Learning Combinations of Multiple Feature Representations for Music Emotion Prediction

Music consists of several structures and patterns evolving through time which greatly influences the human decoding of higher-level cognitive aspects of music like the emotions expressed in music. For tasks, such as genre, tag and emotion recognition, these structures have often been identified and used as individual and non-temporal features and representations. In this work, we address the hypothesis whether using multiple temporal and non-temporal representations of different features is beneficial for modeling music structure with the aim to predict the emotions expressed in music. We test this hypothesis by representing temporal and non-temporal structures using generative models of multiple audio features. The representations are used in a discriminative setting via the Product Probability Kernel and the Gaussian Process model enabling Multiple Kernel Learning, finding optimized combinations of both features and temporal/ non-temporal representations. We show the increased predictive performance using the combination of different features and representations along with the great interpretive prospects of this approach.

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Authors: Madsen, J. (Intern), Jensen, B. S. (Intern), Larsen, J. (Intern)
Pages: 3-8
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Modeling Temporal Structure in Music for Emotion Prediction using Pairwise Comparisons
The temporal structure of music is essential for the cognitive processes related to the emotions expressed in music. However, such temporal information is often disregarded in typical Music Information Retrieval modeling tasks of predicting higher-level cognitive or semantic aspects of music such as emotions, genre, and similarity. This paper...
addresses the specific hypothesis whether temporal information is essential for predicting expressed emotions in music, as a prototypical example of a cognitive aspect of music. We propose to test this hypothesis using a novel processing pipeline: 1) Extracting audio features for each track resulting in a multivariate "feature time series". 2) Using generative models to represent these time series (acquiring a complete track representation). Specifically, we explore the Gaussian Mixture model, Vector Quantization, Autoregressive model, Markov and Hidden Markov models. 3) Utilizing the generative models in a discriminative setting by selecting the Probability Product Kernel as the natural kernel for all considered track representations. We evaluate the representations using a kernel based model specifically extended to support the robust two-alternative forced choice self-report paradigm, used for eliciting expressed emotions in music. The methods are evaluated using two data sets and show increased predictive performance using temporal information, thus supporting the overall hypothesis.

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Main Research Area: Technical/natural sciences
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Bounded Gaussian process regression
We extend the Gaussian process (GP) framework for bounded regression by introducing two bounded likelihood functions that model the noise on the dependent variable explicitly. This is fundamentally different from the implicit noise assumption in the previously suggested warped GP framework. We approximate the intractable posterior distributions by the Laplace approximation and expectation propagation and show the properties of the models on an artificial example. We finally consider two real-world data sets originating from perceptual rating experiments which indicate a significant gain obtained with the proposed explicit noise-model extension.

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Organisations: Department of Applied Mathematics and Computer Science, Cognitive Systems
Authors: Jensen, B. S. (Intern), Nielsen, J. B. (Intern), Larsen, J. (Intern)
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Hearing Aid Personalization
Modern digital hearing aids require and offer a great level of personalization. Today, this personalization is not performed based directly on what the user actually perceives, but on a hearing-care professional’s interpretation of what the user explains about what is perceived. In this paper, an interactive personalization system based on Gaussian process regression and active learning is proposed, which personalize the hearing aids based directly on what the user perceives. Preliminary results demonstrate a significant difference between a truly personalized setting obtained with the proposed system and a setting obtained by the current practice.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Cognitive Systems, Widex A/S
Authors: Nielsen, J. B. (Intern), Nielsen, J. (Ekstern), Jensen, B. S. (Intern), Larsen, J. (Intern)
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Personalized Audio Systems - a Bayesian Approach
Modern audio systems are typically equipped with several user-adjustable parameters unfamiliar to most users listening to the system. To obtain the best possible setting, the user is forced into multi-parameter optimization with respect to the user’s own objective and preference. To address this, the present paper presents a general interactive framework for personalization of such audio systems. The framework builds on Bayesian Gaussian process regression in which a model of the user’s objective function is updated sequentially. The parameter setting to be evaluated in a given trial is selected by model-based sequential experimental design. A Gaussian process model is proposed which incorporates correlation among particular parameters providing better modeling capabilities compared to a standard model. A ve-band equalizer is considered for demonstration purposes, in which the parameters are optimized using the proposed framework. Twelve test subjects obtain a personalized setting with the framework, and these settings are significantly preferred to those obtained with random experimentation.

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Organisations: Department of Applied Mathematics and Computer Science, Cognitive Systems
Authors: Nielsen, J. B. (Intern), Jensen, B. S. (Intern), Hansen, T. J. (Intern), Larsen, J. (Intern)
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Predictive Modeling of Expressed Emotions in Music Using Pairwise Comparisons
We introduce a two-alternative forced-choice (2AFC) experimental paradigm to quantify expressed emotions in music using the arousal and valence (AV) dimensions. A wide range of well-known audio features are investigated for predicting the expressed emotions in music using learning curves and essential baselines. We furthermore investigate the scalability
issues of using 2AFC in quantifying emotions expressed in music on large-scale music databases. The possibility of dividing the annotation task between multiple individuals, while pooling individuals’ comparisons is investigated by looking at the subjective differences of ranking emotion in the AV space. We find this to be problematic due to the large variation in subjects’ rankings of excerpts. Finally, solving scalability issues by reducing the number of pairwise comparisons is analyzed. We compare two active learning schemes to selecting comparisons at random by using learning curves. We show that a suitable predictive model of expressed valence in music can be achieved from only 15% of the total number of comparisons when using the Expected Value of Information (EVOI) active learning scheme. For the arousal dimension we require 9% of the total number of comparisons.

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BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.67 SJR 0.339 SNIP 0.642
Web of Science (2016): Indexed yes
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Scopus rating (2013): SJR 0.36 SNIP 0.761 CiteScore 0.49
ISI indexed (2013): ISI indexed no
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BFI (2012): BFI-level 1
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BFI (2011): BFI-level 1
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Scopus rating (2009): SJR 0.302 SNIP 0.576
Web of Science (2009): Indexed yes
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Scopus rating (2006): SJR 0.317 SNIP 0.661
Web of Science (2006): Indexed yes
Towards a universal representation for audio information retrieval and analysis

A fundamental and general representation of audio and music which integrates multi-modal data sources is important for both application and basic research purposes. In this paper we address this challenge by proposing a multi-modal version of the Latent Dirichlet Allocation model which provides a joint latent representation. We evaluate this representation on the Million Song Dataset by integrating three fundamentally different modalities, namely tags, lyrics, and audio features. We show how the resulting representation is aligned with common 'cognitive' variables such as tags, and provide some evidence for the common assumption that genres form an acceptable categorization when evaluating latent representations of music. We furthermore quantify the model by its predictive performance in terms of genre and style, providing benchmark results for the Million Song Dataset.

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Organisations: Department of Applied Mathematics and Computer Science, Cognitive Systems
Authors: Jensen, B. S. (Intern), Troelsgaard, R. (Intern), Larsen, J. (Intern), Hansen, L. K. (Intern)
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ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
ISI indexed (2012): ISI indexed no
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BFI (2010): BFI-level 1
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Original language: English
Signal Processing and Analysis
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10.1109/ICASSP.2013.6638242
A predictive model of music preference using pairwise comparisons

Music recommendation is an important aspect of many streaming services and multimedia systems, however, it is typically based on so-called collaborative filtering methods. In this paper we consider the recommendation task from a personal viewpoint and examine to which degree music preference can be elicited and predicted using simple and robust queries such as pairwise comparisons. We propose to model - and in turn predict - the pairwise music preference using a very flexible model based on Gaussian Process priors for which we describe the required inference. We further propose a specific covariance function and evaluate the predictive performance on a novel dataset. In a recommendation style setting we obtain a leave-one-out accuracy of 74% compared to 50% with random predictions, showing potential for further refinement and evaluation.

General information

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Organisations: Department of Informatics and Mathematical Modeling, Cognitive Systems, Technical University of Denmark
Authors: Jensen, B. S. (Intern), Gallego, J. S. (Ekstern), Larsen, J. (Intern)
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Music Preference, Kernel Methods, Gaussian Process Priors, Recommendation
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012
Integration of top-down and bottom-up information for audio organization and retrieval
The increasing availability of digital audio and music calls for methods and systems to analyse and organize these digital objects. This thesis investigates three elements related to such systems focusing on the ability to represent and elicit the user's view on the multimedia object and the system output. The aim is to provide organization and processing, which aligns with the understanding and needs of the users.

Audio and music is often characterized by the large amount of heterogenous information. The rst aspect investigated is the integration of such multi-variate and multi-modal information sources based on latent Dirichlet allocation (LDA). The model is used to integrate bottom-up features (reflecting timbre, loudness, tempo and chroma), meta-data aspects (lyrics) and top-down aspects, namely user generated open vocabulary tags. The model and representation is evaluated on the auxiliary task of genre and style classification.

Eliciting the subjective representation and opinion of users is an important aspect in building personalized systems. The thesis contributes with a setup for modelling and elicitation of preference and other cognitive aspects with focus on audio applications. The setup is based on classical regression and choice models placed in the framework of Gaussian processes, which provides flexible non-parametric Bayesian models. The setup consist of a number of likelihood functions suitable for modelling both absolute ratings (direct scaling) and comparative judgements (indirect scaling). Inference is performed by analytical and simulation based methods, including the Laplace approximation and expectation propagation. In order to minimize the cost of the often expensive and lengthy experimentation, sequential experiment design or active learning is supported. The setup is applied in the eld of music emotion modelling and optimization of a parametric audio system with high-dimensional input spaces.

The final aspect, considered in the thesis, concerns the general context of users, such as location and social context. This is important in understanding user behavior and in determining the users current information needs. The thesis investigates the predictability of the user context, in particular location, based on information theoretic bounds and a particular experimental approach based on context sensing using the ubiquitous mobile phone.

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phd291_Jensen_BS.pdf
Publication: Research › Ph.D. thesis – Annual report year: 2013

Modeling Expressed Emotions in Music using Pairwise Comparisons
We introduce a two-alternative forced-choice experimental paradigm to quantify expressed emotions in music using the two wellknown arousal and valence (AV) dimensions. In order to produce AV scores from the pairwise comparisons and to visualize the locations of excerpts in the AV space, we introduce a flexible Gaussian process (GP) framework which learns from the pairwise comparisons directly. A novel dataset is used to evaluate the proposed framework and learning curves
show that the proposed framework needs relative few comparisons in order to achieve satisfactory performance. This is further supported by visualizing the learned locations of excerpts in the AV space. Finally, by examining the predictive performance of the user-specific models we show the importance of modeling subjects individually due to significant subjective differences.

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Source: dtu
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

**Pseudo inputs for pairwise learning with Gaussian processes**
We consider learning and prediction of pairwise comparisons between instances. The problem is motivated from a perceptual view point, where pairwise comparisons serve as an effective and extensively used paradigm. A state-of-the-art method for modeling pairwise data in high dimensional domains is based on a classical pairwise probit likelihood imposed with a Gaussian process prior. While extremely flexible, this non-parametric method struggles with an inconvenient $O(n^3)$ scaling in terms of the $n$ input instances which limits the method only to smaller problems. To overcome this, we derive a specific sparse extension of the classical pairwise likelihood using the pseudo-input formulation. The behavior of the proposed extension is demonstrated on a toy example and on two real-world data sets which outlines the potential gain and pitfalls of the approach. Finally, we discuss the relation to other similar approximations that have been applied in standard Gaussian process regression and classification problems such as FI(T)C and PI(T)C.

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Source-ID: n:oai:DTIC-ART:iel/373905296::22666
Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

**Towards Predicting Expressed Emotion in Music from Pairwise Comparisons**
We introduce five regression models for the modeling of expressed emotion in music using data obtained in a two alternative forced choice listening experiment. The predictive performance of the proposed models is compared using learning curves, showing that all models converge to produce a similar classification error. The predictive ranking of the models is compared using Kendall's tau rank correlation coefficient which shows a difference despite similar classification
error. The variation in predictions across subjects and the difference in ranking is investigated visually in the arousal-valence space and quantified using Kendall's tau.

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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

**Efficient preference learning with pairwise continuous observations and Gaussian Processes**
Human preferences can effectively be elicited using pairwise comparisons and in this paper current state-of-the-art based on binary decisions is extended by a new paradigm which allows subjects to convey their degree of preference as a continuous but bounded response. For this purpose, a novel Betatype likelihood is proposed and applied in a Bayesian regression framework using Gaussian Process priors. Posterior estimation and inference is performed using a Laplace approximation. The potential of the paradigm is demonstrated and discussed in terms of learning rates and robustness by evaluating the predictive performance under various noise conditions on a synthetic dataset. It is demonstrated that the learning rate of the novel paradigm is not only faster under ideal conditions, where continuous responses are naturally more informative than binary decisions, but also under adverse conditions where it seemingly preserves the robustness of the binary paradigm, suggesting that the new paradigm is robust to human inconsistency.

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Organisations: Cognitive Systems, Department of Informatics and Mathematical Modeling
Authors: Jensen, B. S. (Intern), Nielsen, J. B. (Intern), Larsen, J. (Intern)
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Main Research Area: Technical/natural sciences
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Links: http://mlsp2011.conwiz.dk/
Source: orbit
Source-ID: 312716
Publication: Research - peer-review › Article in proceedings – Annual report year: 2011

**On Sparse Multi-Task Gaussian Process Priors for Music Preference Learning**
In this paper we study pairwise preference learning in a music setting with multitask Gaussian processes and examine the effect of sparsity in the input space as well as in the actual judgments. To introduce sparsity in the inputs, we extend a classic pairwise likelihood model to support sparse, multi-task Gaussian process priors based on the pseudo-input
formulation. Sparsity in the actual pairwise judgments is potentially obtained by a sequential experimental design approach, and we discuss the combination of the sequential approach with the pseudo-input preference model. A preliminary simulation shows the performance on a real-world music preference dataset which motivates and demonstrates the potential of the sparse Gaussian process formulation for pairwise likelihoods.

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Organisations: Cognitive Systems, Department of Informatics and Mathematical Modeling
Authors: Nielsen, J. B. (Intern), Jensen, B. S. (Intern), Larsen, J. (Intern)
Publication date: 2011
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 316484
Publication: Research › Paper – Annual report year: 2011

Estimating Human Predictability From Mobile Sensor Data
Quantification of human behavior is of prime interest in many applications ranging from behavioral science to practical applications like GSM resource planning and context-aware services. As proxies for humans, we apply multiple mobile phone sensors all conveying information about human behavior. Using a recent, information theoretic approach it is demonstrated that the trajectories of individual sensors are highly predictable given complete knowledge of the infinite past. We suggest using a new approach to time scale selection which demonstrates that participants have even higher predictability of non-trivial behavior on smaller timer scale than previously considered.

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Organisations: Cognitive Systems, Department of Informatics and Mathematical Modeling
Authors: Jensen, B. S. (Intern), Larsen, J. E. (Intern), Jensen, K. (Intern), Larsen, J. (Intern), Hansen, L. K. (Intern)
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Main Research Area: Technical/natural sciences
DOIs: 10.1109/MLSP.2010.5588997
Source: orbit
Source-ID: 263951
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Predictability of Mobile Phone Associations
Prediction and understanding of human behavior is of high importance in many modern applications and research areas ranging from context-aware services, wireless resource allocation to social sciences. In this study we collect a novel dataset using standard mobile phones and analyze how the predictability of mobile sensors, acting as proxies for humans, change with time scale and sensor type such as GSM and WLAN. Applying recent information theoretic methods, it is demonstrated that an upper bound on predictability is relatively high for all sensors given the complete history (typically above 90%). The relation between time scale and the predictability bound is examined for GSM and WLAN sensors, and both are found to have predictable and non-trivial behavior even on quite short time scales. The analysis provides valuable insight into aspects such as time scale and spatial quantization, state representation, and general behavior. This is of vital interest in the development of context-aware services which rely on forecasting based on mobile phone sensors.

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Publication date: 2010

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Main Research Area: Technical/natural sciences
A service based estimation method for MPSoC performance modelling

This paper presents an abstract service based estimation method for MPSoC performance modelling which allows fast, cycle accurate design space exploration of complex architectures including multi processor configurations at a very early stage in the design phase. The modelling method uses a service oriented model of computation based on Hierarchical Colored Petri Nets and allows the modelling of both software and hardware in one unified model. To illustrate the potential of the method, a small MPSoC system, developed at Bang & Olufsen ICEpower a/s, is modelled and performance estimates are produced for various configurations of the system in order to explore the best possible implementation.
Project: PhD