Structure and Interpretation of Rhythm and Timing*

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Rhythm, as it is performed and perceived, is only sparingly addressed in music theory. Existing theories of rhythmic structure are often restricted to music as notated in a score, and as a result are bound to refrain from making statements about music as it is perceived and appreciated by listeners. This paper outlines a cognitive approach to the study of rhythm and timing that allows for making scientific observations and statements about 'sounding' music, music as it is performed and listened to. This approach was developed over the last few years in the context of the *Music, Mind, Machine* project at the Nijmegen Institute for Cognition of Information.[1]

In addition, the notion of *rhythm space* (the set of all possible performed rhythms) is elaborated into a systematic method for the investigation of the relation between rhythmic structure, expressive timing and tempo. As such the paper presents a research program that aims to develop a theory of music incorporating both the structural and perceptual aspects of musical time.

Introduction

A performed rhythm can sound 'mechanical', 'anticipated', 'laid-back', 'rushing', etc. This is caused by playing some notes somewhat shorter and others longer in duration. But how does a listener perceive the timing of these rhythms and recognize it as being 'rushed' or 'anticipated'? Why is a rhythm with a slightly shorter note not simply a different rhythm? How do rhythm and timing interact?

These are questions not typically addressed in music theory. However, they are fundamental in the development of a cognitive theory of music as performed and listened to. Such a theory ought to make statements about both the structure and interpretation of any performed rhythm. While rhythmic structure has been a topic in several music theoretical

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[1] The research presented in this article was done in close collaboration with Peter Desain, with whom the author currently directs the *Music, Mind, Machine* group at the Nijmegen Institute for Cognition of Information. This research is concerned with the computational modeling of music cognition, using an interdisciplinary approach combining expertise from musicology, psychology, and computer science. See for a discussion on this approach: Peter Desain, Henkjan Honing, Huub van Thienen and Luke Windsor, "Computational modeling of music cognition: problem or solution?", in: *Music Perception* 16 (1998), pp. 151-166.

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investigations,[2] these theories tend to be restricted to music as it is notated in a score, and must therefore refrain from making statements about music as it is perceived and appreciated by listeners.[3] Furthermore, tempo, which it is safe to ignore when studying rhythm as it is notated in a score, becomes an essential component when studying 'sounding' rhythm. In contrast, the performance aspects of music have been extensively studied in music psychology. There is a large body of research that addresses the relation between musical structure and the timing variations as found in music performance. Several proposals have been made for theories on the relation between musical structure (in particular meter and phrase structure) and expressive timing.[4] However, rhythm – defined as the sequential pattern of durations relatively independent of meter or phrase structure[5] – has often been ignored in these studies. We will address this gap in music theory (with regard to the role of timing and tempo) and music perception research (with regard to the role of rhythm proper), and present an outline of a methodology to arrive at a theory of the relation between rhythmic structure, expressive timing, and tempo in 'sounding' music.

Rhythm Perception and Performance

Research on music perception has shown that temporal patterns in music combine two representations of time essentially different: the discrete rhythmic durations as they are symbolized by, for instance, the quarter and eighth notes in a musical score, and the continuous timing variations that characterize an expressive musical performance.[6] A listener is able to separate the information in a performed rhythm into rhythmic categories (the symbolic durations one would notate in an ear training exercise; see Example 1a) and expressive timing (the intentional timing deviations that communicate, for example, the

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[2] Grosvenor Cooper and Leonard B. Meyer, *The rhythmic structure of music*, Chicago 1960; Fred Lerdahl and Ray Jackendoff, *A generative theory of tonal music*, Cambridge 1983.

[3] However, over the last decades in increasing number of musicological studies are concerned with these psychological aspects. See, e.g., John Rink (ed.), *The Practice of Performance: Studies in Musical Interpretation*, Cambridge 1995.

[4] Alf Gabrielsson, "The Performance of Music", in: Diana Deutsch (ed.), *Psychology of Music,* second edition, University of California, San Diego 1999, pp. 501-602.

[5] Justin London, "Rhythm", in: *The New Grove Dictionary of Music and Musicians*, second edition, London 2001, pp. 277-308.

[6] Eric F. Clarke, "Rhythm and Timing in Music", in: Diana Deutsch (ed.), *Psychology of Music,* second edition, University of California, San Diego 1999, pp. 473-500.

structural characteristics of the rhythm, or musical style and idiom). And it could be argued that expressive timing is only perceptable *because* there is categorization, the rhythmic category functioning as a reference relative to which timing deviations are perceived and appreciated.[7]

In music performance research these timing patterns have been modeled primarily as tempo variations, representing tempo as a mathematical function of time. Such a continuous *tempo curve* is obtained by measuring the distances between the onsets of notes at equal distances (e.g., the beat as indicated in the score), and taking its reciprocal (i.e. 1/duration; see Example 1b, a high value representing a faster tempo). Although this is a useful measuring method, tempo curves were shown to fall short as an underlying representation of timing, from both musicological[8] and psychological perspectives.[9] The predictions made by computational models using this representation[10] are insensitive to the actual rhythmic structure of the musical material – they make the same predictions for different rhythms (for further details see the references mentioned under footnotes 8 and 9). In addition, it has been shown that expressive timing will be adapted with regard to the global tempo: at different tempi, different structural levels of the music will be emphasized, the timing being adapted accordingly.[11]

The above suggests the need for a richer representation of timing than is captured by an unstructured tempo curve (i.e., a representation independent of the musical material and with no inherent structure).

Based on these observations, we will outline a method to arrive at a theory of rhythm and timing that addresses the properties mentioned. Using this method it will be possible to

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[7] Peter Desain and Henkjan Honing, "Quantization of musical time: a connectionist approach", in: Peter M. Todd and D. Gareth Loy (eds.), *Music and Connectionism*, Cambridge 1991, pp. 150-167.

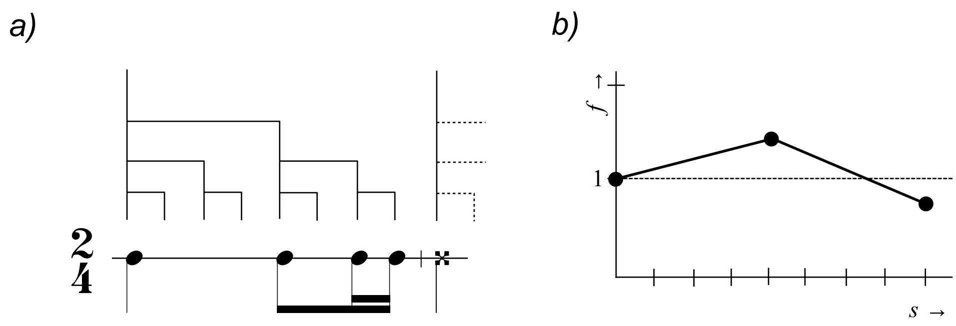
[8] Peter Desain and Henkjan Honing, "Tempo Curves Considered Harmful", in: Jonathan D. Kramer (ed.), *Contemporary Music Review* 7/2 (1993) ("Time in Contemporary Musical Thought"), pp. 123-138. See http://www.nici.kun.nl/mmm/tc for additional sound examples.

[9] Peter Desain and Henkjan Honing, "Does expressive timing in music performance scale proportionally with tempo?", in: *Psychological Research* 56 (1994), pp. 285-292.

[10] Manfred Clynes, "Microstructural Musical Linguistics: Composer's pulses are liked best by the best musicians", in: *Cognition (International Journal of Cognitive Science*), 55 (1995), pp. 269-310; Neil P. M. Todd, "The Dynamics of Dynamics: a Model of Musical Expression", in: *Journal of the Acoustical Society of America* 91/6, pp. 3540-3550.

[11] Eric F. Clarke, "Expression in performance: generativity, perception and semiosis", in: Rink (ed.), *The Practice of Performance*, pp. 21-54.

generalize and abstract from musical style and idiom. And, most importantly, it will allow for a decomposition of the components of ‘sounding’ or performed rhythm.



Example 1. Representations as have been used in a) music theory (a rhythm and its metric interpretation) and b) music psychology (a measured tempo curve). In Example 1a note symbols have been used to represent inter-onset intervals (IOIs). A cross-symbol has been used to emphasize that just the onset is considered. The bullets in Example 1b refer to the measured beat (or pulse) at the quarter note level of a performance of the rhythm shown in a) (*s* is note position in the score, *f* is tempo factor).

Performed Rhythm

Performed rhythm could be considered as consisting of (at least) three components: the rhythmic structure, tempo and timing.[12] A listener is able to separate (or derive) these different types of information from a single performed rhythmic *pattern* (see Example 2).

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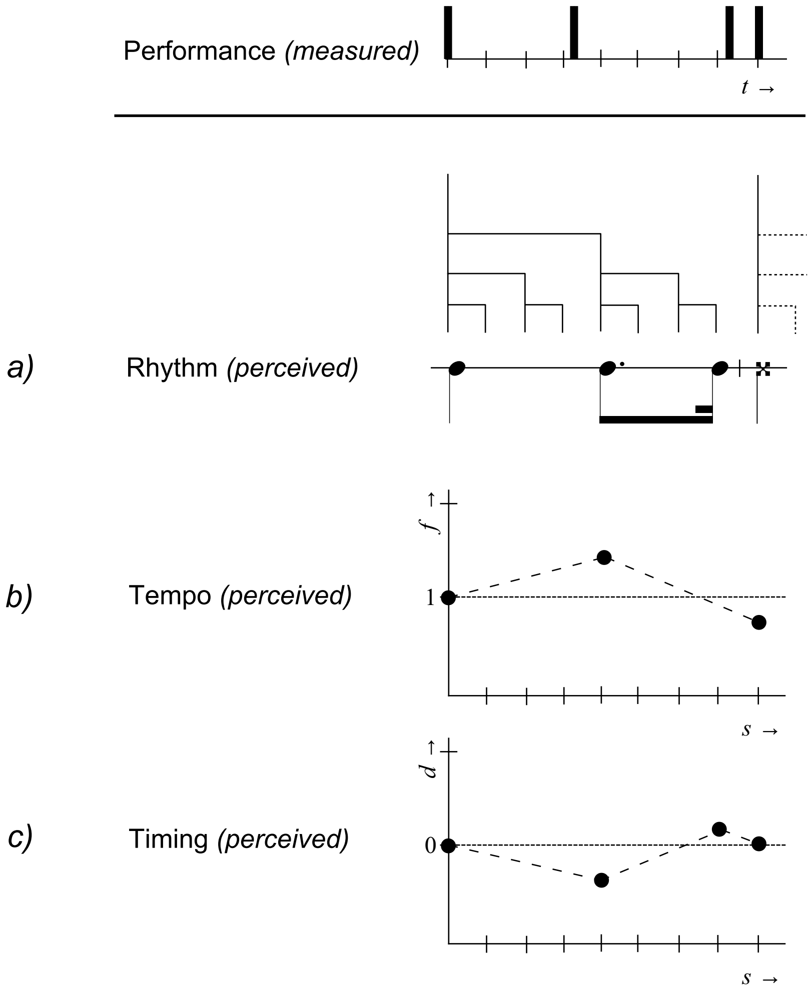
[12] See for a discussion on the formalization of these notions: Henkjan Honing, “From time to time: The representation of timing and tempo”, in: *Computer Music Journal* 35/3 (2001), pp. 50-61.



Example 2. Components of performed rhythm (top): a) rhythmic structure, b) tempo (change), and c) expressive timing (*t* denotes time, *s* position in the score, *f* tempo factor, and *d* timing deviation).

The first component is the perceived rhythm, which can be represented on a discrete, symbolic scale (see Example 2a). We will refer to this perceived rhythm as the *rhythmic category*. (As such this concept differs from the notion of performed rhythm that is measured on a continuous scale). This is similar to rhythm as it is notated in a musical score, which is typically studied in music theory, and is related to the process of categorization[13] as studied in music perception research.

The second component is *tempo*: the impression of the speed (or its changes) of the performed pattern (see Example 2b). Tempo is related to the notion of *tactus* as it has been discussed in

[13] Clarke, "Rhythm and Timing in Music", pp. 489-494.

music theory[14] and to the cognitive process of *beat induction* (how listeners arrive at a sensation of pulse when listening to a rhythm) as it is studied in music perception.[15] Although it is still unclear what exactly constitutes the perception of tempo, it seems to be related – at least in metrical music – to the notion of beat or tactus: the speed at which the pulse of the music passes at a moderate rate (i.e. the metrical level at which one counts the beat).
The third component is expressive *timing* (see Example 2c) that describes the timing deviations in a performance (e.g., accentuating notes by lengthening them for a bit, or playing notes 'after the beat'). These expressive timing patterns will often be performed differently at different tempi. In addition, timing might be perceived independently of any changing tempo (*tempo rubato*). So it could be argued that expressive timing and expressive tempo possibly co-exist as two, relatively independent and perceptable aspects of a performance. The question now is how to study systematically these various components of performed rhythm.

Representing Performed Rhythm

A common method in the study of timing in music performance is to analyze (a corpus of) typical examples of expert performances.[16] This approach, however, may cause difficulties in that the results obtained could easily be dependent on idiosyncrasies or musical style. We therefore chose to consider the space of all possible performances: a so-called rhythm space or *performance space*.[17] This is an abstract mathematical notion. So as to be able to depict such a performance space we will restrict ourselves here to short rhythms: all possible performed rhythms made up of three time intervals (or note durations).[18] In this three-dimensional space every point constitutes a different temporal pattern (e.g., the point labeled A in Example 3a represents the performed rhythm made up of the time intervals 0.25, 0.50, and 0.25 seconds). This infinite set of performances contains musical and unmusical rhythmic patterns, rhythms often encountered in music, and those rarely used. It captures all possible expressive interpretations in any musical style of any rhythm of four onsets. All patterns that

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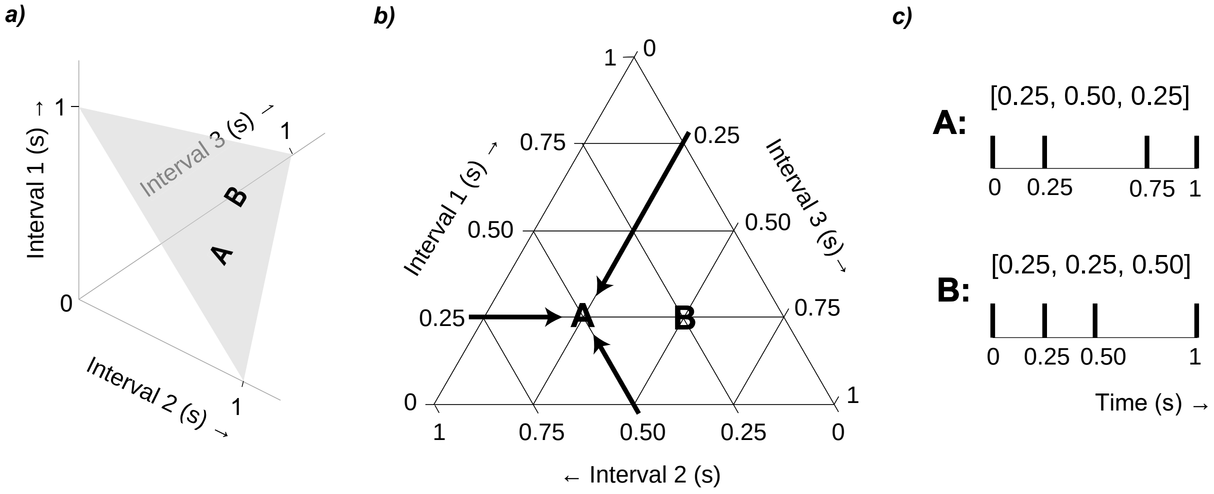
14 Lerdahl & Jackendoff, *A generative theory of tonal music*, p. 21.

15 Peter Desain and Henkjan Honing, "Computational Models of Beat Induction: The Rule-Based Approach", in: *Journal of New Music Research* 28/1 (1999), pp. 29-42.

16 Gerhard Widmer, "Using AI and Machine Learning to Study Expressive Music Performance: Project Survey and First Report", in: *AI Communications* 14/3 (2001), pp. 149-162.

17 Desain and Honing, "Quantization of musical time", pp. 161-162.

add up to a fixed total duration form a diagonal triangular slice in such a performance space. Example 3a shows the triangle for all rhythms that add up to a one-second duration. Looking from above, towards the origin, the triangle can be represented as a ternary plot (see Example 3b).



Example 3a, b, c. a) Performance space: the space of all possible performed rhythms of four notes (i.e. three intervals), b) ternary plot of all rhythms adding up to a one-second duration, and c) two example patterns. These performances of four onset rhythms are single points in the ternary representation shown in b. There the note durations (or interval size) can be located by reading the grid along the direction of the tick marks. For example, the point labeled 'A' corresponds to a rhythmic pattern of four onsets, its first IOI being 0.25, the second being 0.5 and the last IOI 0.25 seconds. (Adapted from Desain & Honing, *The perception of time*.)

The cognitive process of extracting a symbolic representation from a performance, as it is studied in categorization, can be investigated by determining which set of performances will be perceived as interpretations of the same rhythmic pattern (see Example 4). To examine this, a large group of musicians were asked to notate a systematic sampling of the performance space shown in Example 3.[19] This research showed that listeners do not perceive durations on a continuous scale. Instead, rhythmic categories are recognized that function as a reference relative to which the deviations in timing (or expressive character) can be perceived.

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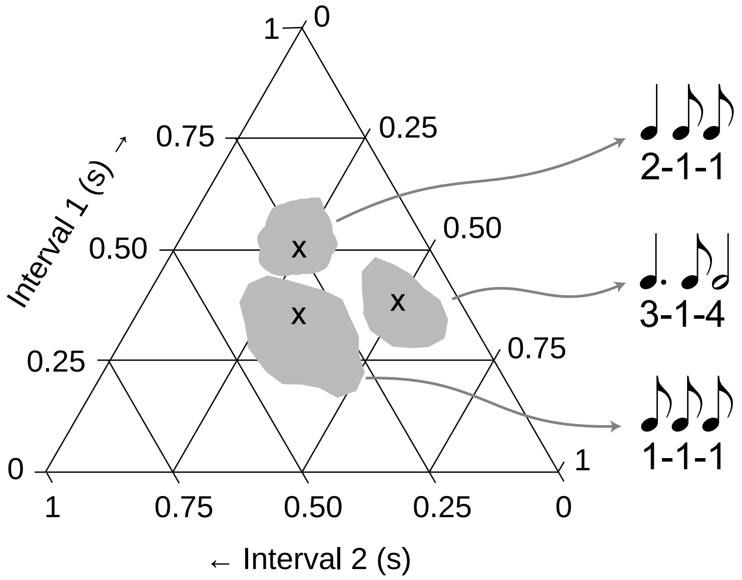
[18] Note that the notion of a performance space can be generalized to *n* time intervals to represent longer rhythmical fragments.



Example 4. Three regions in performance space (marked in gray) and their perceived rhythmic interpretation (black crosses indicate the position of the mechanical rendition of the notated rhythm).

Studies on Rhythm, Tempo and Timing

This performance space representation can be used not only to study rhythmic categorization, but it turns out to be very useful in studying the influence of the other components of rhythm as well. The next sections will briefly describe some of those aspects, to be considered in future research.

The relation between timing and rhythmic structure

While previous research (as discussed above) identified the constraints on the expressive freedom – crossing a category boundary will result in hearing an altogether different rhythm –, it failed to address the possible structure and interpretation of the performance regions themselves. It is unlikely that all positions in a certain region (cf. Example 4) are equal in quality, since they make the difference between one expressive interpretation over another. But could there be just one expressive performance that represents a certain rhythm in the most communicative way? Is there a direct relation between the rhythmical structure and the

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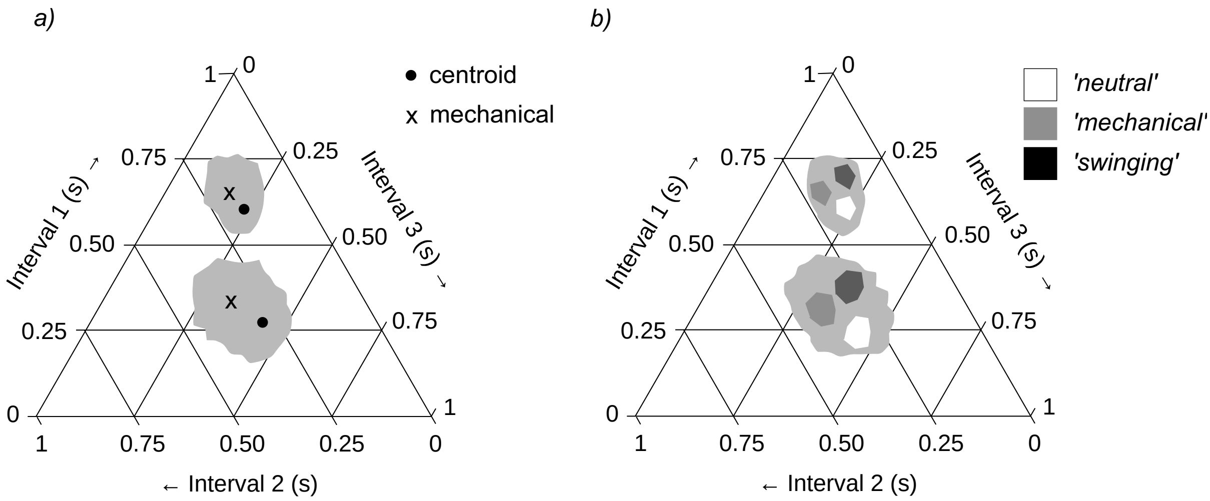
[19] Peter Desain and Henkjan Honing, *The perception of time: the formation of rhythmic categories and metric priming*, Nijmegen 2002. See http://www.nici.kun.nl/mmm/time.html.

mean of the measured timing variations? If so, is there a consistent relation between these prototypical patterns and their location in performance space?

To answer these questions, the performed rhythm that was identified as a certain rhythmic category most often by the participants of the experiment – apparently the most communicative rendition of the rhythm – can be directly related to the structure of the rhythmic category. Generally, these so-called performance *centroids* (the black dots in Example 5a) are not expected to be the mechanical rendition of the rhythm (the position of the black crosses in Example 5a), but will be slightly shifted for most rhythms, indicating that a non-mechanical (i.e. expressively timed) rhythm will be more easily recognized as an interpretation of this particular rhythm than its mechanical rendition.



Example 5. The interpretation of timing: a) the relation between timing and rhythmical structure, and b) between timing and expressive character.

The relation between timing and expressive character

Another way of studying the regions within a category is to consider them as identifying various expressive characters (e.g., 'anticipated, 'rushed', or 'neutral'), which may well be related to familiarity of the listener with the musical idiom, relatively *independent* of the rhythmic structure. Some known results about expressive timing, for instance, typical swing patterns or the slowing down at the end of a fragment,[20] will be re-formalized into hypotheses about these areas. The aim here is to show whether and how distinctive sub-areas are experienced.

[20] Caroline Palmer, "Music Performance", in: *Annual Review of Psychology* 48 (1997), pp. 115-138.

The role of absolute tempo

While for a long time most models of timing in music ignored the influence of absolute tempo – the rate or speed at which a rhythm is performed –, over the last decade, the effect of tempo on music perception and performance has been acknowledged and shown by several researchers. For instance, Stephen Handel[21] showed that the same rhythm presented at a different tempo will not, as a general rule, be recognized as the same rhythm.[22] Nevertheless, it has not been possible to bring forward and validate a model, despite various attempts. One problem in studying these fundamental issues is the dependency of expressive timing on performance style and musical idiom. For this reason we chose to address the role of absolute tempo by studying the perception of rhythm, instead of investigating how a rhythm is performed.

*The role of changing tempo (*tempo rubato*)*

Having addressed rhythmic structure, expressive timing, and the influence of absolute tempo in performed rhythm, we will be in a position to investigate the interaction between expressive timing and expressive tempo. Is timing perceiced independently of tempo, in this way enabling us to hear a note as early or late, even in a musical fragment slowing down? And how could we differentiate between these two types of timing in one performed rhythm? This could be studied by presenting the same set of performed rhythms as have been used in the other studies proposed, embedded in a context of accelerating or decelerating beats, again asking musicians to notate the perceived result. This will yield valuable empirical data on the interaction between timing and tempo. Assuming that the size of the regions (i.e., expressive freedom) changes depending on absolute tempo, we can expect them to gradually change over the course of the rhythm. For instance, when the rhythm 2-1-1 exhibits a large region at tempo 60 and a larger one at tempo 40, the boundaries of the region (expressive freedom) might slowly broaden over the course of the rhythm presented in decelerating context (e.g., a *ritardando*).

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[21] Stephen Handel, “The effect of tempo and tone duration on rhythm discrimination”, in: *Perception & Psychophysics* 54/3 (1993), pp. 370-382.

[22] This will have effects on the technique sometimes used by music transcribers that slow down a recording to identify the precise rhythmic structure of a certain musical fragment: some performed rhythms will be recognized as an altogether different rhythm.

Figural vs. metrical interpretations of rhythm

While we primarily are concerned here with addressing rhythm rather independently of its metric interpretation, a complete theory should, of course, incorporate meter as well. It is puzzling, however, that while meter was shown to exert a strong influence on the recognition of rhythm,[23] existing computational models of meter can explain this phenomenon only to a small extent.[24] This could be considered to be additional empirical support to the idea that there is more to rhythm than meter alone, as has been emphasized in several musicological and music theoretical studies.[25] The latter is in contrast with some computational theories of music perception that take things so far as to consider rhythm to exist solely under metric interpretation.[26] This issue could be studied by investigating the figural aspects of rhythm, considering the surface structure of the rhythm: a sequential pattern of durational accents (in contrast to a hierarchical representation such as meter).

Conclusion

Rhythm and timing have been only sparingly addressed in music theory. A reason for this neglect might well be the methodological difficulties that arise when attempts are made to study ‘sounding’ music. If one wants to make scientific observations and statements about performed music, appropriate experimental and measurement methods, often not readily available in the standard literature, need to be designed. Furthermore, there is a noticeable difference between things measurable and things perceived in performed music (see Example 2). For instance, a meter cannot be directly measured in a performed rhythm – it is actually induced in the listener: the listener actively constructs it while listening to music. Further aspects of rhythm, such as timing and tempo, are also clearly of a perceptual nature. Hence cognition should play an important role in the study of performed rhythm, and methodologies from the cognitive sciences could be used beneficially.

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[23] Clarke, “Rhythm and Timing in Music”, p. 490.

[24] Peter Desain and Henkjan Honing, “Modeling the Effect of Meter in Rhythmic Categorization: Preliminary Results” in: *Journal of Music Perception and Cognition* 7 (2001). See http://www.nici.kun.nl/mmm/time.html.

[25] Justin London, “Rhythm”, pp. 283-287.

[26] H. Christopher Longuet-Higgins, *Mental Processes*, Cambridge 1987, pp. 150-168.

Research on rhythm perception has developed over the last decades from psycho-acoustical studies, studying the perception of time using very simple stimulus material, to true music perception research, where ecologically more valid materials have been used and the effect of musical context has been taken into account. This could be the moment to take advantage of the available knowledge and methods from this research, and to try and contribute to a theory of the perception and representation of musical time, commonly considered a research area crucial to our understanding of the complex processes that enable us to enjoy and perform music.[27]

[27] Thanks to Rokus de Groot, Wim van der Meer, Remko Scha and Barbara Bleij for their remarks on an earlier draft of this paper.