The Role of Tempo in Groove and Swing Timing

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Contents

Abstract

In music the notion of expressive timing, i.e. deliberately playing behind or before the beat, is very common. The question how expressive timing relates to tempo has been subject to research for quite a while. However, the effect of tempo on timing in jazz and pop performance was only scarcely investigated. This thesis investigates the relation between tempo and expressive timing in groove and swing drumming by analyzing the timing of three well-known professional drummers. Furthermore a model is presented that tries to capture this effect of tempo on expressive timing.

In a controlled experiment three expert drummers were asked to perform three musical fragments in sixteen repetitions in six different tempi on a complete midi drum kit. The results show that expressive timing largely depends on the style and tempo of a drum groove. In addition, it is found that expressive timing does not scale proportionally with tempo in a Swing and Funk drumming, but does scale proportionally with tempo in Shuffle drumming.

To model the relation between timing and tempo a knowledge representation is used that separates tempo and expressive timing as different aspects of musical time. The relation between timing and tempo is represented by three swing ratio models which are optimized to fit the newly acquired data.

Acknowledgments

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"Uh . . . Yeah OK"
Tribal Tech, Face First, Track 6

Chapter 1

Introduction

1.1 Capturing the Groove!

"Why does music makes you want to dance?" It goes without saying that dancing has everything to do with the rhythm of music. But what makes a particular rhythm funky or pleasant to dance to? Most people will agree that when the written notes of a score are played exactly as notated (for instance by a computer), it sounds *mechanical* or *unnatural*, although, this can be strongly style and genre dependent. So, a musician probably does something with a rhythm. This must be a difference in the placement of notes in time different than is notated. Musicians frequently refer to this phenomenon of *playing behind* or *before the beat* as *expressive timing*, or simply *timing*. They are known to purposely use expressive timing to embellish their music and to communicate the musical structure to the listener.

This thesis is about expressive timing in groove and swing. In the past two decades expressive timing has been researched extensively. Although this mainly concerned music from the classical genre, recent studies have specifically addressed timing within jazz and popular music as well. When investigating expressive timing in drumming one cannot omit the concept of *groove*. What is groove? It seems to arise spontaneously from musical performances, but what defines groove remains intangible. The musicologist Middleton (1999) tried to define groove as follows:

> "the concept of groove—a term now theorized by analysts but long familiar in musicians' own usage—marks an understanding of rhythmic patterning that underlies its role in producing the characteristic rhythmic *feel* of a piece, a feel created by a repeating formalism within which variation can then take place."

The only way to unravel the mysteries of groove is by thoroughly investigating the rhythmical structure and expressive timing patterns within these grooves.

A particular type of rhythm that cannot be played without expressive timing and serves as a foundation of a variety of grooves is *swing*. The swing rhythm consists of pairs of notes where the duration of the first note is augmented and the duration of the second note is diminished. Music students learning swing are often told that the first note of each of these pairs is to be twice as long as the second, but in practice musicians only play this *triple feel* at certain tempi. The swing rhythm is best known from jazz, but it occurs in a lot of other musical styles as well.

One of the most important aspects of rhythm is *tempo*. It is the speed or pace of a rhythm and highly influences how a piece of music is perceived by listeners. Dances, emotions and moods can change if the tempo of a song changes. Although the relation between expressive timing and tempo has been subject to research, the question how musicians adapt the groove of a piece to tempo remains, to a large extend, unanswered. This thesis focuses explicitly on that question. Can the concept groove and its relation to tempo be captured and formalized? This thesis aims to provide some insights in the relation between tempo and expressive timing in modern drum grooves by presenting a model and some empirical evidence.

1.2 Research Question

The purpose of this thesis is to better understand the relation between tempo and expressive timing in musical performances of drummers. To gain this understanding the following question will be answered:

> "What is the relation between tempo and expressive timing in groove and swing drumming, and can this relation be modeled using a knowledge representation that separates expressive timing and tempo as different aspects of musical timing[1]?"

To answer this question we will introduce new empirical data and a model. In this experiment three well-known expert drummers participated in a controlled experiment in which they were asked to perform three musical fragments of three styles in six different tempi on a MIDI drum kit. This model, to be referred to as the Tempo Dependent Timing (TDT) model, uses a knowledge representation of musical time (named the *timing functions formalism* (TFF); Honing, 2001) which allows to model tempo as well as expressive timing independently.

The following statements are hypothesized:

1. All styles of drumming contain measurable and significant expressive timing.

2. The expressive timing measured in the performance data does not scale proportionally with tempo.

3. The timing functions formalism (Honing, 2001, which will be explained in detail in chapter 3) is capable of capturing the relation between timing and tempo.

4. Systematic irregularities in the part of a groove with the most pulses (e.g. the rhythm on a hi-hat or a ride cymbal), reflect the metrical representation of the drummer and determine the placement of the other percussive instruments (e.g. snare drum and base drum) in the groove. These patterns can therefore be used as a basis to characterize and model modern jazz and pop drumming.

1.3 Relevance to Cognitive Artificial Intelligence

This thesis is written in conclusion of the master Cognitive Artificial Intelligence (CAI) at the University of Utrecht. CAI studies the cognitive capabilities of the human brain by

[1]Note that in this thesis *timing* refers to the placing of notes within any musical context and *expressive timing* refers to the minute deviations from regularity that contribute to the quality of a music performance (Clarke, 1999; Palmer, 1997). Nevertheless, musicians sometimes refer to *expressive timing* when they use the word *timing*.

using computer models. This fruitful combination made that cognitive scientist nowadays use a computer to model brain processes to better understand how the human brain works. Computer scientists on the other hand use ideas from cognitive science to enhance the performance of their programs. CAI combines several disciplines which, in their own way, try to understand intelligence from there own perspective.

One of the most intriguing capabilities of a human being is to listen to, or perform music. It seems to be a fundamental part of our cognitive system. This is clearly demonstrated by the fact that (practically) nobody listens to music as if it were a collection of incoherent sounds. Almost everybody can at least hear a rhythmical pulse. Most people can discern a lot of structure and enjoy listening to music. Listening to music makes use of several high level cognitive functions like memory, attention, perception, expectation and emotion (Palmer, 1997). Some of these capabilities are innate, others we develop during our lifetime. It is most certain that the listening to and the performing of music is a fundamental aspect of our cognitive apparatus.

The area investigating music perception and performance is called music cognition and combines methods of musicology, psychology and computer science. Music cognition tries to understand music perception and performance by formalizing and modeling the mental processes involved in listening to and performing music using a computer. Therefore, music cognition can been seen as a sub-field of CAI. In fact, three aspects of music cognition make this thesis typical for CAI. First of all, computational modeling and empirical experiments are used to unravel the systematic properties of human intelligence. Secondly, a highly cognitive domain of human intelligence is investigated, namely music. Thirdly, the obtained model will be used to evaluate the results in a analysis-by-synthesis method and can be used to create better performing computer programs.

1.4 Outline of This Thesis

The outline of this thesis is as follows: Chapter 2 discusses what is known about timing and tempo in general. The first section of chapter 3 elaborates on the Timing Functions Formalism (TFF). This formalism is a knowledge representation of time in music which separates timing from tempo and forms the basis of the TDT model. The last section of Chapter 3 concerns the implementation of the TFF and the swing ratio combinator, which combines a swing ratio model with the TFF, into the musical Mircroworld.

The setup of the empirical experiment will be elaborated on in chapter 4. In this experiment the performances of three different modern drum grooves, played by three well-know professional drummers in number of different tempi, were recorded using a MIDI drum kit. Chapter 5 discusses the results of this experiment by analyzing the timing deviations with respect to a metronomically perfect grid and the change of swing ratio over tempo. In the last section of Chapter 5 the results are underpinned by correlations. Chapter 6 places the results of Chapter 5 in the context of the discussed literature and presents the swing ratio models that are fitted on the newly acquired data. The thesis is concluded by a summary and suggestions for further research.

Chapter 2

Background

2.1 Expressive Timing

What is expressive timing? Music is often not performed with the exact relative durations as notated by the composer. Musicians vary the intervals between tone onsets to express the structure and the meaning of the music (Palmer, 1997; Clarke, 1999). This does not just hold for performers of classical music but for performers of jazz and pop music as well. In fact, many musicians have extreme difficulty performing music with mechanical precision (Collier & Collier, 1996; Palmer, 1997).

Expressive timing in general and its relation to tempo has been researched for quite some time now. It has been found that the way musicians use expressive timing depends on the structure, style, and tempo of the music. However, how this relation affects jazz and pop drumming is largely unknown. In this chapter a survey will be presented of what is known about expressive timing and its relation to tempo in a broad sense.

Before one can start discussing expressive timing it should be made clear to what extent people can *perceive* micro timing deviations (e.g. expressive timing). This is not an easy question at all. First, we should consider which different time perturbations may occur in music. The difference between these different perturbations becomes obvious when displayed with isochronous beats (see Figure. 2.1). Concerning expressive timing there are two possible perturbations. One is that an inter-onset interval[2] (IOI) is displaced, but the subsequent IOIs are not altered by this displacement (Fig. 2.1a) The other one is that after lengthening or shortening an IOI all subsequent notes are shifted equally in time (Fig. 2.1b). The first of these perturbations, displacement, can be cyclic (Fig. 2.1c), this is typically used in Swing and groove timing. If an IOI is lengthened and all subsequent IOIs are scaled in proportion this is considered a tempo change (Fig. 2.1d).

Friberg and Sundberg (1995) surveyed the research done on the just noticeable difference (JND) of small perturbations in these monotonic isochronous sequences. They concluded that our sensitivity to tempo was greater than our sensitivity to other types of perturbations. This was to be expected since a tempo change affected a greater number of intervals. Compared to one perturbation in displacement a number of IOIs were perturbed in a tempo change and consequently more information was available. For the lengthening and shortening of isochronous sequences Friberg and Sundberg found that in the middle IOI range of about 400 to 1000 ms. the JND was approximately constant to a relative 2.5% of the IOI. For IOIs below

[2] The time between the onsets of two notes.

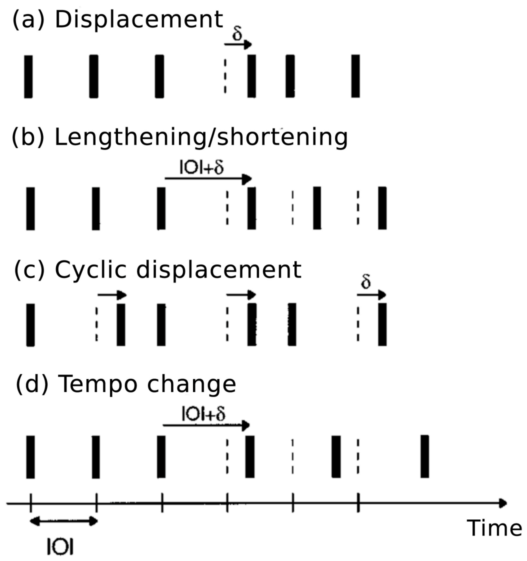

Figure 2.1: Possible time perturbations (adopted from Friberg and Sundberg (1995))

the 250 ms. the JND was approximately constant to 6 ms. However, the authors stressed that the JND depended on a large number of experimental factors. Surprisingly, musical experience was not found to influence the sensitivity of the JND in monotonic isochronous sequences.

It goes without saying that IOI lengthening in an isochronous sequence is different from IOI lengthening in music. The fact that the JND of IOI lengthening depends on a large number of factors, and that these factors increase when stimuli become musically more realistic, was demonstrated by Repp (1992b). He showed that musically literate listeners had difficulty recognizing lengthened IOIs on positions where lengthening was expected. He used an excerpt of a metronomically perfect performance of a piano sonata[3] and lengthened one or two notes randomly chosen from the pool of all eighth-notes in the piece[4]. He varied the amount of lengthening ranging from 6.7% up to 16.8%. The tempo used was 88 beats per minute (BPM) which corresponds to an IOI of 341 ms. for each eighth-note[5]. Note that the lengthening went up to seven times the amount of perturbation that could be detected in a monotonic isochronous sequence at the same tempo. Nevertheless subjects did not report the lengthening on positions that were musically expected to be lengthened. This suggest that at certain positions in the piece a lenghtened IOI sounds more natural than a metronomically perfect IOI.

The positions in the piece were lengthening was not noticed were all related to the grouping structure of the music. This grouping refers to the segmentation of a phrase in smaller sub-phrases, forming hierarchical levels, largely based on pitch relationships (Lerdahl & Jackendoff, 1983). Therefore lengthening in general commonly occurs at the end of major sections, subsections and individual phrases. Note that lengthening of one IOI is no different to delaying an onset (e.g. in relation to Fig. 2.1b) The word lengthening suggests that the duration of a note is longer. Though this is true, the delay of the next onset is perceptually more

[3]The first eight bars of the third movement of Beethoven's Piano Sonata No 18 in E-flat major, Op. 31, No. 3.

[4]Note that this pool covered the total eighth-note grid of the piece.

[5]An eighth-note is twice as long as a quarter note, i.e. beat within this thesis.

salient due to the acoustic decay of the piano sound used. In fact, an onset can be delayed so much that it is perceived as an early onset for the next beat. To explain these results Repp suggested that top–down expectations, elicited by the musical structure, interacted with the subjects' perception of temporal intervals.

Another study showing that our rhythmical perception is largely biased by musical context was done by Desain and Honing (2003). They presented professional musicians with three-tone rhythms drawn randomly from a pool of all three-tone rhythms[6] and asked them to write down (i.e. categorize) the rhythm. The subjects did not perceive a mechanical rendered rhythm as being the prototype rhythm of a category. For instance, they categorized the IOI sequence 1.916:0.976:1.108 (at 60 bpm an IOI of 250 ms.) instead of 2:1:1 as the prototype sequence for the rhythmical category[7]: ♩♫. Desain and Honing found that a small set of categories divides the space of rhythmic performances. When plotted in a three dimensional space, with each axis representing an IOI of the tree-tone rhythm, the rhythmical categories become circular shapes. These categories differed in size and shape, and their location was not centered around the position of a mechanical rendition of the category. The shapes, sizes and positions of the rhythmical categories were heavily dependent on meter as well. When subjects were presented with the context of a triple subdivision at forehand they often categorized a rhythm differently than when they were presented with a duple subdivision[8].

Palmer (1997) wrote an elaborate survey on music *performance* in general. She concluded that performers used expressive timing to communicate the musical structure to the listener. Musicians were able to replicate their expressive performances for a given piece with high precision. Attempts to play without expression dampened the expressive timing patterns, but did not result in performances without expressive timing. Another study showed that experts used more expressive timing than novices and that the amount of expressive timing increased after practicing an unfamiliar piece. Expressive timed phenomena might therefore be partly explained by the intentional play of the performer and partly by less controllable brain processes inherent to human music performance. Evidence of Collier and Collier (1996), presented in section 2.4, supports this hypothesis. Palmers' survey mainly concerned the performance of music from the classical genre. One of the most typical forms of expressive timing in classical music is the melody lead. This is the phenomenon of the melody leading the accompanying voices with 20 to 50 ms. (Goebl, 2001). This has been investigated most extensively for piano music. Melody leads may serve to perceptually separate voices and make the melody more salient.

To summarize, a great number of studies point out that expressive timing plays an important role in music. It helps communicating temporal structure to the listener and listeners are sensitive to it. Expressive timing is continuously variable, reproducible and occurs in a broad range of musical styles.

2.2 The Role of Tempo

It is not very surprising that tempo has an enormous effect on the way musicians play and time. How tempo affects expressive timing in music performance has been subject to investigation for some time as well. Desain and Honing (1993) argued that the relation between tempo

[6]The IOIs were varied between 158 ms. and 684 ms. in steps of 53 ms.

[7]This was measured without the context of a meter.

[8]For some nice examples see: `http://www.nici.kun.nl/mmm/time/time.html` (June 8, 2007)

and timing is not simply proportional (e.g. when a tempo is played twice as fast, the timing deviations do not become twice as small). Researchers have often recorded the performances of professional musicians and measured the timing deviations form note to note, yielding an expressive timing profile. Desain and Honing argued that these timing profiles do not scale proportionally with tempo. A tempo specific timing profile is related to the musical structure. These musical structures tend to have different functions at different tempi and therefore cannot share the same timing profile. Phrases, chord spread and ornaments, like grace notes, thrills and vibrato are examples of phenomena that require specific timing at a specific tempo.

The hypothesis, that timing does not scale proportionally with tempo, is supported by a growing number of studies. Honing (2006) showed that listeners with all sorts of musical backgrounds could recognize if a piece did not have the right timing. This did not only concern music from the classical genre, but jazz (Honing, 2007) and rock (Honing & Ladinig, 2006; Honing & Ladinig, under review) as well. In a series of experiments Honing et al. investigated whether subjects where able to recognize an original recording from a tempo transformed[9] recording. Subjects were presented with a website with couples of audio examples. The audio examples of each couple were excerpts of different performances of the same piece, which originally differed about 20% in tempo. In each couple one of the examples was either speeded up or slowed in order to present the subject two excerpts with the same tempo. The subjects had to decide which of the two excerpts was the original and which was the tempo transformed excerpt[10]. If timing scales proportionally with tempo, it would not be possible to hear a difference between a tempo transposed version of a song and an original recording. The results of all experiments supported the hypothesis that timing does not scale proportionally with tempo. The majortity of the subjects was able to identify the tempo transformed excerpt from the original one. Honing (2006) performed a control experiment where he used the same stimuli and asked a group of audio experts to identify the excerpts that were tempo transposed by focusing on possible artifacts of the tempo transformation. The results were non-significant.

It is clear that tempo relates timing, but how tempo affects expressive timing in modern music remains unclear. Next to this, apart from the studies just mentioned not much of the effect of musical genre is know either. Within the literature swing, as expressive timed rhythm and as musical genre, and its relation to tempo has been researched most extensively (Friberg & Sundström, 2002; Collier & Collier, 1996; Collier & Collier, 2007)Swing and its relation to tempo will be discussed in the next two sections respectively. Nevertheless, if we want to understand why funky music is funky, and why some music makes you want to dance, more research is needed to investigate the relation between timing and tempo.

2.3 Swing

When investigating groove, one cannot leave out *Swing*. The word Swing, in musical sense, has two meanings. It is known as a musical sub-genre of jazz, originated in the early 20^{th} century played by big bands, and as a way of playing consecutive eighth-notes in a long–short

[9]This concerned a transformation in tempo alone and no transformation in pitch. For this transformation state-of-the-art tempo transformation software was used (Bonada, 2000)

[10]In (Honing, 2006) the setup was slightly different, the subjects listened to only one excerpt before they had to decide if it was an original or tempo transposed recording

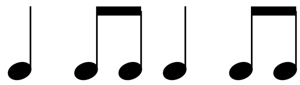

Figure 2.2: The typical jazz swing rhythm, played on the ride cymbal, notated with even eighths, as done by the majority of the musicians.

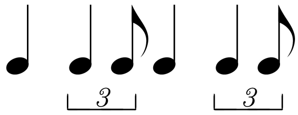

Figure 2.3: The typical jazz swing rhythm notated as how it would sound if played with a triple feel (i.e. with a swing ratio of 2:1).

fashion. Although both meanings of swing are related, since the eighth-notes in the style Swing are played with *swing*, in this section the term swing is treated only as the latter. The swing rhythm has a rich cultural background and forms the basis of many grooves in modern music.

The swing rhythm consists of note pairs where the durations of the odd notes are augmented and the durations of the even notes are diminished. The amount of swing is commonly expressed in the proportion of the length of the first note to the length of the second note. This measure is called the *swing ratio* and is explained in detail in Section 5.4.1 (on page 5.4.1). Students learning the swing are often advised to learn it by listening to records (Friberg & Sundström, 2002). Sometimes however students are taught to play an explicit *triple feel*, that is, a swing ratio of 2:1. Although Swing is not to often played with a *straight feel*, a swing ratio of 1:1, swing rhythms are notated with even eighth-notes by most musicians (see Figure 2.2).

Swing playing is often associated with jazz, but swing occurs in many other musical styles. Therefore a lot of research has been done in swing. However the relation between swing ratios and tempo is less extensively investigated. The most important insights into this relation are provided by a study of Friberg and Sundström (2002). They measured the swing ratios of several jazz recordings. Another experiment, closely related to the experiment presented in this thesis, was done by Collier and Collier (1996). They measured the performance of three experienced drummers when playing the typical jazz swing rhythm on a midi drum pad. These two studies will be elaborated on in the next section.

2.4 Tempo & Swing Ratio

Friberg and Sundström (2002) investigated the relation between swing ratio and tempo in ensemble timing in jazz with two experiments. In the first experiment they used excerpts from 10 to 26 seconds from commercial jazz recordings to measure the swing ratio of the drummers. All drummers could be regarded as well known and had a distinct style of playing. Friberg and Sundström calculated the swing ratio by measuring the lengths of 10 pairs of eighth-notes of the characteristic swing pattern on the ride cymbal (see Example 1 and 2). In their second experiment they used the same recordings but related the analysis of the drums to the performance of the remainder of the ensemble.

The study showed a common pattern of timing related to the tempo and to the played instrument. In total, Friberg and Sundström analyzed recordings of four different drummers

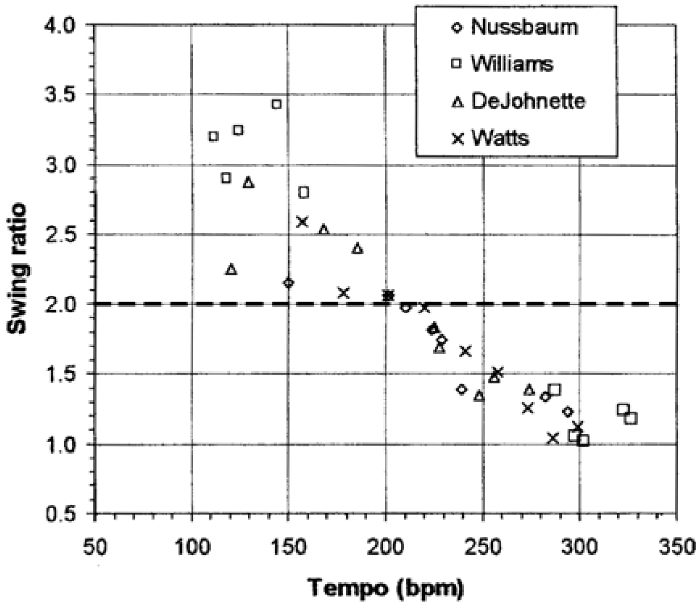

Figure 2.4: Drummer swing ratios adapted form Friberg & Sundström (2002), with the horizontal dotted line indicating the often-mentioned triple feel.

and found that swing ration decreased with increasing tempo (see Fig. 2) and suggested that the relation between swing ratio and tempo could be linear. Friberg and Sundstöm also reported that some excerpts tended to approach a constant swing ratio of 2:1 at slower tempi. Most of the differences in swing ratio were found in the tempi below 200 BPM and were considerable and the largest swing ratios measured were between 3:1 and 3.5:1 (Fig. 2.4). Note that a swing ratio of 3:1 can be written as a dotted eighth-note followed by a sixteenth note. At the highest tempi the swing ratio measured approached 1:1, this means that both eighth-notes have an equal length. It must be noted that the analysis of the swing ratio of Nussbaum had a considerably lower variation. Friberg and Sundström ascribed this to the fact that the Nussbaum recording was a play-along recording and there was no interaction with a soloist.

In addition Friberg and Sundström reported that the second short eighth-note approaches a constant duration 80 of 100 ms. at medium to fast tempi (>150 BPM). This limit could be explained by two phenomena. It could be the lowest inter-onset interval playable for a drummer, or it could be the limit of the perceptual duration of a short stimulus (Efron, 1970).

In the second part of the paper Friberg and Sundström discussed the swing ratios of complete jazz ensembles. They concluded that the jazz ensembles analyzed could be characterized in the following way. The soloist used a smaller swing ratio than the drummer, and the bass was performed with a slight delay compared with the ride cymbal. Friberg and Sundström suggested that the soloist swing ratio might have deviated because the soloist synchronized at the off-beat of the cymbal and purposely delayed the downbeat. The study did not reveal player specific timing characteristics, but the authors believed that each musician has such a preferred timing characteristic.

As mentioned earlier, Collier and Collier (1996) investigated the relation between tempo and swing ratio as well. They asked three drummers, most of them with professional expe-

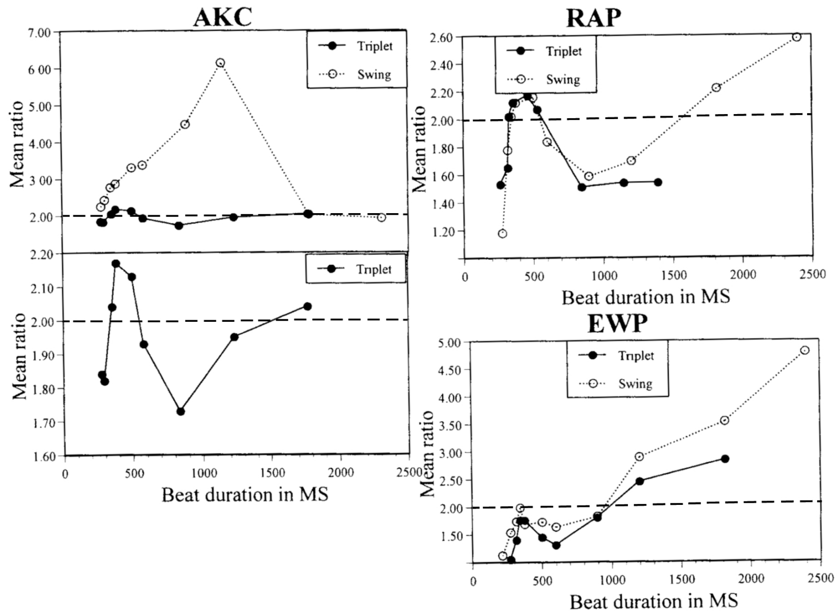

Figure 2.5: Drummer swingratios adopted from Collier & Collier (1996), with again the dotted line indicating the triple feel (i.e. a 2:1 swing ratio).

rience in jazz and pop, to play the typical ride rhythm (see Example 1 and 2) at 11 or 9 different tempi on a midi drum pad. The drummers were asked to play a natural *swing* feel and a strict triple feel at each tempo. It is not clear if all drummers perceived the swing playing differently from the playing of strict triplets.

The results are displayed in figure 3. Note that for subject AKC the triplet graph is reproduced below the primary graph, with the y axis rescaled to a smaller range. The ratios varied widely from the strict 2:1 both in the swing as well as in the strict triplet condition. In the triplet condition all drummers displayed a peak in the swing ratio at about 375 ms. (160 bpm). This peak was identical for the subjects AKC and RAP, at a ratio of 2.17:1, EWP displayed a peak ratio of 1.76:1. A qualitative similarity could be seen between the drummers consisting of a low initial ratio at low tempi, a peak and a turn down, and then an ascending up pattern. It must be noted that this ascending pattern crossed the swing ratio of 2:1 at 50 bpm (inter-onset intervals of 1200 ms. of the quarter-note). If the tempo drops any further the tempi start to become unmusical and very hard to time well. The similarity between AKC and RAP was also reflected by a correlation of .70. Collier and Collier suggested that the lower correlations of the third drummer with the first two could be explained by a shift in the pattern on the abscissa, since the shape of the pattern was quite similar. The swing ratio of 2:1 appeared only at the middle tempi for the strict triple condition.

The swing conditions were similar to those of the triplet for RAP and EWP. This suggests that RAP and EWP tried to play triplets in the swing condition. At intermediate tempi the swing ratio of the swing conditions tended to be slightly greater than the ratios of the strict triplet condition. This tendency was in contradiction with the prediction of Collier and Collier. They predicted that the ratios of the swing conditions would be smaller, based on the popular notion among jazz musicians of playing swing triplets more even than strict triplets.

The fact that the results of the swing condition were similar to the strict triplet condition can be seen as support for the hypothesis that drummers try to play strict triplets when playing swing. Drummers are sometimes taught swing by playing strict triplets. However the experimental design, i.e. the separation of a swing and a triplet conditions, might have forced the differences between these two conditions, since having two conditions might explicitly suggest that there is a difference and therefore bias the drummers to play differently.

2.5 Concluding Remarks

Expressive timing occurs in many different musical genres and its presence is especially prominent in swing. The use of expressive timing, commonly expressed in the swing ratio, is largely dependent on tempo. The expressive timing patterns in Swing, but in music from the classical genre as well, do not seem to scale proportionally with tempo. Note that there could large cultural differences with respect to expressive timing. Therefore all the literature surveyed in this chapter must be placed in the context of the western culture.

Expressive timing can partly be explained by deliberately lengthening or shortening of IOIs by musicians, but not completely. Drummers playing swing often try to play strict triples in swing, but they only succeed to do so at certain tempi. Piano players were not able to play completely without expressive timing, but were able to reproduce an expressive timed performance with extreme accuracy. From the perceptual point of view there is evidence that expressive timed notes sound more natural (i.e. remain unnoticed) at certain positions in classical piano pieces. Perception of rhythm in general is very context dependent. Mental categories differ from the notated, metromically perfect categories and are affected by meter and other musical structure. How perceptual issues like these relate to groove and swing remains unknown.

Hardly any research has been conducted on the use of expressive timing in popular music. The challenge is to see if it is possible to capture the expressive timed elements in modern drumming in a model which has some explanatory power in musical or perceptual terms.

Chapter 3

The Tempo Dependent Timing Model

3.1 Introduction

In this chapter the structure and implementation TDT model are presented. The basis of the model is formed by a common lisp implementation of two knowledge representations designed by Honing: the Timing Functions Framework (TFF) (Honing, 2001) and the musical Microworld (Honing, 1995). The TFF captures timing and tempo, as two different aspects of musical time, into *timing functions*. This is explained in detail in the next section. The musical Microworld is an eleborate representation of music, developed to extend musical score with continues features, e.g. vibrato's, glissando's, etc. The TFF will be integrated a musical Microworld and all is implemented in Common Lisp (Steele & Steele Jr, 1990).

3.2 Time-maps & Timing Functions

There are numerous ways of representing timing and tempo in music. A sophisticated framework for describing relations in musical time is the TFF (Honing, 2001). Within this knowl-

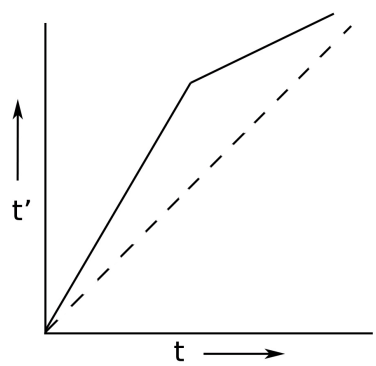

Figure 3.1: An example time-map. The reference line denote the points where the pre-perturbed time equals the perturbed time.

edge representation a *tempo-change* is separated from a timing-change, or *time-shift*. The main difference between a tempo-change and a time-shift is: tempo-changes change the total duration of the piece, and time-shifts change the onsets of individual notes.

The core of the TFF consist out of modified *time-maps*, first developed by Jaffe (1985). A time-map (see Figure 3.1) is a continuous, monotonically[11] increasing function mapping a pre-perturbed time t to a perturbed performance-time t':

$$\mathsf{f}(t) \rightarrow t' \tag{3.1}$$

Time maps can take *score-time* s as their argument for pre-perturbed time, but actually any real number can be used as input. The name score-time is chosen analogously to a musical score, but it is nothing more than a rational[12] number denoting the position on a virtual score. This virtual score is a description of the rhythmic structure of the music containing the pitches, onsets and durations of the notes. The *performance-time* denotes the relative time when the piece is performed.

It is musically important to be able to express the performance-time into the score-time, e.g. the third beat is always a bit delayed or slow down after the fourth measure. A problem of time-maps is, when a performance time is obtained from a score-time the score-time is lost, making it harder to express timing or tempo directly into the score-time. Mathematically a strictly monotonic function always has an inverse and it is therefore always possible to retrieve the score-time. However, Honing (2001) solved this problem in another elegant way by making time-maps a function of score-time as well (see Equation (3.3) and (3.4)). This allows for the direct expression a timing or tempo change in to the score-time.

Honing then defined a *timing function* as a tuple (Equation 3.2) consisting of a *time-shift function* (f^{+}) and a *tempo-change function* ($\mathsf{f}^{\times}$) which both are modified time-maps (see Equation (3.3) and (3.4) respectively). The tempo-change function maps the score-time to a certain tempo and the time-shift function adds expressive timing to the notes. A typical example of an applied time-shift function is displayed in Figure 3.2.

$$\mathbf{f} \equiv \langle \mathsf{f}^{+}, \mathsf{f}^{\times} \rangle \tag{3.2}$$

$$\mathsf{f}^{+}(s,t) \rightarrow t' \tag{3.3}$$

$$\mathsf{f}^{\times}(s,t) \rightarrow t' \tag{3.4}$$

An evaluation function $\mathbf{E}$ calculates a new performance-time given a timing function $\mathbf{f}$, a symbolic score-time s and a performance-time t:

[11]A time-map is *strictly* monotonous (if $x > y$ then $f(x) > f(y)$). Non strict monotonicity (if $x > y$ then $f(x) \geq f(y)$) would not make any sense musically. It would allow a performance time to be accessed by a range of score positions and let different notes on the score coincide in performance time.

[12]Ttime-maps can effortlessly deal with real numbers as well, but it does not make sense to express score data up to the level of real numbers, because the precision of performance and perception lies within milliseconds and rational numbers are accurate enough to represent a musical score up to the millisecond level

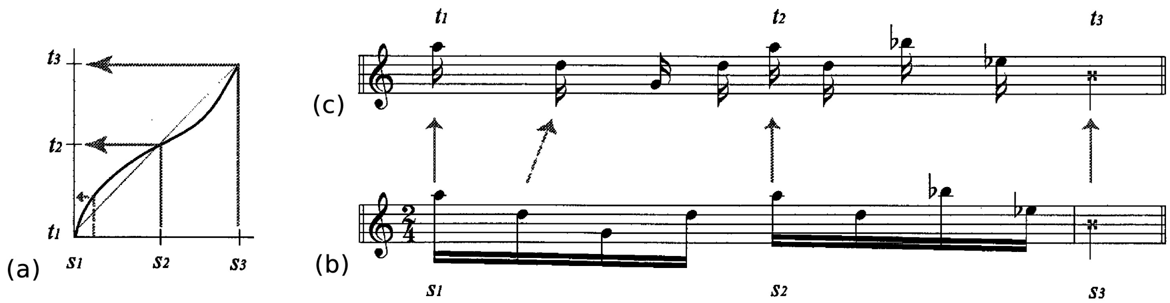

Figure 3.2: A 'give and take' example of a time-shift function (adopted from Honing (2001)). (a) represents the time-shift function, (b) the score and (c) a score with spacing indicating its timing. The time-map expresses a rubato with an acceleration (from t1 to t2) and a deceleration (from t2 to t3).

$$\mathbf{E}(\mathbf{f}, s, t) = \mathsf{f}^{+}(s, \mathsf{f}^{\times}(s, t)) \tag{3.5}$$

The thought behind the evaluation function (3.5) is that first the tempo transformations are applied and a perturbed performance-time is obtained, thereafter the timing deviations that are scaled to that perturbed performance-time are applied. Note that it would not be possible to add expressive timing to a specific note if the score-time was not provide as an argument to a time-map.

3.2.1 Composition & Concatenation

Timing functions allow for Composition and Concatenation. The composition of two arbitrary timing functions is defined by:

$$\mathbf{f} \otimes \mathbf{g} = \langle \mathsf{f}^{+} \otimes \mathsf{g}^{+}, \mathsf{f}^{\times} \otimes \mathsf{g}^{\times} \rangle \tag{3.6}$$

where

$$(\mathsf{f} \otimes \mathsf{g})(s, t) = \mathsf{f}(s, \mathsf{g}(s, t)) \tag{3.7}$$

The symbol $\otimes$ denotes the composition function. Note that the subscript in Equation (3.7) is left out because the type of time-map used is irrelevant, since time-shifts are only composed with time-shifts and tempo-changes are only composed with tempo-changes.

The concatenation of time-maps is less strait forward:

$$\mathbf{f} \oplus_m \mathbf{g} = \langle \mathsf{f}^{+} \oplus_m \mathsf{g}^{+}, \mathsf{f}^{\times} \oplus \mathsf{g}^{\times} \rangle \tag{3.8}$$

where

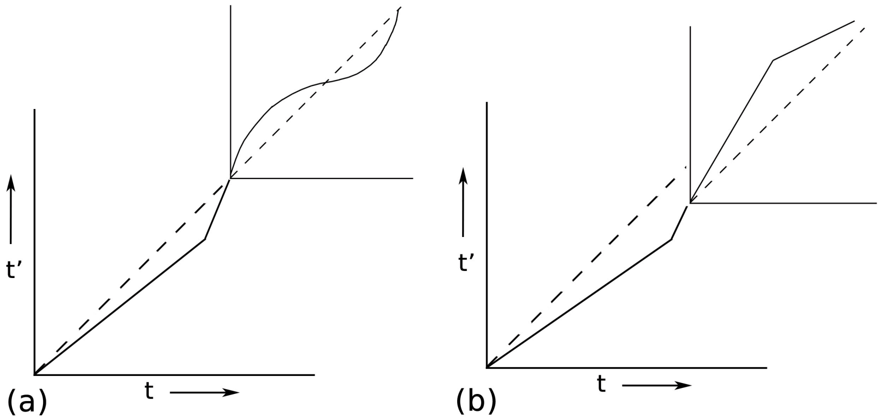

Figure 3.3: The concatenation of time-maps. The time-shift in (a) denotes a concatenation in score-time and the tempo-change in (b) denotes a concatenation in perfomance-time. The reference line denote the points where the pre-perturbed time equals the perturbed time.

$$(\mathsf{f}^{+} \oplus_m \mathsf{g}^{+})(s,t) = \begin{cases} s \leq m & \mathsf{f}^{+}(s,t) \\ s > m & \mathsf{g}^{+}(s,t) \end{cases} \tag{3.9}$$

and

$$(\mathsf{f}^{\times} \oplus_m \mathsf{g}^{\times})(s,t) = \begin{cases} s \leq m & \mathsf{f}^{\times}(s,t) \\ s > m & \mathsf{g}^{\times}(s,t) + \mathsf{f}^{\times}(m, m_{ft}) - \mathsf{g}^{\times}(m, m_{gt}) \end{cases} \tag{3.10}$$

The symbol $\oplus_m$ denotes the concatenation function and m is the position in score-time where f^{+} is joined with g^{+}. Equation (3.9) describes that g^{+} is concatenated at the point where f^{+} ends *in score-time*. The function f^{+} is applied up till m and the function g^{+} after m.

The idea behind Equation (3.10) is to concatenate $\mathsf{g}^{\times}$ to $\mathsf{f}^{\times}$ at the point where $\mathsf{f}^{\times}$ ends *in performance-time*. This point is calculated by obtaining the performance-time from $\mathsf{f}^{\times}$ in m: $\mathsf{f}^{\times}(m, m_{ft})$. Here, m_{ft} is the performance-time corresponding to the the score-time m. If $\mathsf{f}^{\times}$ is the only tempo-change the score-time m equals the performance-time m_{ft}(it is not yet transformed), but if $\mathsf{f}^{\times}$ is a composed tempo-change this performance-time m_{ft} has been perturbed by another tempo-change as described in Equation (3.7). The difference between time-maps concatenated in score-time and performance-time is illustrated by Figure 3.3a and Figure 3.3b respectively.

Because $\mathsf{g}^{\times}$ is a tempo-change function that holds for a certain part in the piece, it has no knowledge of the score-time up till m and expects the score time to be 0 at m. Therefore $\mathsf{g}^{\times}$ has to be corrected and $\mathsf{g}^{\times}(m, m_{gt})$ is subtracted from the function. m_{gt} is again the performance-time of $\mathsf{g}^{\times}$ corresponding to m.

3.2.2 Generalized Timing Functions

In the final section of his paper Honing generalizes timing functions by defining a generalized timing function. A generalized timing function can access all the previous time-shifts and tempo-changes but also the begin-time and end-time (in score-time) over which the function is defined.

$$\boldsymbol{f}(b, e, \mathbf{u}) \rightarrow \mathbf{f} \tag{3.11}$$

Here, b is the begin-time, e the end-time (both rational numbers denoting the symbolic score-time), and $\mathbf{u}$ is a timing function containing all the previous applied time-shifts and tempo-changes. The generalized timing function $\boldsymbol{f}$ is, in fact, a timing function constructor returning a timing function that has access to the begin-time and end-time in score-time, but also in performance-time (b and e applied to $\mathbf{u}$)[13]. Having this information available allows us to describe how the timing and tempo of a piece of music or a particular groove pattern, e.g. swing, are related to it's metrical structure, e.g. position in the phrase structure,. Furthermore, it allows us to model how expressive timing changes when the tempo is changed.

Generalized timing functions can be composed and concatenated as well. Composition of two generalized timing function is given by:

$$(\boldsymbol{f} \otimes \boldsymbol{g})(b, e, \mathbf{u}) = \boldsymbol{f}(b, e, \boldsymbol{g}(b, e, \mathbf{u})) \tag{3.12}$$

Concatenation of two generalized timing functions is given by:

$$(\boldsymbol{f} \oplus_m \boldsymbol{g})(b, e, \mathbf{u}) = \boldsymbol{f}(b, m, \mathbf{u}) \oplus_m \boldsymbol{g}(m, e, \mathbf{u}) \tag{3.13}$$

Here the concatenation symbol $\oplus_m$ denotes the same concatenation as defined in Equation (3.8), (3.9) and (3.10).

3.3 The Tempo Dependent Timing Model

The TDT model uses the knowledge representations of the TFF and the musical Microworld and a swing ratio model to model expressive timing and its relation to tempo. Since the TFF and the musical Microworld alone do not model expressive timing, the actual relation between timing and tempo is described by a swing ratio model. Swing ratio, thoroughly explained in section 5.4.1 (on page 32) is a simple but powerful concept that generalizes over systematic deviations with respect to the score. Given a certain swing ratio at a certain tempo, it is possible to generate a time-shift function placing the swung notes on there of-the-grid positions. Figure 3.4a displays a swing ratio time-shift function of a constant swing ratio. The fluctuating pattern represents the lengthening of the first eighth-note IOI and shortening of the second eighth-note IOI.

[13]Note that one needs at least one tempo-change time-map to map the score-time to the performance-time. The same thing holds for the time-shift time map, but 'no expressive timing' can be modeled by a time-map of the form: $\mathsf{f}^{+}(s, t) = t$. Of course this time-map does not do anything and just returns the performance-time

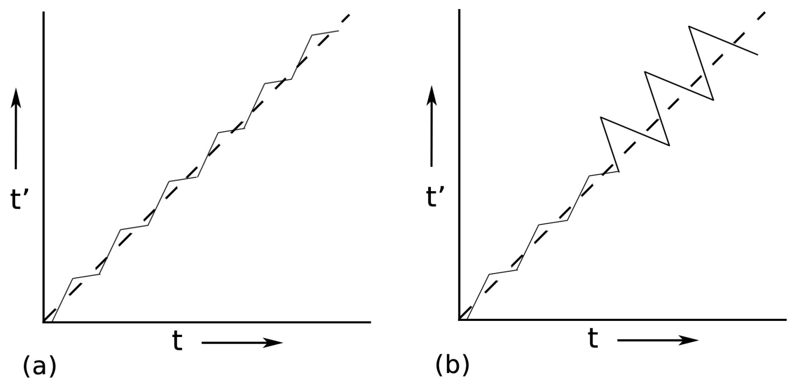

Figure 3.4: In (a) A swing ratio time-shift function with a constant swing ratio is displayed. In (b) a swing ratio time-shift function with a changing swing ratio is displayed.

3.3.1 Swing Ratio Combinator

Using swing ratio as a timing function, what is needed is a model describing the change of swing ratio over tempo. Having a tempo dependent swing ratio model allows for the generation of a swing ratio time-shift for every tempo provided by the tempo-change function. Knowing the complete tempo-change function for a certain piece, it is possible to generate the change of the swing ratio for a piece in one swing ratio time-shift using a generalized timing function. An example tempo depend swing ratio time-shift function is displayed in Figure 3.4b.

For the generation of a swing ratio time-shift functions a *swing ratio combinator* is designed. How swing ratio changes over tempo is not trivial. Therefore the swing ratio combinator cannot function without a swing ratio model. These swing ratio models must either be designed by hand or can be learned from data. For the the actual TDT model the swing ratio time-shift functions are fitted onto empirical drum data which was gathered in an experiment. The experiment is described in chapter 4 and the results in Section 5.4 of Chapter 5 (page 31). In addition, other, more subtle, expressive timing can easily be added by composing the swing ratio time-shift function with time-shift functions describing other expressive behavior extracted from the data. The three final swing ratio models of the three styles investigated are presented in Section6.2 (page. 45) and are based on the newly acquired swing ratio data.

3.4 Implementation

The implementation of the TDT model consist out of an implementation of the TFF, the swing ratio combinator, and the musical Microworld (Honing, 1995) in Common Lisp (Steele & Steele Jr, 1990).. The musical Microworld combines a symbolic discrete score with continuous features. Often a score is made up of note onsets, durations and pitch. The musical Microworld allows to model other continuous phenomena, like glissando vibrato etc., as well. Honing (1995) wrote an elaborate description of the musical Mircrowold and the source code is publicly available. The TFF fits into the Microworld quite nicely. Namely, the one musical thing that can not be modeled within the Microworld alone, and which can very well be modeled by the TFF, are tempo changes and time-shifts. The code of the the TFF and the musical Microworld can be found in the Appendix.

Chapter 4

Experiment

4.1 Musical Material

In order to gain insights into the relation between timing and tempo an experiment was conducted. Three well-known professional drummers participated in this experiment in which they were asked to perform three musical fragments of three styles in six different tempi on a complete MIDI drum kit. Next to a statistical analysis the acquired data were used to optimize the expressive timing components of the TDT model.

The musical material consisted of three drum rhythms of different musical styles: a typical jazz Swing, a popular Funk groove and a Funk Shuffle (see example 3, 4 and 5 respectively). The Swing rhythm was the typical standard jazz rhythm well known amongst musicians. The Funk groove was a groove also known as "the funky drummer" groove. Clyde Stubblefield played this groove in the song "the funky drummer" on the James Brown album "in the jungle groove". The Shuffle example was the groove that Jeff Porcaro played in the piece "Rosanna" and can be found on the Toto album "IV". The Shuffle rhythm is similar to the funky drummer rhythm, with the difference that its metrical grid is based on swing and therefore the eight notes are played in a long-short fashion.

The Swing, Shuffle and Funk excerpts are displayed in Figure 4.1, 4.2 and 4.3 respectively. Within Figure 4.1 a ♩ notated on the g denotes the ride cymbal, a ♩ notated on the lower d denotes a pedal hi-hat, a ♩ notated on the c denotes a snare drum and a ♩ notated on the higher d denotes a tom-tom drum. Within Figure 4.3 and 4.2 a ♩ notated on the e denotes the the closed hi-hat cymbal, a ♩ notated on the c denotes a snare drum and a ♩ notated on d denotes a base drum.

The different rhythms have different ranges of tempi in which they can be played. These boundaries arise as a part of the groove, the part with the lowest or highest event onset

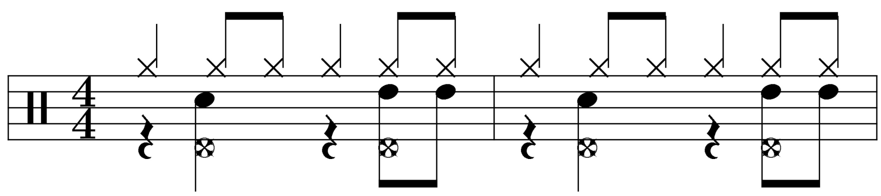

Figure 4.1: The typical jazz Swing rhythm. The eight notes are to be played with swing.

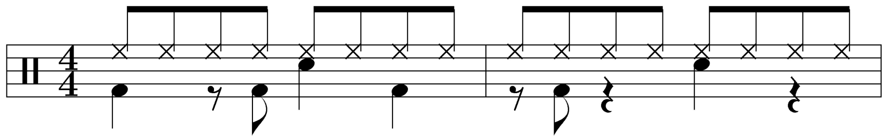

Figure 4.2: The Funk Shuffle rhythm. The eight notes are to be played with swing.

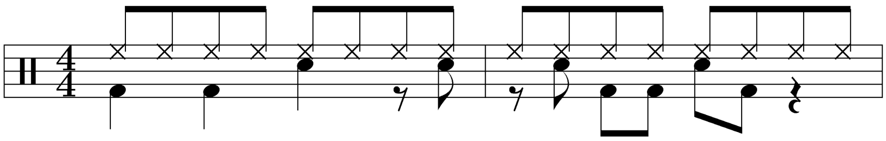

Figure 4.3: The funky drummer rhythm. The eight notes are to played straight.

intervals, is either too fast or too slow to perform. These boundaries vary of course for every drummer and depend on level of expertise. The absolute region of usable tempi, defined as the range within which separate musical events can be heard to have tempo at all, ranges from 30 to 300 BPM (Snyder, 2000). The usable ranges for the recorded grooves were smaller. For the funky drummer and the Shuffle rhythms these ranges are alike, both have a lower boundary of 120 BPM (i.e. a beat duration of 500 ms.) and an upper boundary of roughly 200 BPM (i.e. a beat duration of 300 ms.). For the experiment six different tempi were selected within this range, starting at a quarter note IOI of 300 and subsequently adding 40 ms. to the IOI up to 500 ms. The Swing rhythm can be played in a wider range of tempi, therefore three additional tempi were recorded with quarter note IOI's of 250, 540 and 580 ms.

4.2 Method

4.2.1 Participants

Three well-known professional expert drummers participated in the experiment. They all studied drums at one of the major conservatories in the Netherlands (i.e. Hilversum and Rotterdam). One of them (MS) has lectured at one of these conservatories for years now. All were dutch males a living from performing and lecturing drums. In this thesis the participants will be referred to with their initials: JK, JL and MS.

4.2.2 Equipment

Hardware & Software

The drummers played the rhythms on a Yamaha DTXpress III MIDI drum kit. The MIDI output of the MIDI drum kit was recorded with a Pentium IV computer using a E-MU MIDI interface and running Windows XP Service Pack 2. Steinberg Nuendo multi track software version 3.2.0 was used to register the MIDI. The generation of the metronome was done within Nuendo using a Virtual Studio Technology (VST) plug-in named groove agent version 2.0.0 set to the side stick sound of the slick drum kit. The first beat of a sequence of four beats was approximately twice as loud as the other three beats of the metronome, inducing a $\frac{4}{4}$meter.

Error Estimation

The transmitting of one MIDI command takes 1 ms. (Loy, 1985). In all rhythms except for MS's Swing recordings a maximum of 2 commands were send simultaneously yielding a maximum error of 2 ms. for the MIDI alone. In the Swing recordings of MS three simultaneous onsets might have occurred, which yields an maximum error of 3 ms. The error of the remainder of the equipment, i.e. computer, sound card and software is unknown. Note that the error is considered different from latency. The latency is assumed to be approximately constant and the analysis uses only the relative inter-onset intervals. Although the various soft- and hardware might have certain latencies, the effect on the analysis is considered negligible.

4.2.3 Procedure

The participants were asked to play 2 takes of 16 repetition of each rhythm at each tempi along with a metronome set to the desired tempo. In total 64 measures of each rhythm was recorded at each tempo. All drummers got a written score of the rhythm and were asked not to play any notes that were not written. The drummers were also presented with a quantized, i.e. without expressive timing, audio example of the drum rhythm at forehand. Before the recording of each excerpt the drummers were able to tune into the desired tempo by listening to the metronome.

After the drummers indicated that they were ready, they were asked to start playing after they listened to the metronome for 2 measures. The drummers played the excerpt in accompaniment with the metronome, to ensure that the measured deviations from regularity were expressive timing and not tempo deviations. The tempi were randomized per drummer and per style. The order of the three styles was randomized as well.

4.2.4 Data Processing

Cleaning Up the Data

The data was searched for spurious accents or double onsets, which were removed if found. Incomplete or erroneous cycles were removed completely (leaving the first and the last onset, provided this was a valid onset, intact in order to calculate the IOI of the preceding cycle).

Unfortunately at the time of recording the hi-hat pedal malfunctioned. The hi-hat *pedal* sensor failed in 'opening' the hi-hat accurately enough for analysis. Therefore the pedal hi-hat data of the Swing excerpt was obtained correctly from only one drummer (MS). The hi-hat data of the Swing excerpt performed by JK and JL was removed from the analysis. The malfunctioning of the hi-hat did not affect the use of the hi-hat *cymbal* sensor, consequently all other hi-hat data were recorded without any errors.

Metronome

The metronome that the drummers heard while playing is not used in the analysis. There were to many factors, i.e. sound synthesis and recording latency, that hampered the estimation of the placement where the drummers heard the metronome. Therefore a resulting estimation would lack sufficient detail to be useful in an analysis.

Software

All takes were recorded at separate MIDI tracks. The Nuendo software allowed the midi tracks to be exported in an XML[14] representation. The XML language of exporting was developed by Steinberg and no specification is publicly available. The data were then restructured and exported as a comma separated values text files by custom made software[15] running in Lispworks professional version 5.0.1. The data were further analyzed using the SPSS statistical software package version 15.0.

4.3 Data & Software Availablity

The data collected in the above described experiment, the custom made data processing software and the software of the modeling are freely available for scientific purposes. The data, represented as comma separated values text files, and all the Common Lisp source code can be downloaded from `http://www.hum.uva.nl/mmm/haas/` (June 8, 2007). Note that the core of the TDT model, the TFF and the musical Microworld, are printed in the Appendix (on page 57). For further questions, pleas send an email to `bas.dehaas@phil.uu.nl`.

[14] Extensible Markup Language, see `http://www.w3.org/XML/`(June 8, 2007) for more information

[15] See for the common lisp source code: `https://svn.cs.uu.nl:12443/viewvc/wbhaas/mcg/data-processing/data-processing.lisp?view=log` (June 8, 2007)

Chapter 5

Results

5.1 Systematic Groove Investigation

In this chapter the results of the experiment described in chapter 4 are presented. In chapter 1 it was hypothesized that the systematic irregularities in the hi-hat or ride, i.e. the part of a groove with the most pulses, reflect the metrical representation of a drummer. A drummer uses a metrical representation, as some kind of internal clock, as a reference to place the notes of a groove. The placements of these notes often deviate deliberately from a strict *metronomical* performance, i.e. a performance where all smallest intervals are strictly even-spaced, to embellish a groove.

In this chapter drum performances will be compared with metronomical, strictly even-spaced, *grids*. Knowing the exact deviations with respect to an even-spaced grid allows for the modeling of expressive timing. Metrical grids can be categorized into two major categories: the duple and the triple subdivision of a beat. To be able to get an impression of the systematic timing patterns of a drummer, the timing of the hi-hat cymbal, in the Funk and Shuffle excerpts, and the ride cymbal, in the sing excerpt, are thoroughly analyzed. After analyzing the deviation with respect to the metrical grid, the swing ratio of the hi-hat and ride is examined. The swing ratio is a flexible way of subdividing the beat, opposed to a strict duple or triple subdivision. Thirdly, the findings are underpinned by correlations.

5.2 Consistency

Every drummer performed 32 repetitions of the three excerpts at all tempi. From the recorded onsets of the hi-hat and ride the IOIs are calculated. Because the IOIs equal the relative duration between notes, they are averaged over excerpt cycles. Note that all IOIs are calculated starting with the first note of the bar. To get an impression of the expressive deviation the average measured IOIs of the excerpt are compared with the *metronomically perfect IOIs* calculated from the score at the same tempo. Metronomically perfect IOIs are calculated by measuring the interval between score onsets placed on a perfectly even-spaced metrical grid at a certain tempo, analogue to a metronome. They will be referred to as IOI_ss, i.e. *score* inter-onset intervals, throughout this chapter and are defined as:

$$IOI_s = P_{score} IOI_{beatduration} \tag{5.1}$$

Standard Deviation per Note-type		
Drummer	quarter-note	eighth-note
JK	9	6
JL	10	7
MS	7	5
Average	9	6

Table 5.1: The standard deviation of the quarter-note and the swung eighth-notes of the rhythm played on the ride cymbal of the Swing excerpt. The numbers are rounded to milliseconds after averaging.

Here $IOI_{beatduration}$ is the beat duration in milliseconds at a certain tempo. P_{score} is the proportional length of a note compared to the beat duration and its subdivisions, i.e. if the beat is a quarter-note an eighth-note has an P_{score} of .5. Opposed to IOI_s, the sampled IOI will be referred to as IOI_p, i.e. *performance* inter-onset intervals.

To be able to interpret the expressive deviations from the metrical grid, i.e. the difference between a sampled IOI_p and a IOI_s, it should be clear to what extent the measured deviations from regularity can be interpreted as expressive timing played by the drummers. In other words, how consistent can a drummer reproduce an expressively timed note? To get an indication of the *consistency* the standard deviation, i.e. the average deviation of the mean, is calculated over all cycles of the excerpt at all tempi. However, longer notes tend to be played less consistently proportionally to their IOI length (Repp, 1994). Therefore, comparing the standard deviation of notes of different lengths is not fair. To be able to compare the consistency of a drummer the standard deviation should be compared proportionally to the length of the IOI. Therefore all results of each style will be preceded with a table summarizing the standard deviation per note type and per drummer.

5.3 The Change of Inter-Onset Intervals over Tempo

5.3.1 Swing

The first style to be addressed is Swing. Table 5.1 gives an impression of the consistency of the drummers involved when playing Swing. It is the standard deviations of all 32 repetitions at all tempi in milliseconds per note-type. For the recorded rhythm (Fig. 5.1e), taking a triple subdivision into account, the consistency of the quarter-note is divided by three, the consistency of the first eighth-note by two and the last eighth-note by one, yielding an approximate average grid-point consistency of about 3 ms. The same thing is done in Figure 5.1 as well and will be explained in more detail below.

It can be concluded from Table 5.1 that the drummers can time a quarter-note with an approximate consistency of 9 ms. and an eighth-note with 6 ms. on average. Note that this does not mean that the drummers play the rhythm as notated. Rather, it implies that they can replicate their performances with a precision of 6 to 9 ms. depending on the type of note. This approximation of consistency includes not only consistency of the drummers, but the error of the equipment as well, since only relative IOI_ps are used. Remember that the JND of isochronous sequences is 6 ms. at minimum (see Section 2.1 on page 5). It can therefore be concluded that the inconsistency can barely be perceived by an average human being.

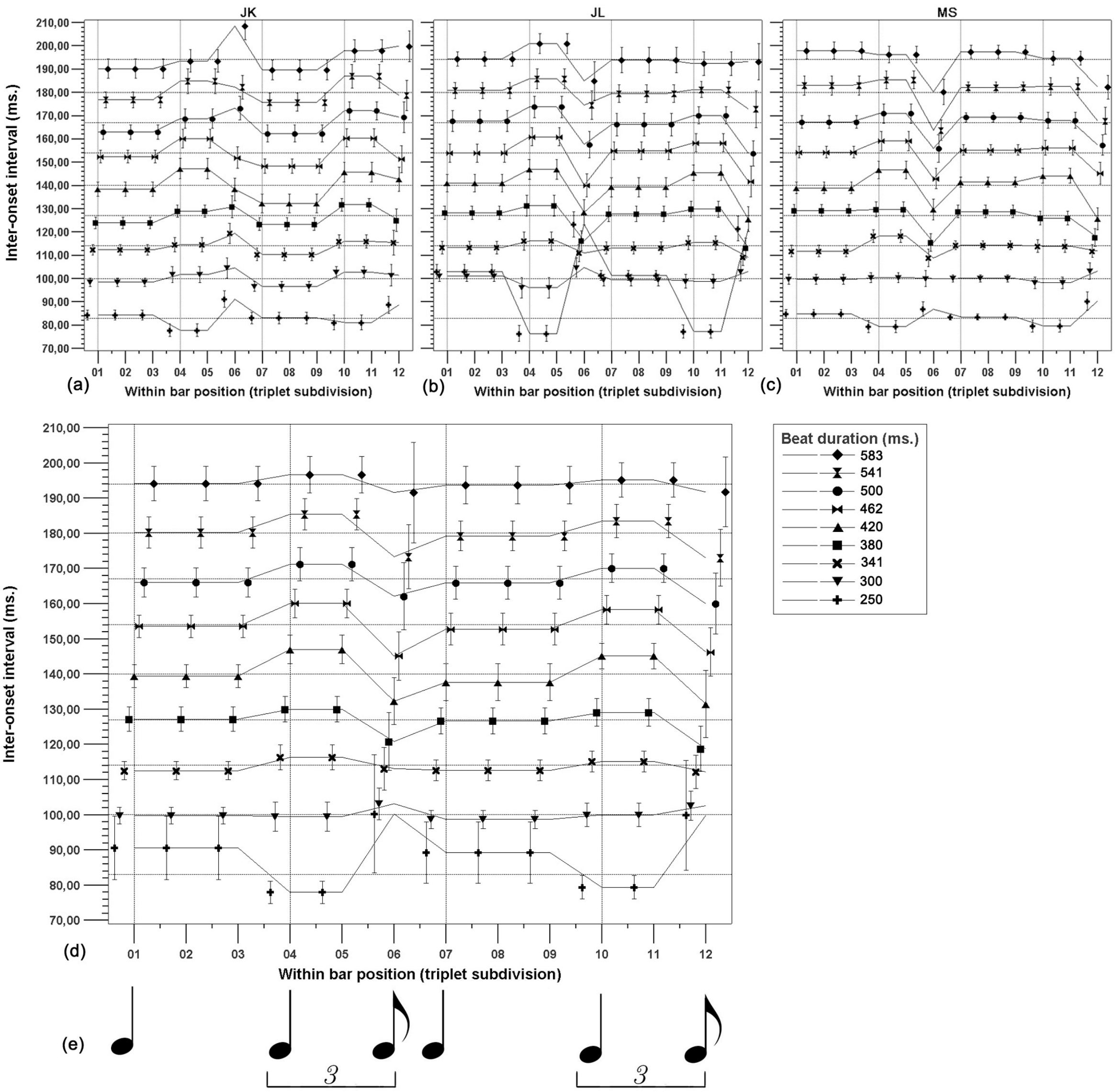

Figure 5.1: The mean interpolated IOI_ps of the Swing excerpt set out against the triplet metrical grid. (a), (b) and (c) show the IOI_ps per individual drummer for JK, JL and MS respectively and (d) displays the average over all drummers. The dots show the mean and the error bars show the standard deviation. The horizontal reference lines denote the IOI_ss of the metronomically perfect triplet subdivisions. The vertical reference lines denote the beat, i.e. the quarter note, and the numbers on the x-axis denote the triple subdivision of the beat. Note that the dis-alignment of the dots is unrelated to the data and functions purely to separate the error bars. Lastly, (e) shows the score of the ride cymbal part of the Swing excerpt.

Figure 5.1[16] shows the expressive deviation from regularity. Figure 5.1a to 5.1c displays the deviation of the individual drummers and Figure 5.1d displays the average deviation. The horizontal reference lines in Figure 5.1 indicate the IOI_s lengths of the recorded tempi.

Musicians are often taught to play Swing by playing triplets. Therefore every beat is subdivided in triplets in the Swing excerpt. To display all expressive deviations at the same proportional scale, the deviation of the quarter-note IOI and the first eighth-note are interpolated. The quarter-note being three, the first eighth-note being two and the last eighth-note being one triplet grid positions long. This results in identical IOI_ps values for some grid positions. This way of displaying expressive deviation is often used in the literature and the resulting identical IOI_ps are called *plateaus* (see Repp, 1992a). In Figure 5.1 a dot above or below a horizontal reference line indicates respectively a delay or a quickening of grid point.

Dividing the beat in triplets is a musical as well as a practical choice. This choice is musical in the sense that musicians report to divide the beat in triplets when playing Swing or Shuffle and therefore displaying a triplet subdivision gives the most realistic impression of the expressive deviation. The choice is practical because the measurements are closer to a triplet than a duple subdivision. Consequently, if a duple subdivision was used the expressive deviations would have been larger and the graph would have been less interpretable.

What is clearly visible from Figure 5.1 is that the interpolated quarter-note IOIs deviate a little and the swung eighth-notes IOIs do deviate largely from the IOI_s lengths. Nevertheless, the average IOI length of the quarter-note does differ significantly from its metronomically perfect counterpart at a small number of tempi for all drummers. This was tested with t-tests ($p < .01$). Because the number of samples (N) is of a respectable size[17], around 64, the significance is explained by the fairly small confidence intervals. The average deviation per triplet grid point lies under 4 ms. Although these deviations are significant, they are barely meaningful taking the consistency of the drummers into account. Thus, it can be concluded that the expressive deviations do not take place at the quarter-note level.

The majority of the swung eighth-notes does deviate with a meaningful amount from the triplet grid. All interpolated eighth-note IOIs, except for a few at the instructed beat duration of 300, 341 and 380 ms., deviate significantly ($p < .01$) from their metronomically perfect counterparts. The significant deviations range per drummer from 3 to 25 ms. per grid point and are meaningful, since they largely exceed the average consistency per grid point. At the fastest tempo, i.e. a beat duration of 250 ms., the largest deviations were measured. Here the first eighth-note is shortened and the second is lengthened, indicating that the rhythm becomes more *straight*, i.e. both eighth-notes are played equally long. A possible explanation could be that the rhythm becomes to fast to play a triple subdivision, this explanation was verbally reported by MS and JL. The expressive deviations averaged over drummers do not scale proportionally with beat duration. In Section 5.5.2 this conclusion is strengthened by correlating the log-transposed tempo-curves of all performances.

The individual drummers show different patterns of expressive deviation, as can be seen in Figure 5.1a to 5.1c. The timing pattern are similar for JL and MS, but quite different

[16]During the recording the metronome required the tempi to be set in BPM. Therefore the BPM numbers calculated from the target beat durations were rounded. In processing the data the actual recorded BPM numbers were translated back to the beat duration and rounded to milliseconds. Due to these roundings the beat durations do not differ precisely 40 ms., but display the exact tempo that was recorded.

[17]Note that this number is twice as big as the number of samples of the Shuffle and Funk excerpts. This is due to the length of the excerpt. Contrary to the Funk and Shuffle example the first bar of the Swing excerpt equals the second bar.

Standard Deviation per Drummer	
Drummer	eighth-note
JK	6
JL	6
MS	5
average	6

Table 5.2: The standard deviation of the swung eighth-notes played of the hi-hat part of the Shuffle excerpt per drummer. The numbers are rounded to milliseconds after averaging.

from JK. Where timing patterns are fairly equal for the first and second part of the bar for JL and MS, these patterns differ in the play of JK. JL shows very large deviations from the triple subdivision at the fastest tempo, i.e. a duration of 250 ms. These deviations can be interpreted as playing reasonably straight. The differences between drummers cannot directly be explained. The error bars displaying the standard deviation in Figure 5.1d reflect the amount of agreement between drummers of how the rhythm should be timed.

What can be concluded so far is that expressive timing is extensively used in the Swing recordings. The eighth-notes deviate more from the IOI_s lengths than the quarter-notes, indicating that the expressive deviation takes place only at the eighth-note level. Although significant, the deviation of the quarter-notes is not considered meaningful, because the amount of deviation equals the amount of standard deviation. The first of the swung eighth-notes was only twice as long as the second at a beat duration of 300 and 342 ms., here the deviation of the triplet subdivision is negligible. At all other tempi, with exception of the fastest tempo, the drummers lengthen and shorten these eighth-notes even more. *Thus, it can be concluded that expressive timing in Swing does not scale proportionately with tempo.* Therefore the relation between these swung eighth-notes and tempo requires a more detailed look. This will be done by analyzing the swing ratio in Section 5.4.2 and 5.5.2.

5.3.2 Shuffle

In Table 5.2 the standard deviation is given for all eighth-notes played in all tempi. From this Table it can be concluded that the average consistency of the drummers in the hi-hat part is 6 ms. Taking a triple subdivision of the beat in to account, this yields a grid point standard deviation of 4 ms. ($= \frac{2}{3} \times 6$). This approximately equals the consistency in the Swing excerpt, but the tempo range of the Shuffle excerpt is smaller.

In Figure 5.2 the deviation of the metronomically perfect metrical grid of the Shuffle excerpt is displayed. As in Swing, the beat is divided in triplets for the same two reasons: it is more musical and more practical. Again the first eighth-note uses two grid units and the second eighth-note one. The performed rhythm does not contain any quarter-notes and covers the complete eighth-note grid.

The deviation from regularity is very clear. All interpolated IOIs deviate significantly from the IOI_ss. The number of recorded excerpts was 32, but a small number of cycles was removed (2–3) because of missing notes. The average deviation ranges from 6 ms. up to well over 25 ms. per grid position for every individual drummer, which is more than the grid point standard deviation. The saw-tooth like shape of the pattern shows clearly that the first eighth-note is shortened and the second eighth-note is lengthened compared to the strict triplet subdivision. This means the rhythm is played somewhere in between the *straight* and

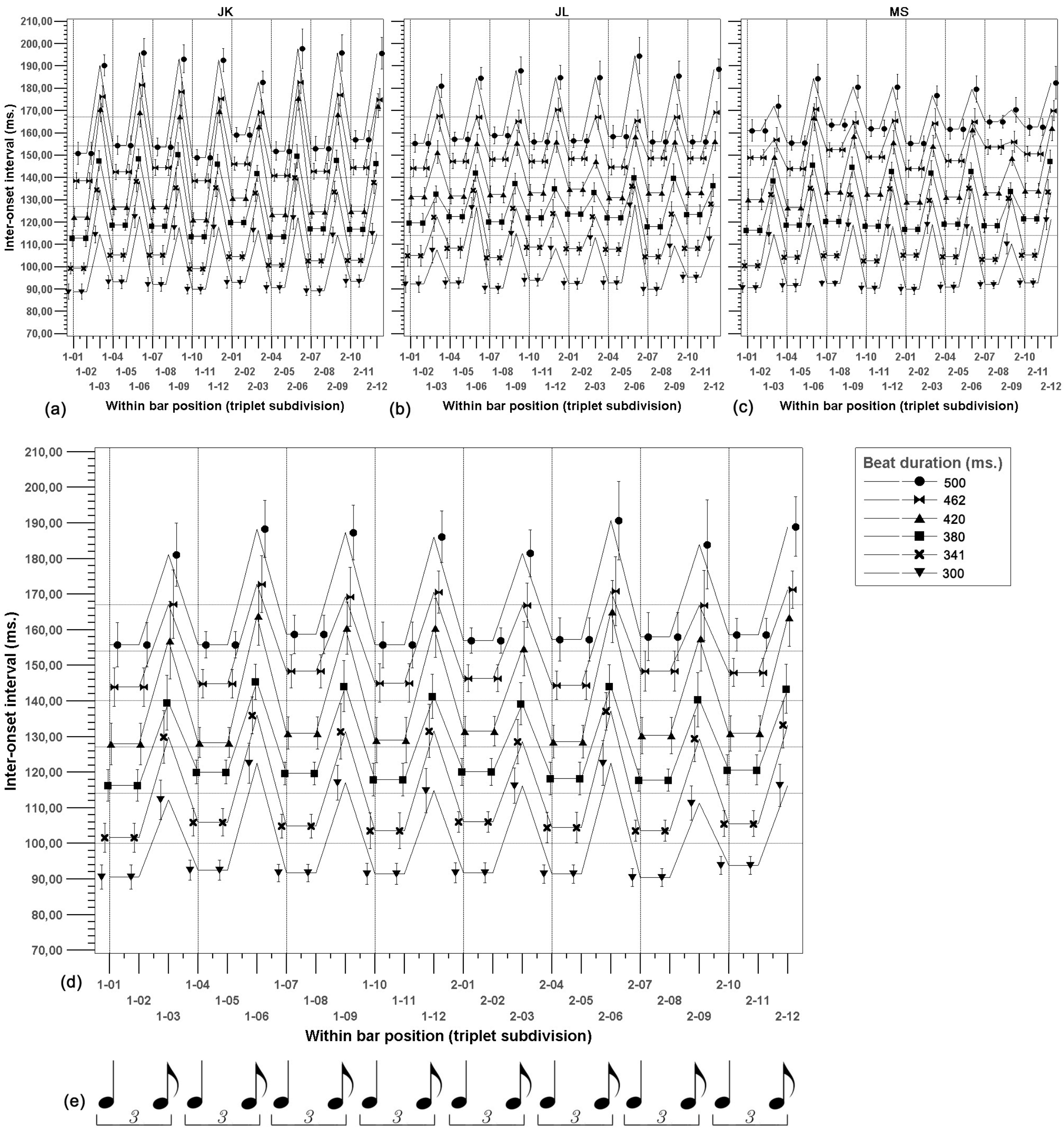

Figure 5.2: The mean interpolated IOI of the Shuffle excerpt set out against the triplet metrical grid. (a), (b) and (c) show the IOIs per individual drummer for JK, JL and MS respectively and (d) displays the average over all drummers. The dots show the mean and the error bars show the standard deviation. The horizontal reference lines denote the IOI of the metronomically perfect triplet subdivision. The vertical reference lines denote the beat and the numbers on the x-axis denote the triple subdivision of the beat. Note that the dis-alignment of the dots is unrelated to the data and functions purely to separate the error bars. Finally, (e) shows the score of the hi-hat cymbal part of the Shuffle excerpt.

Standard Deviation per Drummer	
Drummer	eighth-note
JK	4
JL	6
MS	4
average	5

Table 5.3: The standard deviation of the straight eighth-notes of the hi-hat part of the Funk excerpt per drummer. The numbers are rounded to milliseconds after averaging.

the *triple* feel. This pattern scales proportionally with tempo.

The timing patterns of the different drummers are similar. Large differences can be observed in the deviation with respect to the IOI_ss. JK uses the largest deviations and MS uses the smallest deviations from the triplet grid. The amount of deviation varies over the bar as well and all drummers show more or less the same pattern in this variation. Again it seems a good idea to take a closer look at the relation between the swing ratio and tempo, this will be done in Section 5.4.3.

From the presented findings it can be concluded that the timing of the hi-hat cymbal deviates structurally of the IOI_ss. This deviation establishes a grid with a subdivision somewhere in between a duple and a triple. All drummers show this pattern and agree to a certain extent about how the rhythm should be played. *The recorded expressive timing scales proportionally with tempo within the Shuffle excerpt.* All deviations are meaningful and the measured consistency approximately equals the consistency measured in the Swing excerpt.

5.3.3 Funk

The standard deviation of the Funk example is summarized in Table 5.3. As opposed to the Swing and the Shuffle example it is more musical and practical to use a duple subdivision, i.e. ordinary eighth-notes, for analysis. If a triple subdivision was used the deviations of the triple grid would have been very large. Due to the duple subdivision no interpolation is needed and the raw eighth-note IOIs can be plotted against the grid position (Fig. 5.3). Consequently, the standard deviation summarized in Table 5.3 equals the standard deviation of the grid points.

Figure 5.3 shows the deviations of the IOI_s of the Funk excerpt. As in the Shuffle example there were 32 cycles recorded, a small number was deleted because there were missing onsets. At fast tempi, i.e. smaller IOIs, some measured IOIs deviate significantly ($p < .01$) form their metronomical counterparts, but these deviations do not cross the standard deviation of 5 ms. up to a beat duration of 341 ms. (i.e. an eighth-note length of 170.5 ms.). Overall the average deviation ranges within 10 ms. above or below the IOI_s lengths. The individual drummers show some high and low peaks at different positions within the bars, that deviate up to 20 ms., but no common pattern between drummers can be discerned. It is not clear what causes the deviations. Looking at the interaction with the other instruments, i.e. base- and snare-drum, in the groove might provide some answers. The timing patterns of the individual drummers do not seem to scale proportionally with tempo.

For the Funk example it can be concluded that the drummers use the least amount of systematic deviation of the IOI_ss compared to the other two styles. Although there is quite some deviation of the duple metrical grid, the three drummers lack a common pattern. *In*

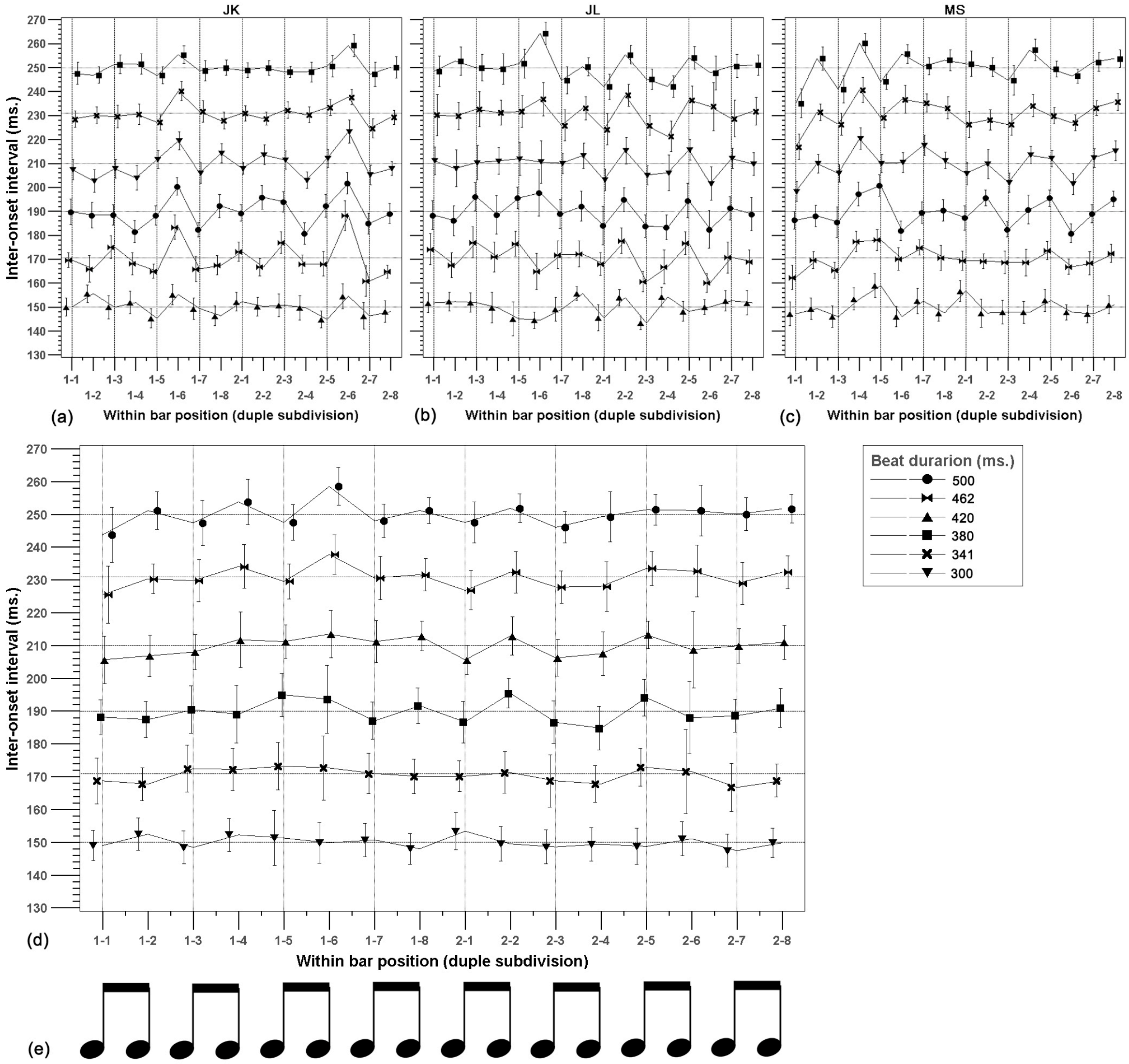

Figure 5.3: The mean interpolated IOI of the Funk excerpt set out against the duple metrical grid. (a), (b) and (c) show the IOIs per individual drummer for JK, JL and MS respectively and (d) displays the average over all drummers. The dots show the mean and the error bars show the standard deviation. The horizontal reference lines denote the IOI of the metronomically perfect triplet subdivision. The vertical reference lines denote the beat and the numbers on the x-axis denote the triple subdivision of the beat. Note that the dis-alignment of the dots is unrelated to the data and functions purely to separate the error bars. Lastly, (e) shows the score of the hi-hat cymbal part of the Funk excerpt.

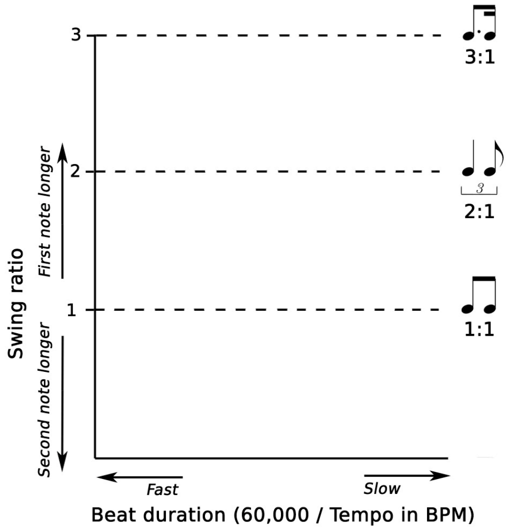

Figure 5.4: An example swing ratio graph, illustrating the meaning of the swing ratio. Reference lines denote three major rhythmic categories and there corresponding swing ratios.

the Funk excerpt tempo does not scale proportionally with tempo. The relation between the other percussive instruments and the rhythmical structure of the groove and interaction with the other drums might provide some insights into the measured deviation patterns played on the hi-hat cymbal. The consistency of the drummers of the Funk recording approximately equals the precision of the other two styles.

5.4 Swing Ratio

In the previous Section it was shown that a triple or duple subdivision of the beat can explain a large part of the deviation from the score[18]. Nevertheless, it was seen that there was quite some regular expressive behavior that could not be explained by the subdivision alone. In the following Section we will generalize over the pairs of eighth-notes by looking at the proportional lengths of their IOIs. This proportion is called the swing ratio and will be explained in detail in Section 5.4.1. Examining the swing ratio of the obtained results enables the current research to be placed in the context of the research expounded in chapter 2. Note that the following analysis is a different look at the same data presented in the previous Section.

5.4.1 Swing Ratio Explained

Swing ratio is an abstract notion. It can be used to describe a metrical grid by looking at the pairs of consecutive notes that form the grid. Looking at two swung notes, the swing ratio represents the proportional IOI length of these two notes. The swing ratio is therefore obtained by dividing the first eighth-note[19] IOI by the second eighth-note IOI, for every couple of swung notes. If straight eighth-notes are played and both eighth-notes are equally long the swing ratio is 1:1. In the often-mentioned triple feel is performed the swing ratio is, not very surprising, 2:1. The swing ratio is a simple concept that allows for generalization over different kinds of metrical grids. Therefore the swing ratio is very suitable for modeling metrical grids.

In the following sections the swing ratio will be analyzed by a number of graphs. These graphs are similar to the graph displayed in Figure 5.4. On the x-axis beat duration is placed, i.e. the length of the quarter-note[20]. On the y-axis the swing ratio is displayed. Reference lines are placed at the 1:1 swing ratio, where both eighth-notes are equally long, the 2:1 swing ratio, equaling the triple feel, and the 3:1 swing ratio, which equals a dotted eighth-note and a sixteenth-note. If the swing ratio is smaller than 1:1, consequently the second note becomes shorter than the first one. Graphs like Figure 5.4 provide clear insights into the change of the metrical grid in relation to beat duration.

5.4.2 Swing

Figure 5.5a displays how the swing ratio changes over tempo in the Swing excerpt. At high tempi, i.e. lower IOI numbers on the x-axis, the mean swing ratio is in between 1.6:1 and 2:1 and tends to become lower as tempo increases. The lowest measured swing ratio was 1.05:1, at a beat duration of 250 ms. At medium tempi the mean swing ratio is greater than 2:1 and at slower tempi the swing ratio approaches 2:1.

In Figure 5.5b the swing ratio of the different drummers is displayed. All drummers follow the pattern of a low swing ratio at high tempi followed by a swing ratio above 2:1 at medium tempi and approaching 2:1 at slower tempi. This pattern is more pronounced in JL's drumming. He uses the highest (2.61:1) as well as the lowest (1.26:1) mean swing ratios. The swing ratios of JK and MS are very similar, although the swing ratio of JK is higher than the swing ratio of MS at medium to high tempi. Only at a beat duration of 300 ms. and 500 ms. the swing ratios of JK do not deviate significantly from the 2:1 ratio. This can be seen in Figure 5.5b since, apart from the two mentioned cases, all confidence intervals are well below or above the 2:1 reference line. Remarkably, this could not be concluded directly from Figure 5.1a (Section 5.3.1 at page 24).

The findings presented above cannot be explained completely yet. The low swing ratio at

[18] It must be noted that the majority of the musicians will not consider the performance of a triple subdivision, where a duple subdivision is used for notation, as in Swing or Shuffle, expressive timing. It is a convention to use a straight notation and play swung eighth-notes. Strictly speaking the triplet notation better describes the performed notes, but the triplet notation becomes quite complicated and when a musician knows all notes should be played with Swing it is often not necessary to use the triplet notation in order to play what is meant to be played. Furthermore, in jazz freedom of rhythmical expression, i.e. playing notes not strictly as notated, is quite common.

[19] The Swing rhythm most frequently occurs at the eighth-note metrical level, but sometimes at the sixteenth-note level as well.

[20] If a tempo is given in BPM, the beat duration in milliseconds can be calculated by dividing 60,000 by the tempo in BPM.

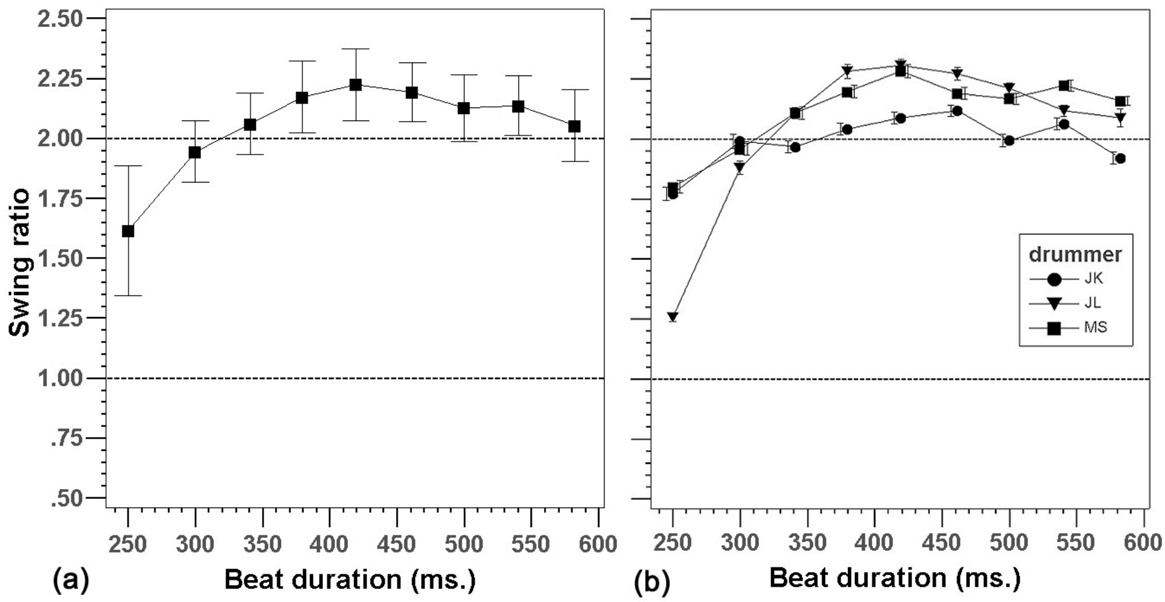

Figure 5.5: The drummer's swing ratio as a function of beat duration for the Swing excerpt. The data points display the mean swing ratio played by the drummers on the ride cymbal. In (a) the average is displayed and in (b) the ratio per individual drummer. The error bars in (a) display the standard deviation, and the error bars in (b) display the 99% confidence interval. The reference lines indicate the triple feel at the 2:1 swing ratio, and the straight feel at the 1:1 ratio.

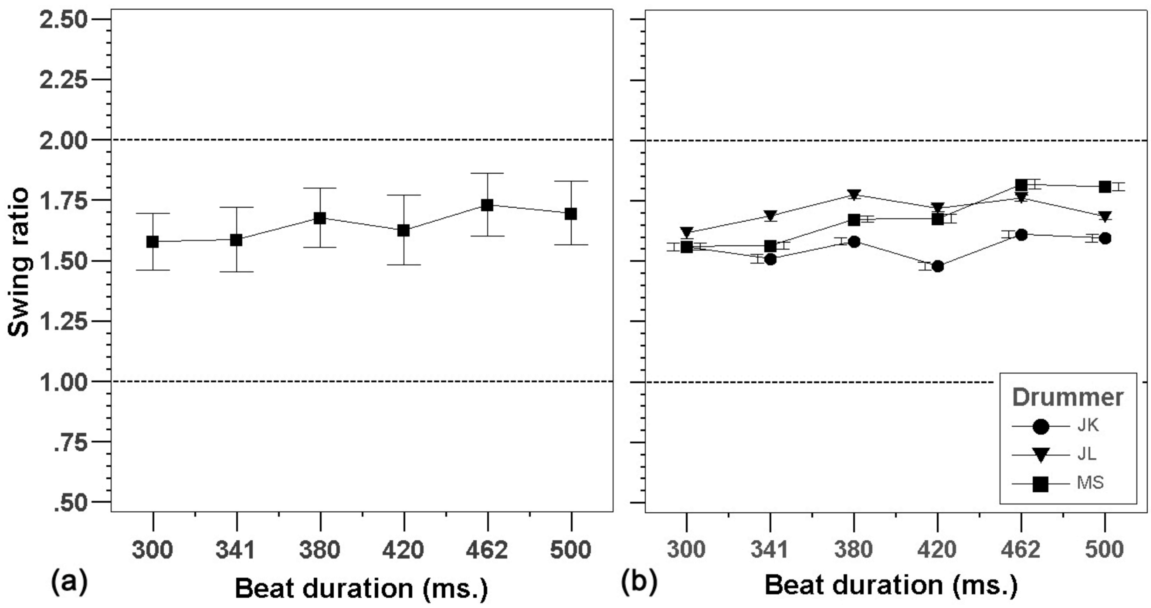

Figure 5.6: The drummer's swing ratio as a function of beat duration for the Shuffle rhythm. The data points display the mean swing ratio played by the drummers on the hi-hat cymbal. In (a) the average is displayed and in (b) the ratio per individual drummer. The error bars in (a) display the standard deviation, and the error bars in (b) display the 99% confidence interval. The reference lines indicate the triple feel at the 2:1 swing ratio, and the straight feel at the 1:1 ratio.

high tempi might be explained by the fact that the tempo becomes to fast to play a triplet and the drummers let the drum stick bounce at the ride cymbal. This is frequently reported by drummers. MS and JL reported this as well (verbally) after they did the experiment. What can again be confirmed is that swing ratio, which represents the expressive timing, does not scale proportionally with tempo.

5.4.3 Shuffle

The swing ratios of the Shuffle excerpt are displayed in Figure 5.6a. This swing ratio was obtained by dividing the odd eight note IOI by the even eight note IOI's of the hi-hat part of the Shuffle excerpt (see Figure 4.2 at page 20). Although the eighth-notes are played with swing, as in the Swing rhythm, the swing ratio pattern looks differently compared to the Swing rhythm. The mean swing ratio is between 1.5:1 and 1.75:1 at all tempi and the trend is to slowly increase the swing ratio as tempo decreases. Note that the tempo range is smaller, since the Shuffle rhythm was recorded at six and the Swing rhythm at nine different tempi.

The swing ratios of the different drummers displayed in Figure 5.6b show a common pattern. All swing ratios are in the 1.25:1 to 2:1 swing ratio range, except for a few outliers above the 2:1 swing ratio. The general trend of an increasing swing ratio at slower tempi can be seen with all drummers. However, the drummers do not obey this trend when the IOI of the quarter note is 420 ms., here a small dip in swing ratio is visible. Figure 5.6b shows clearly that all swing ratios from all drummers differ significantly from either the 2:1 or the 1:1 swing ratio, since no confidence interval reaches either the 2:1 or 1:1 reference line.

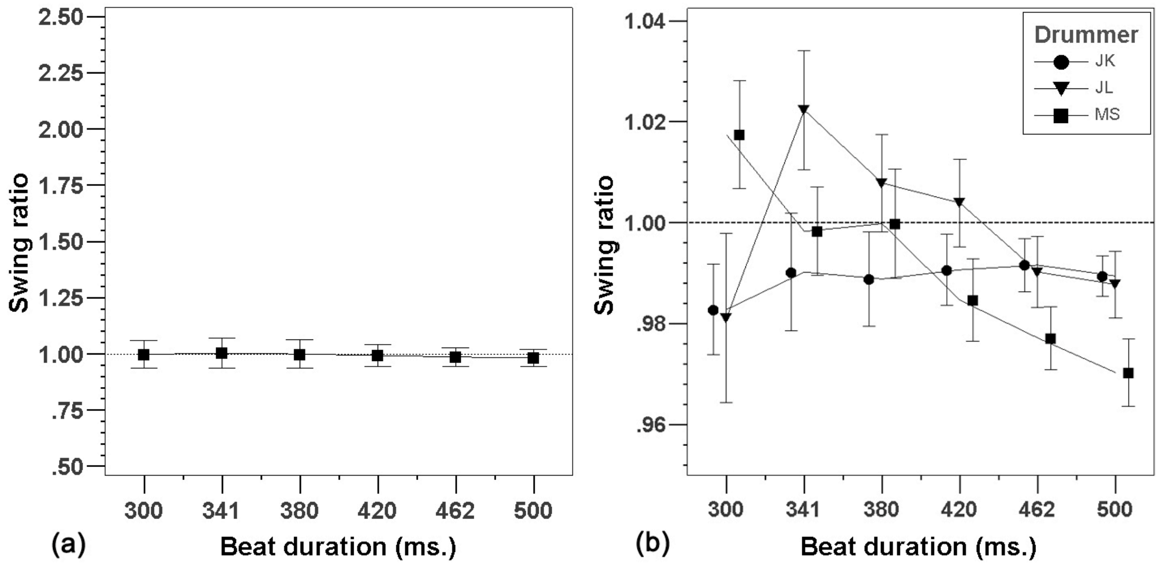

Figure 5.7: Swing ratio of the Funk rhythm as a function of beat duration. In (a) the average is displayed and in (b) the ratio per individual drummer. Note that (b) zooms in on the swing ratio axis to clarify the differences between the drummers. The dots denote the mean swing ratio and the error bars denote the standard deviation in (a) and the 99% confidence itnervals at (b). The dotted reference line denotes the swing ratio where the eight notes are equally long, i.e. straight eighths.

The presented results show clearly that drummers choose to use a swing ratio between 1:1 and 2:1. Why they did so cannot be explained. Note that a swing ratio of 1.5:1 could be notated as a quintuplet with the first three notes bounded together and the last two bounded together, which at first sight does not appear to be an every day rhythm, but is played with great consistency by the recorded drummers.

5.4.4 Funk

The swing ratio of the Funk rhythm, displayed in Figure 5.7a, is calculated in the same way as the Shuffle rhythm by dividing the odd eighth-note IOIs by the even eight note IOIs. The swing ratio changes very little over tempo and stays approximately constant at 1:1, which means that both eighth-notes have an equal duration. This is not very surprising since in the Funk rhythm the eighth-notes are expected to be played *straight*. There is a minimal tendency to play with a swing ratio smaller than 1:1 at very slow tempi, which was observed in Section 5.3.3 as well. This means that the second eighth-note is slightly longer than the first one.

All drummers use a fairly constant swing ratio from about 1:1 at all tempi, but more often smaller than greater. This deviation from the 1:1 ratio is significant for all drummers at the two slowest tempi, as was seen in the Section 5.3.3 but due to the margin of error not considered meaningful. *Swing ratio does not change meaningfully with respect to tempo. Other timing patterns, unrelated to the swing ratio, do not scale proportionally to tempo.*

5.5 Correlations

To strengthen the conclusions made about proportional scaling of timing with respect to tempo, made in the former sections of this chapter, the performances of the different tempi are correlated.

5.5.1 Analysis by Tempo Curve Explained

One way of representing expressive deviations in music is calculating the deviation of the metrical grid from event to event. This has been done in Section 5.3. However, if we want to correlate different performances of several tempi this representation of the data is not very suitable because the different IOI_p lengths at the various tempi will swamp all timing effects. A solution for this problem is to normalize the IOI_p with respect to the IOI_s length, yielding the percentage of deviation. Such a representation is frequently referred to as a *tempo curve* because it can be seen as a *local* tempo deviation, from grid position to grid position, in contrast to the *global* tempo, i.e. the average tempo of the piece. A correlation between two tempo curves of performances of different tempi is high if the expressive lengthening and shortening is proportional to the length of the IOI_s at that tempo.

Furthermore, it is more musical to compare timing at a logarithmic scale (Desain & Honing, 1994). Therefore the interpolated, normalized IOI_ps are log-transformed as well. The calculation of a tempo curve is expressed in Equation 5.2. Here $IOI_{performance}$ is the measured IOI_p, $IOI_{beatduration}$ is the beat duration, i.e. the IOI_s of a quarter note, and P_{score} is the relative proportion of the beat as written in the score. Note that, as in Section 5.3, the P_{score} interpolates an IOI_p over grid positions, yielding several plateaus (for the Swing and Shuffle excerpts).

$$D = \ln\left(\frac{IOI_{performance}}{P_{score} IOI_{beatduration}}\right) \tag{5.2}$$

5.5.2 Swing

In Table 5.4 the correlations between the log-transformed tempo curves of the performances of all tempi are displayed per drummer. All the recorded cycles of one tempo are appended as if it were one performance and correlated with the appended cycles of the other tempi. In total 54 (of the 64) cycles of the Swing excerpt are used, yielding 648 measured grid positions for all 9 tempi.

All drummers show more or less the same pattern. Between timing patterns at medium to slow tempi a positive and sometimes high correlation is measured, reflecting that timing behavior scales proportionally with beat duration. Especially the inter-tempo correlations of JL and MS are moderately strong and positive in the medium to slower tempo range. The high tempi, i.e. beat durations < 341 ms., correlate negatively and very poorly with the slow and medium tempi, i.e. beat durations between 583 and 341 ms. This indicates a difference in timing patterns between tempi. The average overall correlation is very poor (.18). *This confirms the conclusion, stated before in Section 5.3.1 and 5.4.2, that expressive timing on the ride cymbal does not scale proportionately with tempo within the recorded Swing excerpt.* However, within the medium to slow tempo range timing patterns are proportionally more alike.

Inter-tempo Correlations of the Swing Excerpt per Drummer

Drummer	Beat duration	583	541	500	462	420	380	341	300	250
MS	583	1								
	541	.33	1							
	500	.46	.41	1						
	462	.21	.50	.36	1					
	420	.26	.49	.40	.64	1				
	380	.32	.43	.46	.43	.44	1			
	341	.49	.28	.46	.28	.29	.39	1		
	300	.53	.34	.46	.35	.44	.46	.49	1	
	250	.26	-.32	.00	-.40	-.32	-.13	.12	.13	1
	Average									.27
JL	583	1								
	541	.34	1							
	500	.21	.50	1						
	462	.35	.46	.66	1					
	420	.32	.53	.70	.68	1				
	380	.30	.50	.70	.68	.72	1			
	341	.20	.33	.41	.37	.43	.43	1		
	300	-.35	-.44	-.37	-.52	-.44	-.41	-.24	1	
	250	-.39	-.55	-.65	-.70	-.74	-.65	-.49	.57	1
	Average									.08
MS	583	1								
	541	.71	1							
	500	.69	.65	1						
	462	.63	.65	.72	1					
	420	.60	.72	.70	.71	1				
	380	.73	.74	.64	.63	.65	1			
	341	.27	.42	.43	.47	.48	.38	1		
	300	-.18	-.26	-.16	-.17	-.25	-.18	.08	1	
	250	-.39	-.52	-.47	-.59	-.68	-.37	-.40	.28	1
	Average									.17
Grand Average										.17

Table 5.4: The correlations between the log-transformed tempo curves of the Swing excerpt at all tempi per drummer.

Inter-tempo Correlations of the Shuffle Excerpt per Drummer							
Drummer	Beat duration	500	462	420	380	341	300
JK	500	1					
	462	.93	1				
	420	.94	.95	1			
	380	.93	.94	.95	1		
	341	.94	.94	.95	.94	1	
	300	.92	.93	.94	.93	.93	1
	Average						.94
JK	500	1					
	462	.86	1				
	420	.89	.85	1			
	380	.82	.78	.84	1		
	341	.85	.78	.83	.81	1	
	300	.86	.79	.84	.84	.86	1
	Average						.84
JK	500	1					
	462	.79	1				
	420	.83	.82	1			
	380	.81	.81	.90	1		
	341	.78	.76	.89	.91	1	
	300	.83	.81	.91	.93	.93	1
	Average						.87
Grand Average							.88

Table 5.5: The correlations between the log-transformed tempo curves of the Shuffle excerpt at all tempi per drummer.

5.5.3 Shuffle

The correlations in Table 5.5 display the correlations between the log-transformed tempo curves of the Shuffle performances at the 6 different tempi. They are calculated in the same way as the correlations in the former sub-Section. For the Shuffle excerpt 30 (of the 32) cycles were used. Taking the triple subdivision into account this yields 720 correlated grid positions per tempi. The differences between the timing patterns of the three drummers are small. *The average inter-tempo correlation is .87, confirming the conclusion made earlier that expressive timing of the hi-hat cymbal scales proportionally with tempo within the recorded Shuffle excerpt.*

5.5.4 Funk

Table 5.6 shows the correlations of the log-transformed tempo curves of the Funk performances of different tempi per drummer. Again the same method is used as in the two former sections. For the calculation of all correlations 29 (of the 32) cycles of the excerpt were used, except for the correlations with JL his performance at a beat duration of 300 ms., providing 646 correlated grid points per tempo. Due to a larger number of incomplete or erroneous cycles, only 19 cycles (i.e. 304 grid positions) were used of JL his performance at a beat

Inter-tempo Correlations of the Funk Excerpt per Drummer

Drummer	Beat duration	500	462	420	380	341	300
JK	500	1					
	462	.33	1				
	420	.39	.41	1			
	380	.33	.36	.63	1		
	341	.43	.49	.49	.49	1	
	300	.15	.28	.12	.19	.32	1
	Average						.36
JL	500	1					
	462	.37	1				
	420	.25	.24	1			
	380	.20	.15	.30	1		
	341	.07	.04	.28	.35	1	
	300	-.03	.16	.04	-.15	.04	1
	Average						.36
MS	500	1					
	462	.58	1				
	420	.55	.59	1			
	380	.16	.16	.39	1		
	341	.27	.37	.46	.42	1	
	300	.09	.07	.24	.34	.42	1
	Average						.13
Grand Average							.28

Table 5.6: The correlations between the log-transformed expressive deviations of the Funk excerpt at all tempi per drummer.

duration of 300 ms. The inter-tempo correlations are mostly positive and rather low. The performances at medium to slow tempi correlate more highly than the performances at high tempi. Consequently, the overall correlation is fairly low (.28) as well. *This confirms the conclusion that timing of the hi-hat cymbal does not scale proportionally with tempo within the recorded Funk excerpt.*

The inter-tempo correlations of the Shuffle excerpt are much higher than the inter-tempo correlations of the Funk excerpt. However the grooves are, apart from the subdivision of the metrical grid, musically not that different. It might be that the higher correlation is mainly caused by the rather large deviation of the triple subdivision and that this deviation has dampened other more subtle timing deviations as measured in the performances of the Funk excerpt. Since the swing ratio of the Shuffle excerpt is about 3:2, looking at the deviation of the quintuple subdivision might provide some insights in more subtle deviations.

5.6 Concluding Remarks

The consistency did not differ between styles or between drummers. The standard deviation, as an indication of the consistency of the drummers and the error of the equipment, is on average smaller than 6 ms. per eighth-note which is barely perceivable for an average human being. In all performances expressive deviations largely exceed the standard deviation and are considered meaningful.

If the expressive timing profiles of the hi-hat and ride cymbals of the three styles are compared, it can be concluded that the three styles all use systematic expressive timing differently. Also the amount of expressive timing varies. The Funk excerpt is performed with less expressive timing than the other two styles. Within Swing and Funk the timing patterns do not scale proportionally with tempo. The timing of the hi-hat within the Shuffle excerpt does scale proportionally with tempo. However, subtle timing deviations might have been dampened by the large deviation of the triple subdivision in comparing the correlations of the log-transposed tempo curves. The use of triple and duple subdivision can provide some insights in the expressive deviation, but can certainly not explain all deviations. The swing ratio is very suitable for explaining expressive deviations and their change over tempo and can therefore be used to model the relation between timing and tempo.

Chapter 6

Discussion

6.1 Swing Ratio Comparison

In this chapter the results presented in the previous chapter will be placed in the context of the research discussed in chapter 2. The most important study concerning jazz drumming is the study of Friberg and Sundström (2002), which will be discussed in the next section. The most similar study done is the study of Collier and Collier (1996), this study will be discussed in section 6.1.2. Both studies strictly concerned jazz music.

6.1.1 Friberg & Sundström

In Figure 6.1 the findings of the previous chapter are displayed together with the results of Friberg and Sundström (2002). First of all it must be noted that the method of data collection of Friberg and Sundström is very different from the method used to gather the data for this thesis. Friberg and Sundström measured the swing ratios played on the ride cymbal of a small number of drummers from well known jazz recordings and looked how the swing ratio changed over tempo.

The three most important differences are: first, they measured the swing ratio of drummers playing in complete ensembles, while for this thesis solo drumming was recorded. Second, to ensure that the deviations from the metrical grid were caused by expressive timing and not by tempo deviations, the drummers recorded for this thesis played along with a metronome, the drummers measured by Friberg and Sundström were not. Third, Friberg and Sundström measured 10 to 26 seconds of performances. For this thesis per tempo 64 repetitions were recorded. From every repetition 2 swing ratio's were calculated, adding up to 128 swing ratio measurements per tempo, yielding approximately 1152 data points. The complete dataset of Friberg and Sunström, on the other hand, consists out of 36 data points. Especially the last two points allow for the conclusion that the data presented in this thesis is far more accurate that the Friberg and Sundström data. The first point might have biased the results of Friberg and Sundström in a different direction than the data presented in this thesis, because interplay with other musicians probably affected the timing of the drummers.

Friberg and Sundström found rather large swing ratios in their swing analysis. Especially at slow tempi the swing ratio's tend to range up to 3.5:1 (Fig. 6.1a[21]), meaning that the second

[21] Note that a *tempo* scale is used and the slow tempi are displayed on the left and the high tempi on the right side of the figure

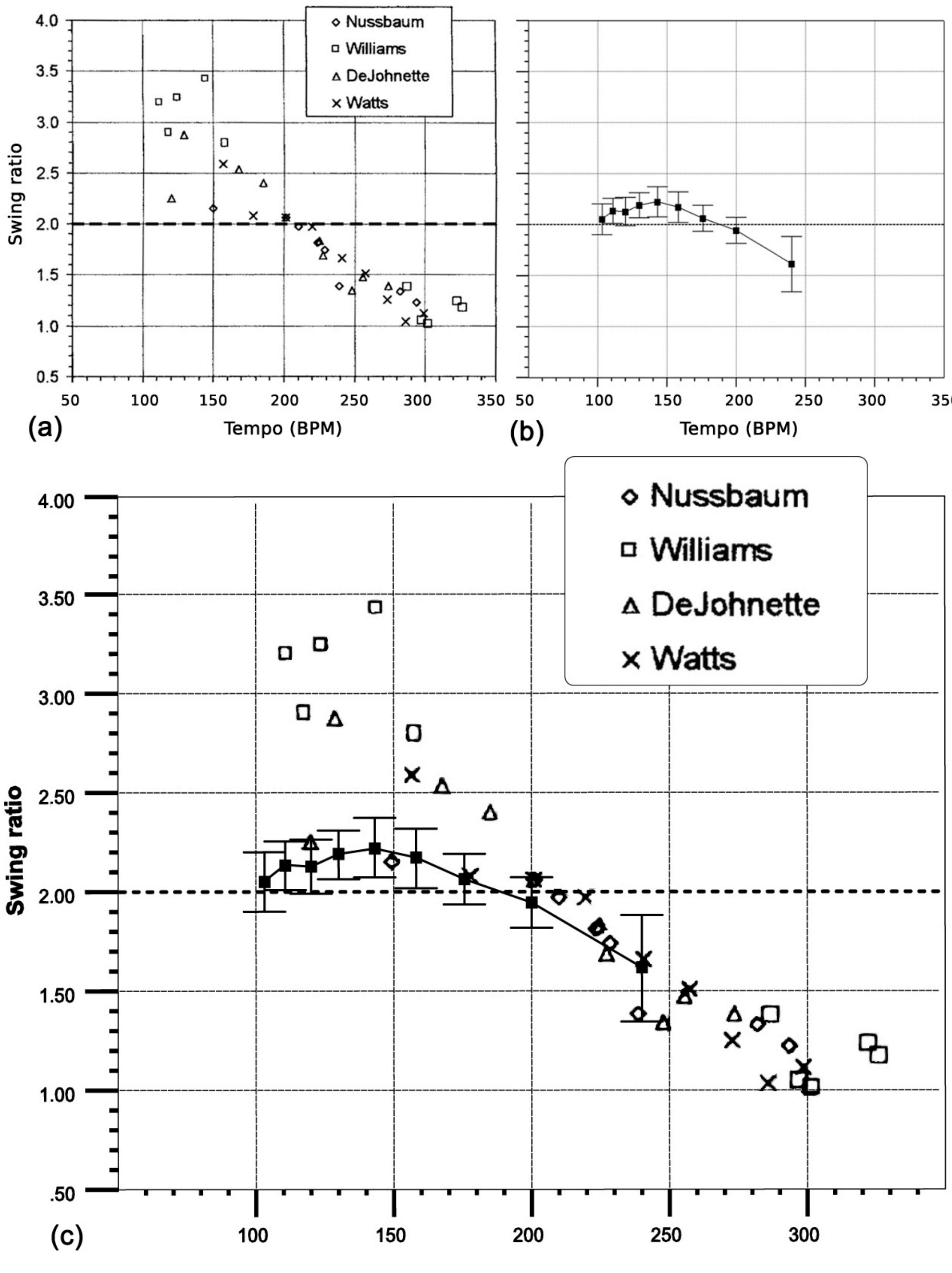

Figure 6.1: both the results of Friberg and Sundström (2002) and the results presented in this thesis displayed separately in (a) and (b) respectively and in one plot (c). The error bars display the standard deviation. The reference line denotes the strict triple feel. Note that the results presented in the previous chapter are scaled to fit the scaling of the Friberg and Sundström picture. Therefore the scale on the x-axis is a BPM scale. This means that slower tempi are on the left side and faster tempi on the right side

note is shorter than a sixteenth note. This contradicts the findings presented in this thesis, where the swing ratios tend approach a constant swing ratio of 2:1, i.e. the characteristic *triple feel*. Possible explanations could be the interplay between the drummer, as part of the rhythm section, and the soloist. In classical string quartets complex timing asynchronizations between voices are observed as well (Rasch, 1981).

Soloists are often learned to play more with a *straight feel* than their accompanying rhythm section, i.e. with a swing ratio lower than 2:1, is reported by Friberg and Sundström (2002). It is sometimes mentioned that players want their performance to be *balanced*. So, if the soloist plays more straight, i.e. with a smaller swing ratio, the drummer plays with a higher swing ratio. It might have been that the Tony Williams played such a high swing ratio because it balanced the interplay with the soloist. Another indication that extreme swing ratio's are caused by interplay with a soloist is given by the measurements of Nussbaum. The analyzed record of Nussbaum was a play-along record, and did not contain any interaction with a soloist either. Nussbaum approximated a swing ratio of 2:1 at medium to slower tempi (< 200).

However it must be kept in mind that another explanation of the difference could be that the Friberg and Sundström dataset might be too small, since the dataset only contains 12 data points in the area considered. Next to this it should be taken into account that five out of the six data point with the highest swing ratio are from one drummer, namely Tony Williams. *Taking the mentioned arguments into account it is concluded that the data presented by Friberg and Sundström is not enough evidence for the conclusion that there exist an approximately* linear *trend of decreasing swing ratio with increasing tempo, which they clearly suggest.*

6.1.2 Collier & Collier

Opposed to Friberg and Sundström the method of Collier and Collier (1996) was comparable with the method presented in chapter 4. Collier and Collier asked three drummer to play the Swing rhythm and strict triplets at a number of different tempi. Although, there are many similarities with the experiment presented in this thesis, there are important differences as well: first, Collier and Collier did not use a metronome, and for the recordings presented in the previous chapter a metronome was used. Second, Collier and Collier used one drum pad as opposed to a complete drum kit that was used in the experiment presented in this thesis. Third, Collier and Collier used two different conditions: the swing and the strict triplet condition.

Both the data of Collier and Collier as well as the data presented in this thesis are plotted in Figure 6.2. Note that the data of Collier and Collier was measured and re-plotted[22]. This re-plotting was done in order to be able to display all results of Collier and Collier and the results presented in this thesis in one picture at the same scales. As can be seen in Figure 6.2a and 6.2b Collier and Collier recorded not only fast, mid-range and slow tempi, but very slow tempi as well (67 to 25 BPM, equaling beat duration of 896 to 2400 ms.). To be able to compare the two datasets, the data point below 97 BPM (a beat duration of 620 ms.) are discarded in Figure 6.2c and 6.2d.

The measurements of RAP (one of the drummers recorded by Collier and Collier, see 6.2a) are very similar to the measurements presented in the previous chapter. It must be

[22]The data was measured by hand from the graphs presented in (Collier & Collier, 1996), see Figure 2.4 at page 11. Due to use of different scales the accuracy of the measurements might vary from point to point.

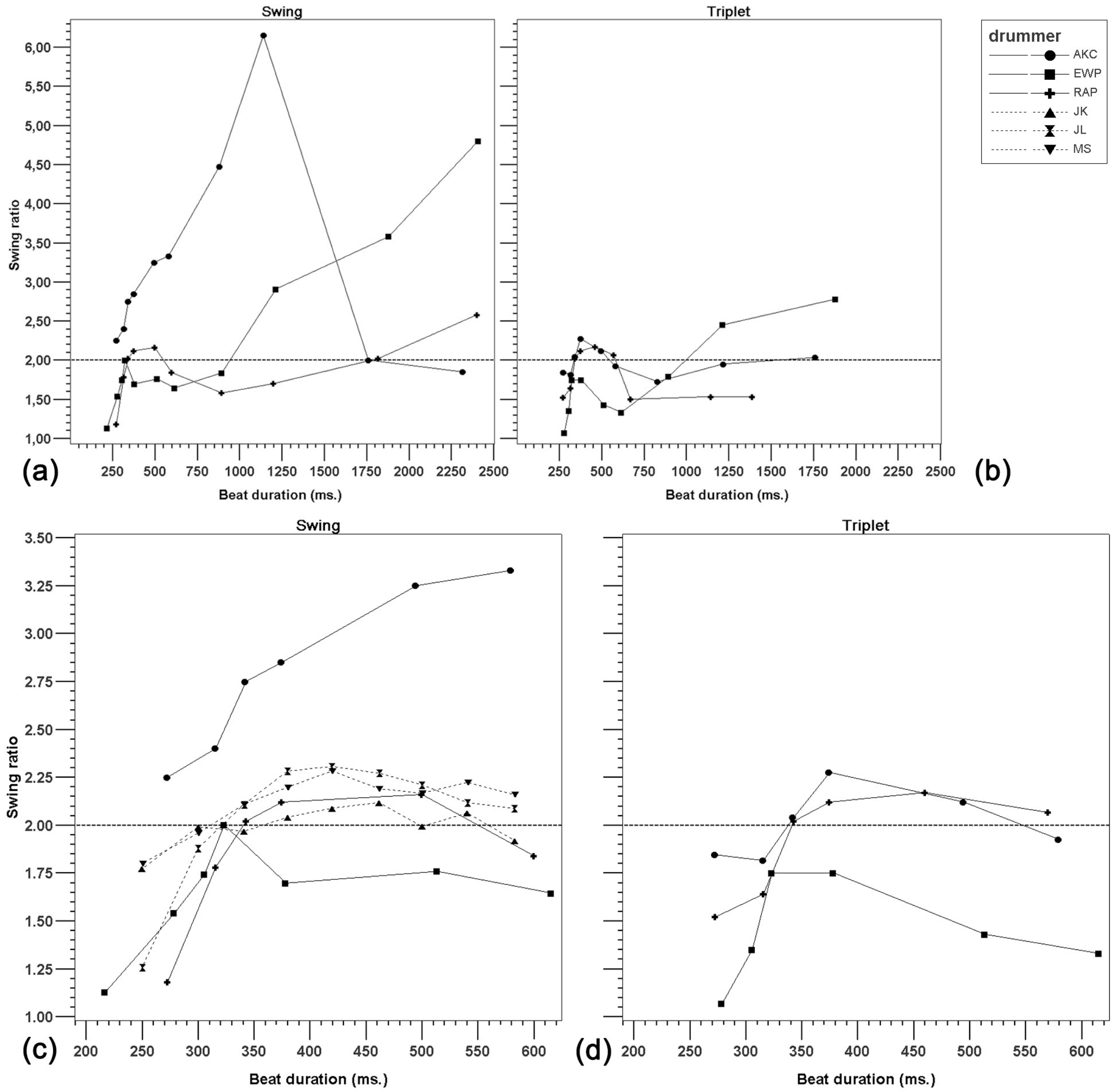

Figure 6.2: the ride cymbal data from Collier and Collier (1996), for the swing condition (a) and the triplet condition (b). In (c) the Collier and Collier data is plotted together with the data acquired for this thesis. (d) displays the triplet condition again. In (c) and (d) the measurements with a beat duration longer than 620 ms. are discarded. All dots show the mean of all measurements. The dotted lines show the results of the experiment presented in this thesis the solid lines show the Collier and Collier data. The reference line denotes the strict triple subdivision

noted that RAP was very precise at playing the target tempo as well. Since no metronome was used the other drummers drifted away from the target tempo, sometimes up to 50 ∼ 80 ms. (rough estimation) per average beat. Strangely, RAP had the greatest tempo drift in the strict triplet condition. The other drummers show very different behavior, which can hardly be compared with either the other drummers of the Collier and Collier experiment or the drummers recorded for this thesis. The swing ratio data of EWP and AKC might have been biased by the rather large tempo drift. No relation ship between the amount of tempo drift and swing ratio can be discerned up till now. A thorough look into the original dataset might offer some answers. A last factor that could have been of influence is the fact that Collier and Collier did not use a complete drum kid but just one MIDI pad. This might have influenced the drumming experience of the participants.

The results of the strict triplet condition of the experiment of Collier and Collier (Fig. 6.2b and 6.2d) show a pattern more similar to the swing data presented in this thesis than the results of their swing condition. Although none of the drummers actually succeeds in playing a strict triple feel, i.e. a 2:1 swing ratio. The choice of using two conditions might have biased the results in the direction of greater differences between the results of the two conditions, since asking to play a strict triplet and a Swing rhythm suggest that there exist a difference between the two.

6.2 Swing Ratio Models

In the previous chapter it was shown that a lot of the expressive deviation from the metrical grid can be explained by the swing ratio. Therefore the swing ratio can be seen as a powerful tool for modeling expressive timing. These swing ratio models, with the parameters adjusted to fit the sampled swing ratio data, can be used by the *swing ratio combinator* (see Section 3.3.1 on page 18) of the TDT model. In the next two subsections the swing ratio models for Swing, Shuffle and Funk are presented.

6.2.1 Swing

The swing ratio model for the Swing excerpt is based on the data of the Swing recording which was thoroughly analyzed in Section 5.4.2 of the previous chapter (on page 32). Within the Swing data two different processes can be distinguished: the process of playing the appropriate swing ratio, which is greater than 2:1, at slower tempi, and the process of playing a low swing ratio at high tempi. These two processes are modeled by two linear equations that are concatenated at a beat duration of m (= 368 ms.[23]). The second process, describing a swing ratio above the 2:1 ratio, could have been modeled by the mean of the data $> m$ alone, but the slope[24] was considered meaningful. The model is formally defined as:

$$R_{swing} = \begin{cases} IOI_{beatduration} \leq m & aIOI_{beatduration} + b \\ IOI_{beatduration} > m & cIOI_{beatduration} + d \end{cases} \tag{6.1}$$

[23]This is the optimal concatenation point found by the parameter optimization.

[24]Note that the slope parameters in Table 6.1 are very small because the number representing the swing ratio is a factor 100 smaller than the number representing the beat duration.

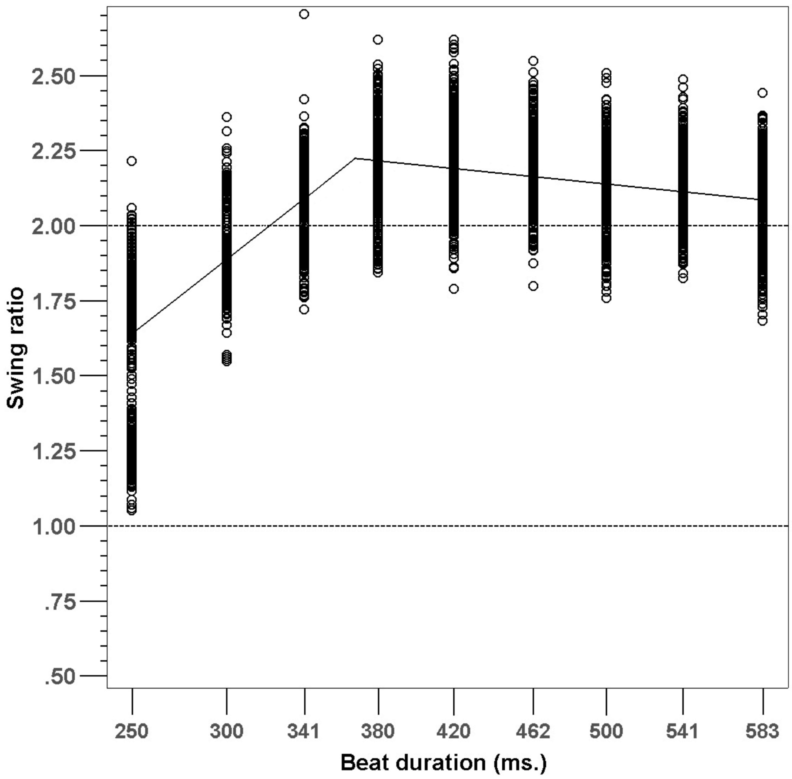

Figure 6.3: A scatter plot of the sampled swing ratio data of the Swing excerpt together with the plotted swing ratio model.

Here, R_{swing} denotes the swing ratio, $IOI_{beatduration}$ denotes the beat duration and a,b,c,d and m are the parameters. These parameters are adjusted to fit the swing ratio data using non-linear regression (Motulsky & Ransnas, 1987). The result of the fit is shown in Figure 6.3 and Table 6.1 shows the fitted values of the parameters a to m. The quality of the model is expressed by an R^2 of .54, which is considered high given the spread of the data.

6.2.2 Shuffle & Funk

For the Shuffle and Funk excerpts two very similar linear models without a slope parameter are used (see Fig. 6.4a and Fig. 6.4b respectively). Since the Shuffle excerpt does not scale proportionally to tempo a linear equation is a logical choice. It is possible to fit a linear model with a slope parameter on the data, but the slope parameter will be close to zero and the negligible difference with the mean swing ratio would make the slope parameter meaningless. The swing ratio of the Shuffle excerpt is fixed to the mean of the data which is 1.65:1

The Funk excerpt did not scale proportional to tempo. However, there was no clear change in swing ratio with respect to tempo (see Section 5.4.4 and Figure 5.7 at page 35). The swing ratio is therefore chosen to be 1:1 for all tempi, because the fitted linear model, using a slope

Parameter Estimation	
Parameter	Estimate
a	.399
b	4.96E-3
c	2.46
d	-6.416E-4
m	368

Table 6.1: The estimated values after fitting the swing ratio model on to the data of the Swing excerpt.

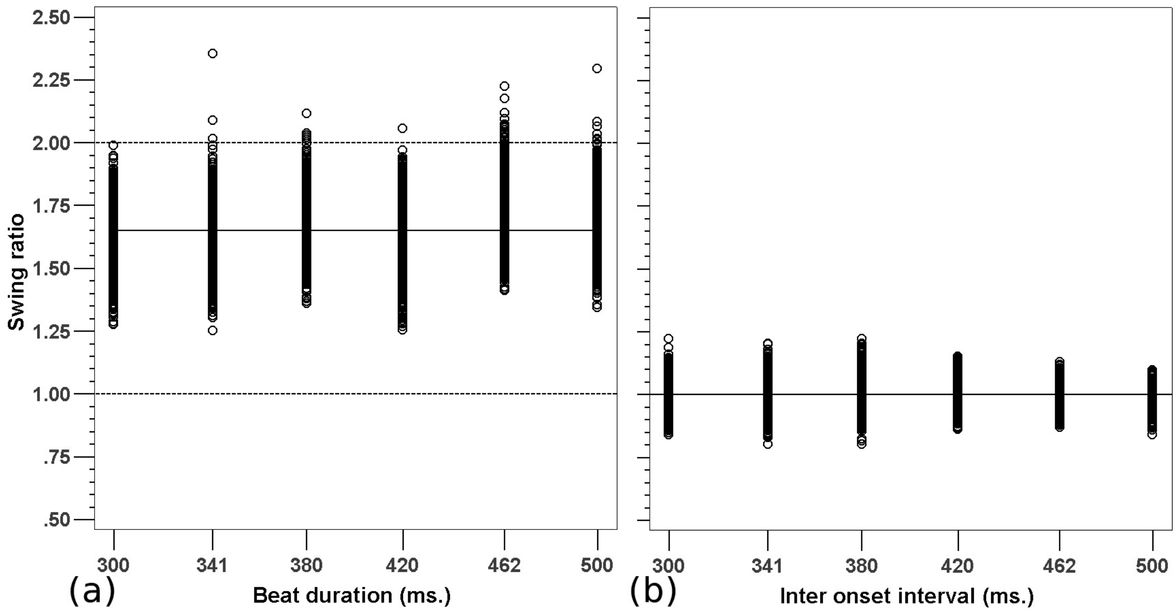

Figure 6.4: Two scatter plots of the sampled swing ratio data together with the plotted swing ratio models. The data and the model of the Shuffle excerpt is plotted in (a) and the data and the model of the Funk excerpt is plotted in (b).

next to an intercept parameter, does not deviate meaningfully from the 1:1 swing ratio. It is clear that here is a lot of room for improvement.

All the models presented in this thesis were linear or a combination of linear models. This was a clear design choice, because more complex model would be over-fitting the data (Pitt & Myung, 2002) and the parameters would be less explainable.

Chapter 7

Conclusions & Future Research

7.1 Summary

In this thesis newly gained insights into the relation between expressive timing and tempo in musical performances of jazz en groove drumming were presented. By conducting and analyzing an experiment interesting expressive timing patterns were revealed. These patterns were interpreted, compared to relevant literature and used for developing the TDT model.

Three drummers performed excerpts of three different styles at a number of different tempi. These performances were recorded using a MIDI drum kit. Systematic irregularities in the rhythms played on the hi-hat cymbal, in the Funk and Shuffle excerpt, and on the ride cymbal, in the Swing excerpt, were used to analyze the different expressive timing patterns of the grooves. Within all styles a significant and meaningful amount of expressive timing was measured. As opposed to what was hypothesized, the expressive timing measured in the performance of the shuffle excerpt did scale proportionally with tempo. Within the Swing and Shuffle excerpts the measured expressive timing did not scale proportionally with tempo, as was hypothesized in the introductory chapter. The results presented in this thesis are considered a solid description of the relation between swing ratio in the swing rhythm and tempo.

In chapter 2 expressive timing and its relation to tempo were elaborately surveyed. The newly acquired results were compared with the most important studies of expressive timing in modern jazz drumming. Parts of the data of Friberg and Sundström (2002) differed from the results presented in this thesis. The differences could be explained by the interplay between their recorded drummers and other musicians or by the small amount of data points gathered by them. Hence, the data presented by Friberg and Sundström was not considered enough evidence for the conclusion that there exist an approximately linear trend of decreasing swing ratio with increasing tempo. Although the experimental setup of (Collier & Collier, 1996) is fairly similar to the method used in this thesis, some of their results are very different. These differences were ascribed to the control of tempo within their experimental method and the choice of doing a triplet and a Swing condition.

It was shown that swing ratio is not only suitable for explaining expressive deviations and their change over tempo, it was shown that it could be used as a powerful tool in modeling expressive timing as well. This was done by implementing the TFF into the musical Mircroworld and using the swing ratio combinator to generate swing ratio time-shift functions. To model the change of swing ratio over tempo, linear models were fitted to the Funk and

Shuffle data and a combination of linear models was fitted to Swing data to capture the expressive behavior.

7.2 Future Research

There still remain a lot of unanswered questions regarding expressive timing and its relation to tempo, especially in jazz en pop music. Some of these answers might be found by doing more analyses on the data gathered for this thesis. There are very strong indications that the systematic irregularities in the hi-hat and ride cymbal rhythms capture the majority of expressive timing. However by thoroughly analyzing the deviations of the snare, base and tom-tom drums, this assumption can be verified. It could be that some expressive deviations in these instruments can explain some of the deviations in the hi-hat pattern of the Funk excerpt. Furthermore, such an analysis might yield some interesting voice leading patterns as well. These patterns can be implemented as timing depended time-shift functions in the TDT model and add other subtle expressive timing to a score.

To test the TDT model an analysis-by-synthesis can be done by setting up another experiment. The drummers that participated in the experiment described in this thesis should be presented audio examples of all excerpts at all tempi. Half of these examples must be rendered using the TDT model and half should be their own recordings. The performance of the TDT can be expressed through the ability of the drummers to identify their own drumming.

Another follow-up experiment could be done by analyzing a complete ensemble. For instance recording a quartet, consisting of a drums, base, piano and a lead instrument, e.g. a guitar or saxophone, could provide some new insights. Probably some interesting timing patterns can be discerned between the various instruments. An analysis of the interplay between soloist and rhythm section could provide some explanations in the differences between the data presented in this thesis and the data of Friberg and Sundström (2002).

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Glossary

bar In music notation a bar denotes a period in time set by a fixed number of metrical units. In this thesis only $\frac{4}{4}$meters are use were a bar equals four quarter-notes., 23

beat A beat is a perceived pulse marking equal durational units. These units set the most basic level of metrical organization. Often, and always within this thesis, the beat equals the quarter note in the score., 1

beat duration The beat duration is the inter-onset interval length of the beat. Beat duration is an alternative, and obviously related, way of expressing tempo. If the beat duration in milliseconds is known, the tempo in BPM can be calculated by dividing 60,000 by the beat duration., 19, 38, 43

duple subdivision A beat can be subdivided by number equal metrical units. In case of a duple subdivision the beat is subdivided by two and in case of a triple subdivision the beat is subdivided in two sub-units, 7, 29, 40

eighth-note An eighth-note is a rhythmical score unit equaling half the length of a quarter-note and twice the length of an sixteenth-note., 6, 8, 10, 23, 27, 29

expressive timing Expressive timing refers to the concept of adjusting the placements of notes with respect to an established beat in subtle ways by playing some notes slightly before or after the beat., 1, 5, 7

inter-onset interval The time interval, measured in milliseconds, between two notes is called the inter-onset interval (IOI), 5

meter Meter defines the number of rhythmical units that make up a bar in music notation. A $\frac{4}{4}$meter in music notation defines that a bar equals 4 quarter-notes., 20

metronome A device that produces a regulated audible and/or visual pulse, usually used to establish a steady beat, or tempo for the performance of musical compositions. It is an invaluable practice tool for musicians that goes back hundreds of years., 21, 23

metronomically perfect IOI Metronomically perfect IOI are calculated by measuring the interval between score onsets placed on a perfectly even-spaced metrical grid, analogue to a metronome., 23

off-beat In a $\frac{4}{4}$meter the first and third beat are the strongest beats, i.e. naturally the most salient. The second and fourth beat are weaker. In case of a duple subdivision the eighth-notes in between the beats are even weaker and are often referred to as off-beats., 10

quarter-note A quarter note, or crotchet, is the most commonly used note in music notation. Often the tempo is denoted by the number of quarter-notes in a minute, therefore in all metrical scores used in this thesis the quarter-note equals the beat., 11, 23, 27

rhythm section The section of an ensemble supporting the melody or soloist. This section can consist out of a drummer and a base player, but can contain a harmony instrument as well., 43, 50

straight feel the swing rhythm played without swing. This means that the eighth-notes are played equally long, i.e. with a swing ration of 1:1., 9, 43

Swing Swing, as musical genre or style, is a style in jazz music developed in around the 1920s. It was often performed by big bands., 8

swing Swing, as a rhythm, is a way of playing of consecutive eighth-notes in a long-short fashion., 1, 8

swing ratio swing expressed by the IOI length of the first note proportionally to the second note., 9, 17, 41

tempo the rate at which beats occur, and therefore often expressed as beats per minute (BPM). Tempo is closely related to beat duration. If a tempo is given in BPM, the beat duration in milliseconds can be calculated by dividing 60,000 by the tempo in BPM., 1, 7, 23

triple feel the swing rhythm played using a strict triple subdivision, where the first eighth-note uses 2 triplets and the second 1 triplet. The swing ratio equals 2:1 in the strict triple feel., 1, 31, 41

triple subdivision A beat can be subdivided by number equal metrical units. In case of a triple subdivision the beat is subdivided by three sub-units, 7, 23, 29, 38

voice leading The relationship between the successive pitches of simultaneous moving parts or voices is called the voice leading., 50

Appendix: Common Lisp Source Code

In this appendix the Common Lisp implementation of the TDT model is presented. In the full version of the program (see Section 4.3 on page 22) a Macintosh based portmidi MIDI implementation[25] is available for generating audible results. Using the code below one should replace `pseudo-midi-ouput` with `play-midi-output`. `pseudo-midi-ouput` prints the midi information to the screen in a readable fashion.

GTF.lisp

```
;;; THE VIBRATO PROBLEM: COMPARING TWO SOLUTIONS, CMJ 19(3)
;;; APPENDIX C: GTF MICROWORLD
;;; *******************************************************
;;; *******************************************************
;;; GTF microworld
;;; Micro-version of Generalized Time Functions
;;; (with naming and order of arguments adjusted
;;; to match top-level syntax of ACF microworld)
;;; In Common Lisp (copy right) 1993, Desain & Honing
;;; Stripped version by Henkjan Honing.
;;;
;;; Adapted to the Timing-functions framework (TFF)
;;; by Bas de Haas <bas.dehaas@phil.uu.nl> (copy right) 2006
;;; *******************************************************
;;; delayed evaluation utilities

(defmacro delay ((start factor env) &body form)
  "Return a musical object generator"
  `#'(lambda (,start ,factor, env) ,@form))

(defun force (generator start factor env)
  "Return an explicit musical object"
  (funcall generator start factor env))

;;; *******************************************************
;;; basic musical objects

(defun make-event (data end-time)
  "Return event data structure"
  (list data end-time))
```

[25] `http://www.cs.cmu.edu/~music/portmusic/` (June 8, 2007)

```
(defun note (pitch duration amplitude &optional (gtif nil))
  "Return a musical object generator of a note"
  (delay (start factor env)
    (let ((stretched-duration (* duration factor)))
      (make-event (list
                   (list :start start
                         :duration stretched-duration
                         :performance-start (or gtif start)
                         :performance-end (or gtif (+ start stretched-duration))
                         :pitch pitch
                         :amplitude amplitude
                         :environment env))
                  (+ start stretched-duration)))))

(defun pause (duration)
  "Return a musical object generator of a pause"
  (delay (start factor env)
    (declare (ignore env))
    (make-event nil (+ start (* duration factor)))))

;;; ********************************************************
;;; compound musical objects (time structuring)

(defun seq (&rest elements)
  "Return musical object generator of a sequential object"
  (delay (start factor env)
    (loop for element in elements
          as next-start = start then end
          as (events end) = (force element
                                   next-start factor env)
          append events into result
          finally (return (make-event result end)))))

(defun sim (&rest elements)
  "Return a musical object generator of a parallel object"
  (delay (start factor env)
    (loop for element in elements
        as (events end) = (force element start factor env)
        append events into result
        maximize end into end-time
        finally (return (make-event result end-time)))))

;;; ********************************************************
;;; time transformation

(defun stretch (amount object)
  "Return musical object generator of a stretched object"
  (delay (start factor env)
    (force object start (* amount factor) env)))

;;; ********************************************************
;;; time function utilities (abstraction and application)

(defmacro anonymous-gtf ((start duration time) &body form)
  "Return a generalized time function (GTF)"
  `#'(lambda (,start ,duration ,time) ,@form))
```

```
(defun time-funcall (gtf-or-constant start duration time)
  "Return result of applying GTF to its arguments"
  (if (functionp gtf-or-constant)
    (funcall gtf-or-constant start duration time)
    gtf-or-constant))

(defun time-fun-compose (operator &rest gtfs)
  "Return a GTF composed of operator applied to GTF's"
  (anonymous-gtf (start duration time)
    (apply operator
           (mapcar #'(lambda (gtf)
                       (time-funcall gtf
                                     start duration time))
                   gtfs))))

(defun time-fun-+ (&rest time-funs)
  "Return added time-functions"
  (apply #'time-fun-compose #'+ time-funs))

(defun global-to-local-gtf (gtf start duration)
  "Return a global GTF that can be referenced locally"
  (anonymous-gtf (local-start local-duration time)
    (declare (ignore local-start local-duration))
    (time-funcall gtf start duration time)))

;;; ******************************************************
;;; time function constructors

(defun ramp (from to)
  "Return a linear interpolating ramp time function"
  (anonymous-gtf (start duration time)
    (let ((progress (/ (- time start) duration)))
      (+ from (* progress (- to from))))))

(defun oscillator (offset frequency depth)
  "Return a sine wave time function"
  (anonymous-gtf (start duration time)
    (declare (ignore duration))
    (+ offset
       (* depth
          (sin (* 2 pi (- time start) frequency))))))

;;; ******************************************************
;;; attaching GTF's to musical objects

(defmacro attach-gtf (gtf start duration)
  "Return a GTF, with its start and duration fixed"
  (let ((local-start (gensym "local-start"))
        (local-duration (gensym "local-duration"))
        (time (gensym "time")))
    `(anonymous-gtf (,local-start ,local-duration ,time)
       (time-funcall
        (global-to-local-gtf ,gtf ,start ,duration)
        ,local-start ,local-duration ,time))))

(defmacro with-attached-gtfs (bindings expression)
  "Make bindings from GTF's to embedded musical object"
```

```
  (let ((duration (gensym "duration"))
        (start (gensym "start"))
        (factor (gensym "factor"))
        (env (gensym "environment")))
    `(delay (,start ,factor ,env)
       (let* ((,duration nil)
              ,@(loop for (var fun) in bindings
                      collect (list var
                                    `(attach-gtf ,fun
                                                 ,start
                                                 ,duration))))
         (destructuring-bind (events end)
                             (force ,expression
                                    ,start ,factor ,env)
           (setf ,duration (- end ,start))
           (make-event events end))))))

;;; *********************************************************
;;; attribute transformation constructor

(defun attribute-transform (keyword gtf operator generator)
  "Return musical object generator of a transformed object"
  (delay (start factor env)
    (let ((duration nil))
      (destructuring-bind (events end)
         (force generator
                start
                factor
                (modify-env env
                            keyword
                            (attach-gtf gtf
                                        start
                                        duration)
                            operator))
        (setf duration (- end start))
        (make-event events end)))))

(defun modify-env (env attribute gtf operator)
  "Return a modified environment for attribute"
  (let ((env-fun (getf env attribute)))
    (list* attribute
           (if env-fun
             #'(lambda (val object)
                 (funcall env-fun
                          (time-fun-compose operator
                                            gtf
                                            val)
                          object))
             #'(lambda (val object)
                 (declare (ignore object))
                 (time-fun-compose operator gtf val)))
           env)))

(defun get-event-attribute (event key)
  "Return fully transformed attribute time function"
  (let ((original (getf event key))
        (transform (getf (getf event :environment) key)))
```

```
    (if transform
      (funcall transform original event)
      original)))

;;; ********************************************************
;;; attribute transformations

(defun trans (pitch-gtf object)
  "Return a pitch-transformed musical object"
  (attribute-transform :pitch pitch-gtf #'+ object))

(defun loud (amplitude-gtf object)
  "Return an amplitude-transformed musical object"
  (attribute-transform :amplitude amplitude-gtf #'+ object))

;;; ********************************************************
;;; Some helper functions

(defun loop-pattern (number-of-times pattern)
  "returns a GTF representation of a GTF pattern that is looped number-of-times times"
  (loop repeat (1- number-of-times) with result = pattern
        do(setf result (seq pattern result))
        finally (return result)))

;;; ********************************************************
;;; GTF & Timing Functions (GTIF)

(defmacro attach-gtif (musical-object gtif)
  "returns a musical obect with an gtif attached to it, or repaces an
old gtif with a new one"
  (let ((duration (gensym "duration"))
        (start (gensym "start"))
        (factor (gensym "factor"))
        (env (gensym "environment")))
    `(delay (,start ,factor ,env)
       (let* ((,duration nil)
              (forced-musical-object (force ,musical-object ,start ,factor ,env)))
         (destructuring-bind (events end)
             (loop for event in (first forced-musical-object)
                   do (setf (getf event :performance-start) ,gtif)
                      (setf (getf event :performance-end) ,gtif)
                   finally return forced-musical-object)
           (setf ,duration (- end ,start))
       (make-event events end))))))

(defun calc-score-end (pattern &key (score-start 0))
  "calculates the final score-time from a GTF musical object"
  (let* ((forced-object (loop for event in (first (force pattern score-start 1 nil))
                              collect event))
         (last-note (first (last forced-object)))
         (start-last-note (getf last-note :start))
         (duration-last-note (getf last-note :duration)))
    (+ start-last-note duration-last-note)))

;;; ********************************************************
;;; output sampling
```

```
(defun sample (gtf start duration
                   &optional (resolution 1/4))
  "Return list of sampled values or constant"
  (if (functionp gtf)
    (loop for count from 0.0
          to (floor (/ duration resolution))
          as time = (+ start (* count resolution))
          collect (time-funcall gtf start duration time))
    gtf))
```

TFF.lisp

```
;;; FROM TIME TO TIME: THE REPRESENTATION OF TIMING AND TEMPO
;;; ******************************************************
;;; ******************************************************
;;; Timing Functions Framework extending the GTF microworld
;;; In Common Lisp (copy right) 2006, Bas de Haas <bas.dehaas@phil.uu.nl>
;;; See, Honing, H. (2001). "From time to time: The representation
;;; of timing and tempo." Computer Music Journal, 35 (3), 50-61.
;;; for a detailed desciption.
;;; ******************************************************
;;; time-maps level

(defun tm-funcall (time-map score-time performance-time)
  "returns a new performance-time given a time-map, score-time,
performance-time and the optional arguments: score start-time,
score end-time, performance-start-time and performance-end-tim.
The optional arguments will not be called if the optional arguments
are not provided (nil)"
      (funcall time-map score-time performance-time))

(defmacro anonymous-tm ((score-time performance-time ) &body form)
  "returns a anonymous time-map which can be a time-shift or a tempo-change.
The time-map has optional access to the score start-time end-time performance
start-time and performance end time. A two argument tm will be generated
if the optional arguments are not provided (nil)"
      `#'(lambda (,score-time ,performance-time) ,@form))

(defun identity-tm ()
  "returns a time-map that does not change the tempo, does not add
any expressive timing, and just returns the performance-time"
  (anonymous-tm (score-time performance-time)
      (declare (ignore score-time))
       performance-time))

;;; ******************************************************
;;; generalized timing-functions level

;; start-time: rational number denoting the symbolic starting score-time
;; end-time: rational number denoting the symbolic ending score-time
(defun anonymous-gtif (start-score-time end-score-time tif
                        &optional (previous-applied-tif (make-tif)))
 "Return a timing function, a tuple of a time-shift and tempo-change function."
 (let ((performance-start-time (tif-funcall previous-applied-tif
                                start-score-time start-score-time))
       (performance-end-time (tif-funcall previous-applied-tif
```

```
                                end-score-time end-score-time)))
    ;; bind performance-start-time and performance-end-time
    ;; lexically, the current performance times given
    ;; the previously applied timing transformations (u).
   (make-tif
    ;; Construct a TIF consisting of two time-maps.
    :tempo-change (anonymous-tm (score-time performance-time)
                      (tm-funcall (get-tif :tempo-change tif) score-time performance-time)
                      ;; Return a tempo-change time-map,
                      ;; a function of score-time and performance-time,
                      ;; with access to score-begin (start-time), score-end (end-time),
                      ;; performance-begin time and performance-end time,
                      ;; and previous applied timing transformations.
                             )
    :time-shift   (anonymous-tm (score-time performance-time)
                      (tm-funcall (get-tif :time-shift tif)  score-time performance-time)
                      ;; with access to score and performances times (as above)
                      ;; Return a time-shift time-map,
                             )
    :start-score-time start-score-time
    :end-score-time end-score-time
    :performance-start-time performance-start-time
    :performance-end-time performance-end-time)
   ))

;;; ********************************************************
;;; timing-functions level
(defun make-tif (&key (time-shift (identity-tm)) (tempo-change (identity-tm))
                      (start-score-time nil) (end-score-time nil)
                      (performance-start-time nil) (performance-end-time nil))
  "returns a Timing-function containing a time-shift and a tempo-change time-map"
  (list :time-shift time-shift :tempo-change tempo-change
        :start-score-time start-score-time
        :end-score-time end-score-time
        :performance-start-time performance-start-time
        :performance-end-time performance-end-time))

(defun tif-funcall (tif score-time performance-time)
  "returns a tempo-changed and time-shifted performance time"
  (let ((tempo-changed-performance-time
         (tm-funcall (get-tif :tempo-change tif) score-time performance-time )))
    (tm-funcall (get-tif :time-shift tif) score-time tempo-changed-performance-time)))

(defun get-tif (keyword tif)
  "returns the a property of a timing function tif. The keyword sets which
property (e.g. :time-shift, :tempo-change etc.)"
  (getf tif keyword))

;;; ********************************************************
;;; some example time-maps

(defun constant-tempo (tempo-factor)
  "returns a time-map that changes the tempo with a constant factor"
  (anonymous-tm (score-time performance-time)
      (declare (ignore score-time))
      (* tempo-factor performance-time)))
```

```
(defun delay-a-beat (which-beat &key (beats-per-bar 4)(delay 0.2))
  "return a time-map that delays a beat in a bar, given a delay and a meter"
  (anonymous-tm (score-time performance-time)
      (if (eq (mod (- score-time which-beat) beats-per-bar) 0)
          (+ performance-time delay)
        performance-time)))

;;; ********************************************************
;;; composition & concatenation

(defun compose-tm (tm-applied-first tm-applied-second)
  "returns a time-map that consists out of the composition of two time-maps"
  (anonymous-tm (score-time performance-time)
    (tm-funcall tm-applied-second score-time
                (tm-funcall tm-applied-first score-time performance-time))))

(defun concatenate-time-shifts(first-time-shift second-time-shift concat-score-time)
  "returns a time-map that consists out of a the concatenation of two time-shifts"
  (anonymous-tm (score-time performance-time)
    (if (<= score-time concat-score-time)
        (tm-funcall first-time-shift score-time performance-time )
      (tm-funcall second-time-shift score-time performance-time))))

(defun concatenate-tempo-changes (first-tempo-change second-tempo-change
                                  concat-score-time concat-perf-time)
  "returns a time-map that consists out of a the concatenation of two tempo-changes"
  (anonymous-tm (score-time performance-time)
    (if (<= score-time concat-score-time)
        (tm-funcall first-tempo-change score-time performance-time)
      (let ((first-tempo-change-concat-point
             (tm-funcall first-tempo-change concat-score-time concat-perf-time))
            (second-tempo-change-concat-point
             (* -1 (tm-funcall second-tempo-change concat-score-time concat-perf-time))))
        (+
         (tm-funcall second-tempo-change score-time performance-time)
          first-tempo-change-concat-point
          second-tempo-change-concat-point)))))

(defun compose-tif (tif-applied-first tif-applied-second)
  "returns a tif composed out of two timing functions"
  (make-tif
   :time-shift (compose-tm (get-tif :time-shift tif-applied-first)
                           (get-tif :time-shift tif-applied-second))
   :tempo-change (compose-tm (get-tif :tempo-change tif-applied-first)
                           (get-tif :tempo-change tif-applied-second))))

(defun compose-tifs (list-of-tifs &optional (composed-tif nil))
  "returns a tif composed of two or more timing functions"
  (if (equal composed-tif nil) (compose-tifs (rest list-of-tifs) (first list-of-tifs))
    (if (equal list-of-tifs nil) composed-tif
      (compose-tifs (rest list-of-tifs)
                    (compose-tif (funcall composed-tif) (funcall (first list-of-tifs)))))))

(defun concatenate-tif (tif-applied-first tif-applied-second
                        concat-score-time concat-perf-time)
  "returns a tif that is the concatenation of two timing-functions"
  (make-tif
```

```
   :time-shift (concatenate-time-shifts (get-tif :time-shift tif-applied-first)
                           (get-tif :time-shift tif-applied-second)
                           concat-score-time)
   :tempo-change (concatenate-tempo-changes (get-tif :tempo-change tif-applied-first)
                           (get-tif :tempo-change tif-applied-second)
                           concat-score-time concat-perf-time)))

;;; *********************************************************
;;; output
(defun force-MIDI-output (musical-object)
  "Forces the event times of a GTF musical object.
N.B. pitch and amplitude GTF's should still be sampled"
  (loop for event in (first (force musical-object 0 1 nil))
        do (setf (getf event :pitch)
                 (get-event-attribute  event :pitch))
        (setf (getf event :amplitude)
              (get-event-attribute  event :amplitude))
        (let* ((start (getf event :start))
               (end (+ (getf event :duration) start)))
          (setf (getf event :performance-start)
                (if (tifp (getf event :performance-start))
                    (tif-funcall (getf event :performance-start) start start)
                  (getf event :performance-start)))
          (setf (getf event :performance-end)
                (if (tifp (getf event :performance-end))
                    (tif-funcall (getf event :performance-end) end end)
                  (getf event :performance-end))))
        collecting event into result
        finally(return (sort result #'< :key #'(lambda (x) (getf x :performance-start))))))

(defun pseudo-midi-output (musical-object)
 "pseudo-midi-output prints the information that would otherwise
be passed on to a midi sound generations system In the full version of
the GTF/TFF program (see Section 4.3 for download information) a portmidi
implementation is available. Printing the whole portmidi implementation
would take to much space.  replacing this function by \"send-MIDI-output\"
will give an audible result."
  (loop for event in (force-MIDI-output musical-object)
        do(let* ((velocity (getf event :amplitude))
                 (score-start (getf event :start))
                 (start (round (getf event :performance-start)))
              (end  (round (getf event :performance-end)))
              (pitch (sample (getf event :pitch) start (- end start) 1)))
            (format t "~%[NOTE ~{~S ~}]"
          (list :beat-pos score-start :performance-start start
                :duration (- end start) :pitch pitch :velocity velocity)))))

;;; *********************************************************
;;; some helper functions

(defun bd-to-bpm (bd)
  "calculates the tempo in beats per minute from the beat duration (ms)"
  (* 60000 (expt bd -1)))

(defun bpm-to-bd (tempo-in-bpm)
  "calculates the beat duration (ms) from a tempo in beats per minute"
  (bd-to-bpm tempo-in-bpm)) ;ioi-to-bmp is it own inverse function
```

```
(defun tifp (tif-or-not)
  "returns true if tif-or-not is a tif and false if tif-or-not is something else.
Tifp does this by checking if tif-or-not is a list with a length of 12 and if contains a
time-shift and a tempo-change timemap."
  (if (listp tif-or-not)
      (if (getf tif-or-not :time-shift) ; is tif-or-not a property list
        (if (equal (length tif-or-not) 12)
            (if (and (functionp (get-tif :time-shift tif-or-not))
                     (functionp (get-tif :tempo-change tif-or-not)))
                t
              nil)))))

;;; ***********************************************************
;;; basic gtifs

(defun straight-eights (score-start score-end tempo-in-bpm)
  "returns a GTF without exrpessive timing"
  (anonymous-gtif score-start score-end
                   (make-tif :tempo-change
                             (constant-tempo (bpm-to-bd tempo-in-bpm)))))
```

SRC.lisp

```
;;; SWING RATIO COMBINATOR
;;; ***********************************************************
;;; ***********************************************************
;;; Data implemented in the Timing Functions Framework
;;; which extends the GTF microworld
;;; In Common Lisp 2006, Bas de Haas <bas.dehaas@phil.uu.nl>
;;; This file depends on GTF microworld and TFF
;;; ***********************************************************
;;; Some GTF patterns

(defun ride-pattern (&key (pitch 51) (duration 1) (amplitude 127) (gtif nil))
  "defines the common ride pattern played in jazz in the GTF formalism"
  (seq (note pitch duration amplitude gtif)
       (pause duration)
       (note pitch duration amplitude gtif)
       (note pitch duration amplitude gtif)))

(defun four-beats (&key (pitch 51) (duration 1) (amplitude 127) (gtif nil))
  "A bar with for beats"
  (seq (note pitch duration amplitude gtif)
       (note pitch duration amplitude gtif)
       (note pitch duration amplitude gtif)
       (note pitch duration amplitude gtif)))

;;; ***********************************************************
;;; swing functions

(defun swing (score-start score-end swing-ratio &key (IOI 250))
  "returns a GTIF tempo transforming a score to a constant tempo with
a swing interpretation according to a swing-ratio"
  (let ((delay (/ IOI swing-ratio)))
    (anonymous-gtif score-start score-end
```

```
                    (make-tif
                     :tempo-change (constant-tempo IOI)
                     :time-shift   (anonymous-tm (score-time performance-time)
                                     (if (eq (mod (1+ score-time) 2) 0)
                                         (+ performance-time delay)
                                       performance-time))))))

;;; ********************************************************
;;; swing ratio models

(defun linear-swing-ratio-model (tempo-in-bpm &key (slope 0) (intercept *shuffle-mean-sr*))
  "returns the swing ratio given by a linear model. The default value is
the fitted value from the Shuffle excerpt"
  (+ (* tempo-in-bpm slope) intercept))

(defun Swing-swing-ratio-model (tempo-in-bpm &key (slope-b *b*) (intercept-a *a*)
                                             (slope-d *d*) (intercept-c *c*) (m *m*))
  "returns the swing ratio given by a linear model. The default value is
the fitted value from the Shuffle excerpt"
  (let ((beat-duration (bpm-to-bd tempo-in-bpm)))
    (if (<= beat-duration m)
        (+ (* beat-duration slope-b ) intercept-a)
      (+ (* beat-duration slope-d) intercept-c))))

;;; ********************************************************
;;; the optimized parameters of the swing ratio models

;; Swing
(defparameter *a* .399 "intercept of the first linear function")
(defparameter *b* 0.000496 "slope of the first linear function")
(defparameter *c* 2.46 "intercept of the second linear function")
(defparameter *d* -0.00006416 "slope of the second linear function")
(defparameter *m* 368 "concatenation point (beat durations in ms)")

;; Shuffle
(defparameter *shuffle-mean-sr* 1.65 "mean swing ratio of the Shuffle excerpt")

;; Funk
(defparameter *funk-mean-sr* 1 "mean swing ratio of the Funk excerpt")

;;; ********************************************************
;;; top level functions

(defun play-swing-pattern (pattern tempo-in-bpm &key
                                   (number-of-loops 8)
                                   (score-start 0)
                                   (model #'linear-swing-ratio-model)
                                   (swing-ratio nil))
  "plays a GTF musical object (pattern), attaches a swing Timing function
to it and plays the patternfor a number of timens (default: 8 times)"
  (let* ((score-end (calc-score-end pattern :score-start score-start))
         (ratio (or swing-ratio (funcall model tempo-in-bpm)))
         (IOI (bpm-to-bd tempo-in-bpm))
         (swing-gtif (swing score-start (* number-of-loops score-end) ratio :IOI IOI))
         (pattern-with-swing-gtif (attach-gtif pattern swing-gtif)))
    (pseudo-midi-output (loop-pattern number-of-loops pattern-with-swing-gtif))))
(defun output-no-expressive-timing (pattern tempo-in-bpm &key
```

```
                                        (number-of-loops 8) (score-start 0))

"Outputs a GTF musical object without expressive timing at a certain tempo (in bpm)"
  (let* ((score-end (calc-score-end pattern :score-start score-start))
         (gtif (straight-eights score-start score-end tempo-in-bpm))
         (pattern-with-gtif (attach-gtif pattern gtif)))
    (pseudo-midi-output (loop-pattern number-of-loops pattern-with-gtif))))

(defun output-swing-pattern-linear-model (pattern tempo-in-bpm &key
                                              (number-of-loops 8) (score-start 0))
  "Outputs a GTF musical object (pattern), with the swing timing from the linear model
for a number of timens (default: 8 times)"
  (play-swing-pattern pattern tempo-in-bpm :number-of-loops number-of-loops
                      :score-start score-start :model #'linear-swing-ratio-model))

(defun output-swing-pattern-classical (pattern tempo-in-bpm &key
                                            (number-of-loops 8) (score-start 0))
  "Outputs a GTF musical object (pattern), with the classical 1:2 swing-ratio timing
for a number of timens (default: 8 times)"
  (play-swing-pattern pattern tempo-in-bpm :number-of-loops number-of-loops
                      :score-start score-start :swing-ratio 2))
#|
;;; *********************************************************
;;; examples
(play-swing-pattern (ride-pattern) 100 :number-of-loops 2
                    :score-start 0 :model #'Swing-swing-ratio-model)
[NOTE :BEAT-POS 0 :PERFORMANCE-START 0 :DURATION 848 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 2 :PERFORMANCE-START 1200 :DURATION 848 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 3 :PERFORMANCE-START 2048 :DURATION 352 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 4 :PERFORMANCE-START 2400 :DURATION 848 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 6 :PERFORMANCE-START 3600 :DURATION 848 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 7 :PERFORMANCE-START 4448 :DURATION 352 :PITCH 51 :VELOCITY 127 ]
NIL

;; shuffle output according to the Shuffle swing ratio model:
(output-swing-pattern-linear-model (four-beats) 160 :number-of-loops 2)=>
[NOTE :BEAT-POS 0 :PERFORMANCE-START 0 :DURATION 602 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 1 :PERFORMANCE-START 602 :DURATION 148 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 2 :PERFORMANCE-START 750 :DURATION 602 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 3 :PERFORMANCE-START 1352 :DURATION 148 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 4 :PERFORMANCE-START 1500 :DURATION 602 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 5 :PERFORMANCE-START 2102 :DURATION 148 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 6 :PERFORMANCE-START 2250 :DURATION 602 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 7 :PERFORMANCE-START 2852 :DURATION 148 :PITCH 51 :VELOCITY 127 ]
NIL

;; the classical 2:1 swing ratio
(output-swing-pattern-classical (ride-pattern) 100 :number-of-loops 2) =>
[NOTE :BEAT-POS 0 :PERFORMANCE-START 0 :DURATION 900 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 2 :PERFORMANCE-START 1200 :DURATION 900 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 3 :PERFORMANCE-START 2100 :DURATION 300 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 4 :PERFORMANCE-START 2400 :DURATION 900 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 6 :PERFORMANCE-START 3600 :DURATION 900 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 7 :PERFORMANCE-START 4500 :DURATION 300 :PITCH 51 :VELOCITY 127 ]
NIL

;; no expressive timing:
```

```
(output-no-expressive-timing (ride-pattern) 100 :number-of-loops 2)=>
[NOTE :BEAT-POS 0 :PERFORMANCE-START 0 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 2 :PERFORMANCE-START 1200 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 3 :PERFORMANCE-START 1800 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 4 :PERFORMANCE-START 2400 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 6 :PERFORMANCE-START 3600 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
[NOTE :BEAT-POS 7 :PERFORMANCE-START 4200 :DURATION 600 :PITCH 51 :VELOCITY 127 ]
NIL
|#
```