pitch class after the presentation of a) C major; and b) C minor tonal contexts (after [2]). Tonal hierarchies for other keys are obtained by shifting the stability values circularly.

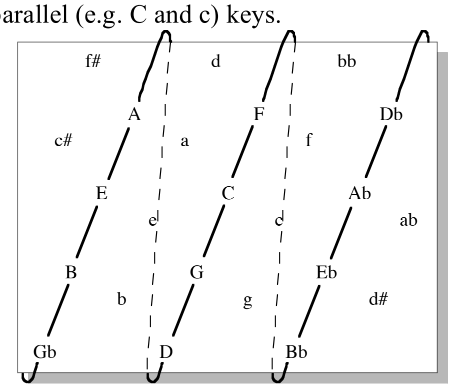
It has been found that the pitch-class distributions of various Western musical styles bear a great similarity to the tonal hierarchies depicted in Figure 1. It has been suggested that listeners acquire the tonal hierarchies by learning these statistical distributions while listening to music. The key-finding algorithm by Krumhansl and Schmuckler (see [3]) is based on the comparison between the pitch-class distribution of the piece under examination and the tonal hierarchies. More specifically, it correlates the pitch-class distribution of the piece with the tone profiles of each of the 24 keys. The key with the highest correlation with the pitch-class distribution is considered as the key of the piece.

3. DYNAMICS OF TONALITY PERCEPTION

As music unfolds in time, the tonality percept often changes. In particular, at some point the tonality can be clearer than at some other point. Furthermore, the particular piece of music may contain modulations from one key to another. These changes in perceived tonality may be important in the creation of expectancies and tension.

Toiviainen and Krumhansl [4] introduced a method for quantifying the temporal evolution of tonality percept. In the method, referred to as thee continuous probe tone method, listeners were presented with a piece of music to one ear and a continuously sounding probe tone to the other ear. The listeners' task was to rate the degree to which the probe tone fitted with the music at each point in time. The process was repeated for all probe tones of the chromatic scale. This yielded a dynamically changing 12-dimensional stability profile.

This dynamic process was modeled with a system consisting of a model of short-term memory and a self-organizing map (SOM; [5]). In the model, the SOM is first trained with the Krumhansl-Kessler profiles and had the structure shown in Figure 2. The configuration of the map corresponds to music-theoretic notions. For instance, keys that are a perfect fifth apart (e.g. C and G) are proximally located, as are relative (e.g. C and a) as well as parallel (e.g. C and c) keys.



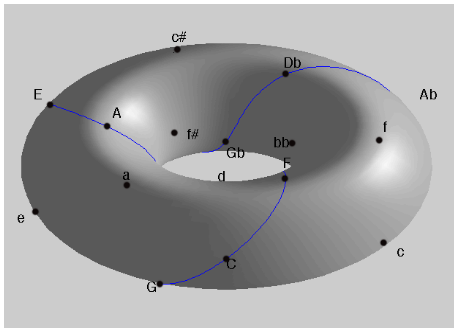


Fig. 2. Structure of a self-organizing map trained with the tonal hierarchies of the 24 keys (12 major and 12 minor). The subfigure on the top depicts the map in two dimensions (opposite edges are considered to be joined to each other); the subfigure on the right depicts the map in three dimensions.

After the training, the SOM is fed with the contents of a dynamic short-term memory of pitch classes obtained from a piece of music. The short-term memory is implemented as a bank of leaky integrators and at each given point of time contains information about recent pitch classes content in the music. When fed to the trained SOM, the content of the short-term memory evokes a dynamically changing activation pattern. This pattern is taken to model the locus and clarity of perceived tonality at any given time. High activation corresponds to high tonal clarity (i.e. great similarity between the content of short-term memory and some of the tonal schemata learned by the SOM. Examples of these activation patterns are shown in Figure 3.

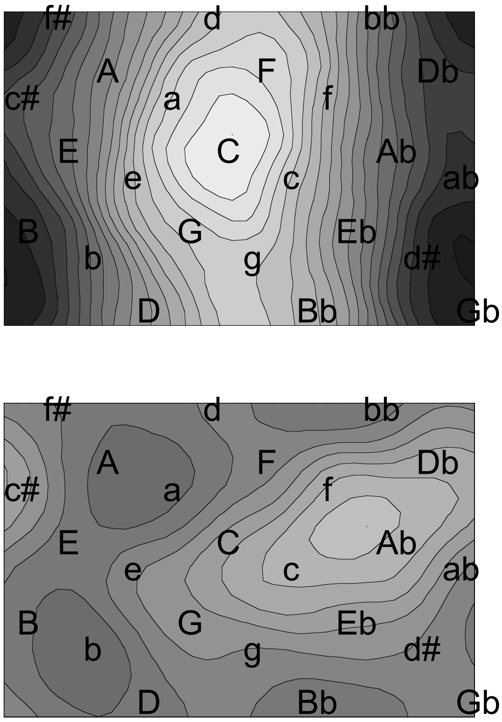


Fig. 3. Two activation patterns of a SOM evoked by short-term pitch class memory. Light and dark areas represent high and low activation, respectively. Top: clear tonality at the vicinity of C major; Bottom: unclear tonality.

In addition to the visualization of the computational short-term memory, the trained SOM can be used for the visualization of the dynamic ratings obtained from the continuous probe tone experiment. The activation patterns obtained from these two kinds of input can be compared to qualitatively assess the convergence between the empirical data and the model. In their study, Toiviainen and Krumhansl [4] found that the model's output correlated well with the dynamic ratings given by listeners. A QuickTime animation showing the listeners' and the model's dynamic response to an organ *duetto* by J. S. Bach is available at [6].

4. CONCLUSION

This article has discussed empirical and computational approaches that aim at deepening our understanding of time-dependent processes involved in the perception of tonality. In addition to the context of tonality, dynamic phenomena of music perception have been empirically and computationally investigated in relation to, for instance, rhythm perception [7-9] and melodic expectancies [10]. Understanding these mental processes is crucial, because they form the basis for our appreciation of music by facilitating the organization of its rhythmic, melodic, and tonal structure, and by creating expectations about continuations at various musical levels. These again may be constituents of higher-level phenomena related to musical experience, such as musical tension and music-induced emotions.

5. REFERENCES

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