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Striking movements: Movement strategies and expression in percussive playing

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Abstract

This thesis concerns two aspects of movement and performance in percussion playing, First, the playing of an accent, a simple but much used and practised element in drumming, and second; the perception and communication of specific emotional intentions through movements during performances on marimba.

Papers I and II investigated the execution and interpretation of an accent performed for different playing conditions. Players' movements, striking velocities and timing patterns were studied for different tempi, dynamic levels and striking surfaces. It was found that the players used differing movement strategies when playing and that they interpreted the accent differently, something that was reflected in their movement trajectories. Strokes at greater dynamic levels were played from a greater height and with higher striking velocities. All players initiated the accented strokes from a greater height, and delivered the accent with increased striking velocity compared to unaccented strokes. The interval beginning with the accented stroke was also prolonged, generally by delaying the following stroke. Recurrent cyclic patterns in the players' timing performances. In a listening test listeners perceived the strokes grouped according to the cyclic patterns.

Paper III studied how emotional intent was conveyed to observers through the movements of a marimba player. A percussionist was filmed when playing a piece with the expressive intentions Happiness, Sadness, Anger and Fear on marimba. Observers rated the emotional content and movement cues in the videos clips shown without sound. Results showed that the observers were able to identify the intentions Sadness, Anger, and Happiness, but not Fear. The rated movement cues showed that an Angry performance was characterized by large, fast, uneven and jerky movements, Happy performances by large, somewhat fast movements, and Sad performances by small, slow, even, and smooth movements.

Keywords: drumming, percussion, movement strategies, instrument interaction, timing, emotional expression

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List of papers

Paper I:
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Paper II:
Dahl, S. 2002 Playing the accent - comparing striking velocity and timing in an ostinato rhythm performed by four drummers.
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Paper III:
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Author's contribution to the papers

Paper I:
This work was carried out entirely by author S. Dahl.

Paper II:
This work was carried out entirely by author S. Dahl.

Paper III:
The major part of the work was carried out by author S. Dahl. Co-author A. Friberg performed the statistical analysis and participated in editing the manuscript.

Contents

rhythm (rith'm), n. [Fr. *rhythme*, L. *rhythmus*, from Gr. *rhythmos*, measure, measured, motion, from *rhein*, to flow.]

1. (a) flow, movement, procedure, etc. characterized by basically regular recurrence of elements or features, as beat, or accent, in alternation with opposite or different elements or features; as, the *rhythm* of speech, of the heart, of an engine, of dancing, of seasons, etc.; (b) such recurrence; pattern of flow or movement.

2. in art, aesthetic relation of part to part and of parts to the whole; pattern of arrangement; as the *rhythm* of a picture, of a statue, of a building, etc.

3. in music (a) regular (or, occasionally, somewhat irregular) recurrence of grouped strong and weak beats, or heavily and lightly accented tones, in alternation; arrangement of successive tones, usually in measures, according to their relative accentuation and duration; (b) form or pattern of this; as rumba *rhythm*, triple *rhythm*.

4. in prosody, (a) basically regular recurrence of grouped, stressed and unstressed, long and short, or high-pitched and low-pitched syllables in alternation; arrangement of successive syllables, as in metrical units (feet) or cadences, according to their relative stress, quantity, and pitch: in English, rhythm depends on accent as composed of interconnected stress, quantity, pitch, and pause; (b) form or pattern of this; as iambic *rhythm*.

(Webster's new twentieth century dictionary, 2nd edition, 1966).

Part I

Introduction

Chapter 1

Introduction

Causing an object to resonate by striking it is a simple task, a child can easily do it. Maybe it is because the task is so simple that humans started doing it repeatedly, forming rhythms. Whatever the basic reason, we have nourished our preference for striking, tapping, clapping and drumming rhythms for a considerable time now; the oldest known membrane headed drums existed already 10,000 years ago (Hart and Stevens, 1990).

Rhythm can be viewed as events occurring at specific moments in time, and if striking a drum is easy, doing so at the right moment is harder. All musicians strive to master rhythm and timing in their performances, but for percussionists these words carry a special importance. Keeping a steady rhythm and tempo are fundamental elements in any percussion training. Furthermore, in many ensembles, the function of the percussionist/drummer is to be *the* timekeeper.

Percussion instruments generally produce sounds with impulse-like characteristics. Normally the note onsets are well defined, the durations short, and in general the player has little control over the tone, once initiated. The note can be shortened by dampening (e.g. by forcing the mallet to stay in contact with the drumhead after the hit), but it cannot be lengthened. While, for instance, players of wind instruments have close control of the vibrating air column during the full duration of a note, the percussion player's direct contact with the instrument is limited to a few milliseconds. This implies that whatever the resulting striking force and dampening effect the percussionist wants to induce would need to be integrated in the entire striking gesture. The mallet will strike the drumhead (or some other object) with the velocity and effective mass supplied by the player's movement, and the same striking gesture will also determine the contact duration.

Percussion includes a vast variety of instruments, both membranophones (e.g. drums) and idiophones (e.g. cymbals, wood blocks, etc). Each instrument has its specific characteristics and limitations. In order to modify the timbre or the fundamental frequency a percussion player can strike at different positions, or choose a mallet with a different mass, hardness and/or shape. The stiffness and tension of a drumhead can also be adjusted. However, in a normal playing situation there is seldom time for such types of adjustments. A change of timbre or pitch is typically achieved by striking another instrument. For instance, world-renowned solo percussionist Evelyn Glennie has a collection of 1400 instruments and on average travels with 1.7 tons of equipment.

Normal percussion playing requires that the player perform the same rhythm on different instruments with differing physical properties. A change of instrument changes the kinesthetic feedback to the player. Percussion instruments are also positioned at varying distances from the player, who has to plan the movements in order to reach the right spot at the right time[1]. In many respects, percussion playing can be viewed as a matter of finding a compromise that allows the desired expression within time constraints. A playing technique that can be adapted to the feedback from the instrument would then be highly important to reduce the degree of compromise. It could be hypothesized that skilled players could take advantage of the conditions at hand to maximize the desired effects (such as expression, time that can be used for preparation, etc) and minimize the undesired effects (performance errors, strain etc). In this view, a skilled player aims at using *continuous* movements (the playing style and body language) to control *discrete events* in time (the impacts). The movements used in percussion playing generally involve large movement gestures for note production. It seems reasonable to hypothesize that these gestures are closely coupled to the intended musical expression.

The work presented in this thesis focuses on the movements and timing in percussion playing. The first two studies investigated the playing of an accent, a simple but much practised element in drumming. The third study deals with the perception of expressive movements in performances on marimba.

1.1 Why study players' movements?

Player-instrument interaction. In the interaction between player and instrument the movements play a key role. Control through movement is central for all player-instrument interactions (including the theremin and contemporary music controllers where there is no physical/tactile connection between the player and instrument). To excel as a performer on a musical instrument, the mechanical system defined by the combination of body and instrument needs to be fine-tuned and refined during many years of practice. In short, musicians spend an amazing amount of time mastering their movements to perfection.

However, to have learned control does not necessarily mean that you are consciously aware of what movements you are doing. Furthermore, the movements can be too small or too fast to be observed with the human eye. In many cases teachers and students have to rely on metaphors or intuition to induce the right 'gut feeling'. But to be able to actually *see* what is happening and which movements that are

[1]For instance, a drum set player normally has to reach about one meter between the hi-hat at one end of the drum set and a cymbal at the other end.

used would bring valuable insights. Music professor H. Winold explains why she used high-speed cameras to study cello performances (Winold, 1984):

> "High speed photography intrigued me first when I saw a small segment of a Heifetz[2] film in slow motion. Suddenly I could see preparatory movements, reaching for groups of notes, and minute adjustments required by particular passages in Heifetz's hand, a hand that had seemed almost motionless at regular speed. "

Many of Winold's recorded subjects were surprised to see that they were playing a vibrato in a different way than they had thought. Guettler (1992) found that using electromyography could be useful for visualizing techniques for vibrato playing on the double bass.

All ways are good except the bad ways? A sustainable carrier as a musician requires a consciousness of ergonomic issues. There is nothing wrong with learning instrument control intuitively. We learn skilled movements intuitively in all possible situations, e.g. typing, ball games, skipping rope. But what happens when the learned movement causes health problems? Musicians are a group of people who perform very specified movements over long periods of time, and can suffer from strain-related injuries (see survey in Kaladjev, 2000).

Movement analysis and evaluation is difficult for performing artists, since the result of the movement (the music) always is evaluated subjectively. There has been a more extensive use of measurement techniques to study movements in sports and athletics, since in these areas an achieved improvement is often easily measured in physical quantities like seconds or meters. Further studies of musicians' movements are important for self-monitoring and didactic reasons, but also for investigating relationships between learned movement patterns, strain and injuries.

Body language. Musicians move their bodies in ways not always directly related to, or needed for, the production of notes. Changes in posture, large body sway or other types of movements (conscious or unconscious) can be seen in performing musicians. Wanderley (2002) refers to these movements as *ancillary*, *accompanist*, or *non-obvious* movements. Some of these movements are, however, clearly intended to be expressive, or used for communication. For this reason these movements can be viewed as a kind of body language. Four aspects that can influence this body language have been suggested by Davidson and Correia (2002): (1) Communication with co-performers, (2) individual interpretations of the narrative or expressive/emotional elements of the music, (3) the performer's own experiences and behaviors, and (4) the aim to interact and entertain an audience.

Observers are able to use the information in body movements to discriminate between different expressive intentions, emotions or affects. This has been shown

[2] Jascha Heifetz (1901-1987), Russian American violinist, considered one of the greatest violinists.

both for music and dance performances (eg Walk and Homan, 1984; Dittrich et al., 1996; Davidson, 1994), but also for every-day arm movements like drinking and lifting (eg Pollick et al., 2001; Paterson et al., 2001). Still, the nature of body language, and the vital elements for conveying the information to observers are not yet fully understood.

Reasons for studying movement. To summarize; the study of body movements in music performance can provide valuable insights into how musicians perform and communicate when playing music. In particular, three objectives for studying musicians' movement can be outlined:

- To describe playing techniques and their effect on the production of sound.
- To increase the knowledge about 'efficiency' and 'ergonomics' in skilled movements used for artistic – as opposed to competitive – purposes.
- To explore visual communication through movements in music performance.

1.2 Skilled movements

Skilled performers (e.g. musicians, sportsmen, professional bricklayers etc) are somehow able to be (Abernethy et al., 1997):

- fast, yet accurate,
- consistent, yet adaptable,
- maximally effective, yet with a minimum of attention and effort.

Not only that, when experts perform difficult tasks these tasks frequently appear to be easy. Specialized movements performed by a skilled person are known to appear smooth, something that characterize efficient energy exchanges (Wickstrom, 1990).

Motor skill. Several theories of motor skill have been considered in the context of musical performance (see Gabrielsson, 1999). Two fundamental theories have been particularly discussed: *closed-loop theory* and *open-loop theory* (also called *motor program theory*). According to the closed-loop theory, an internal reference for the movement is compared to sensory feedback from the proprioceptors in joints and muscles. The movement is then adjusted and compared with new incoming sensory feedback. It is argued that a closed-loop could not produce movements fast enough to be used in, for example, trills. Instead these types of movements would be performed without the help of proprioceptory feedback; open-loop. According to this theory each movement is specified in a motor command, which is carried out without any alteration or comparison to feedback.

How skilled movements are learned and developed is not completely understood. What is known is that practice makes better, if not perfect. Even in relatively simple tasks there is room for decreasing the execution time after more than a million practices. For instance, after rolling several millions of cigars, the performance of workers continued to improve over the next million rollings (Crossman, 1959, see Abernethy et al., 1997). Motor skills are also specific to the trained task and are not necessarily easily transferred to other tasks.

It has been proposed that when learning skills, the learner passes through three stages (Fitts and Posner, 1967). First there is the *cognitive* phase during which the learner has to identify and understand what to do. Cues in the environment and feedback on the performance are important to help him/her develop a plan of action. During the *associative* phase that follows, there is a shift from what needs to be done to *how* it should be done, and an overall plan is forming. The movements are refined by specifically practising the task that is to be learned. How long this phase lasts is dependent on the complexity of the task as well as on the performer' talent. Some, but far from all, learners reach the third *autonomous* phase. This is a very advanced stage where the task has become so "automatic" that the performer can devote his/her attention elsewhere without impaired performance. There is no longer any need to continuously keep a conscious check on feedback to maintain control. The movement has become 'open-loop'.

Movement strategies. There are movement strategies used by expert athletes and sportsmen that distinguish them from less skilled practitioners (see Abernethy et al., 1997; Wickstrom, 1983). Sports involving striking or throwing movements (as in tennis, or baseball pitching or hitting) seem to have as a common aim to prolong the elongated arc during which acceleration occurs. For instance, a baseball player initiates a stroke from a turned position with one hip facing the approaching ball and the bat positioned at the opposite side of the body. The stroke starts with a step towards the ball, after which the hip, trunk, and arm rotates, swinging the bat forward.

1.3 Interpretation and expression in music performance

Expression. Playing music is not just a matter of mastering a playing technique. We also expect the music to move and engage us in some manner, to be *expressive.* To date there has been a great deal of studies on what musicians do to be expressive and how expression is conveyed to listeners (see eg Deutsch, 1999; Juslin and Sloboda, 2001).

Specifically for *emotional* expression Gabrielsson and Juslin (1996); Juslin (2000, 2001) have listed the acoustical cues, i.e. the pieces of information extracted from the sounds that help listeners detect emotional intentions. The most important cues used are tempo, sound level, articulation, tone attack, and timbre. For instance, a sad performance is characterized by slow tempo, legato articulation, and low sound level, while a happy performance is characterized by fast mean tempo, staccato articulation, and high sound level.

Some attempts have been made to isolate cues in order to find when and how they have the highest influence on the perceived expression. Juslin and Madison (1999) manipulated piano performances with differing emotional intentions (Happiness, Anger, Sadness, and Fear) and asked listeners to rate the expressiveness of these performances. The results showed that the decoding accuracy for the intentions Anger and Sadness suffered greatly when variations in tempo and dynamic level were removed and substituted for the mean tempo and key velocities across all performances. The Happy and Fearful performances, however, seemed to rely more on variability in articulation. When the articulation was kept constant throughout performances (that is, note durations occupied 0.7 of the interval between onsets) Happy and Fearful performances were recognized to lesser extent.

In an experiment designed to identify which acoustic cues contribute to the perceived "expressiveness" of a performance, Juslin (1997) explored 108 cue combinations in synthesized performances. The most expressive combination was (in order of strength) legato articulation, soft spectrum, slow tempo, high sound level, and slow tone attacks. Juslin noted that there seemed to be a strong relationship between the rated expressiveness and the means to express sadness/tenderness.

Let us now consider how the acoustic cues mentioned above relate to percussion performance. For instance playing legato with slow tone attacks can be a problem in percussion playing. Are there any limitations to expressivity for non-tonal rhythms? Will listeners recognize a sad drum performance? Or, in other words, can you express the same emotions through percussion instruments as through other instruments?

There are some examples of studies including percussion instruments. When Behrens and Green (1993) asked listeners to rate Sad, Angry and Scared solo improvisations performed on timpani, Anger seemed to be readily recognized, while the Sad and Scared improvisations were rated much lower. Other instruments included in the study (violin, trumpet, and voice) were much more successful in conveying the Sad intention. Fear was best recognized when performed on the violin. No acoustic measures of the performances were made in their study.

Laukka and Gabrielsson (2000) combined their investigation of listeners' discriminations of different emotional intent in performed rhythm patterns with acoustic measurements. They found that the emotions Happy, Sad, Angry and Fearful were more easily communicated than Tender and Solemn. The sound levels, timing variations and tempi used by the two drummers playing the rhythm patterns were compared for the different intentions. The softest sound levels were found for Sad and Tender performances, and the loudest for Angry, which was performed about 10 dB louder. The happy swing performance was played at a mean tempo more than three times that of the mean of the sad performance (192 compared to 61 beats per minute). The Fearful performances varied so much in tempo that the authors felt it was meaningless to talk about a mean tempo.

In summary, previous studies show that tempo and dynamic level are important cues in decoding emotion in musical performance and the acoustical cues found for emotional expression in percussion performances seem similar to the cues found for other instruments.

Timing. There has been an overwhelming number of research accounts of timing in musical performance (see e.g. Gabrielsson, 1999, for a survey). A commonly reported feature is that note durations are practically never played according to their nominal (notated) value. Although small integer ratios (1:1, 1:2, and 1:3) are fundamental in musical notation, the durations of notes with these ratios are systematically lengthened or shortened by players. Although most studies have concerned performances on piano, the systematic variations in the timing of rhythm patterns have also been reported for drumming (e.g. Gabrielsson, 1974; Friberg and Sundström, 2002).

Not all timing variations are systematic, however. Embedded in the timing of music performance lies random variations. These random timing variations can be hard to distinguish from intended lengthening or shortenings of individual note durations. In order to estimate the influence of random components on music performance it can be useful to compare with studies of isochronous finger tapping (e.g. Michon, 1967; Wing and Kristofferson, 1973). In these cases the random variations in timing generally appear as short-term variations with negative first-order dependency (alternating long and short durations between onsets), and long-term drifts in tempo (see overview in Madison, 2001a). Reported standard deviations for isochronous tapping (synchronization with an external clock, or continuation after the clock has stopped) usually are between 3 and 6 % (see comparisons in Juslin et al., 2002). In recordings of isochronous tapping sequences performed by three professional drummers, Madison (2000) observed an average standard deviation of 2.8 % of the mean inter-tap interval. In studies concerning temporal drift in tapping Madison (2001b) reported that, on average, each interval was lengthened or shortened with up to 0.29 %.

The perception of variations in timing depends on the type of perturbation and when it occurs. For instance, at phrase boundaries listeners expect performers to make large deviations from the nominal note durations. However, the same lengthening of a note that passes undetected by listeners at a phrase boundary can be detected when appearing in the middle of a phrase (Repp, 1992). A survey of the *Just Noticeable Difference (JND)* in different experiments on time discrimination in short isochronous sequences has been made by Friberg and Sundberg (1995). For tempi with inter-onset intervals (IOIs) between 200 and 1200 ms JND varies between 2 and 9 % of IOI, depending on the type of timing manipulation done. Reported JNDs for tempo changes are lower, around 2 % (e.g. Drake and Botte, 1993; Madison, 2001a).

Accents. According to Cooper and Meyer (1963) an accent is “a stimulus (in a series of stimuli) which is marked for consciousness in some way”. A number of different types of accents are defined in the literature. Parncutt (ress) divided accents into *performed* accents that are added by the musician, and *immanent* accents that are perceived as accented even in a nominally performed score (see also Friberg and Battel, 2002, for citation). The performed accents frequently coincide with the immanent accents.

Lerdahl and Jackendoff (1983) defined *Phenomenal*, *Structural* and *Metrical* accents. The Phenomenal accent is a local intensification, meaning intensity changes or changes in register, timbre, duration, or simultaneous note density. Structural accents are connected to the structure, e.g. a cadence arrival or departure in the music that causes the note to be perceived as accented. The metrical accent is perceived as accented because of its metrical location, its position within the measure.

In a number of studies on music performance, accented tones have been found to be played lengthened, legato (tied to the following note) and with increased loudness (see e.g. Gabrielsson, 1999, 1974; Drake and Palmer, 1993; Clarke, 1988). A study by Gabrielsson (1974) included rhythms performed on snare (side) drum, bongo drum, and piano. All of the rhythms on drums were played with the highest peak amplitude for the first sound event in the measure (metrical accent). This also applied to the rhythms played on a single note on the piano. The only exceptions were found for the rhythms with a notated accent, where the accent received higher or equally high peak amplitude.

Accents have also been studied in finger tapping experiments. Similar to music performance Billon et al. (1996) found that an accented finger tap was performed with higher force and longer contact duration. The inter-tap intervals were prolonged after, but shortened before, an accented tap. The movement times for an accented tap were shorter than for other taps, and were initiated from a higher position.

In drumming, one of the most commonly used features is to accent a stroke by increasing loudness and much time and effort is spent to master the technique.

1.4 The playing

In drumming, techniques are taught to facilitate the playing of strokes at different dynamic levels, particulary in snare drum playing. These techniques take advantage of the fact that a normal drumhead is elastic and therefore will, so to speak, 'send the stick back to where it came from'. The general method of beating a single stroke can be described as follows by Shivas in The Art of Tympanist and Drummer:

> “The actual stroke may be quite aptly likened to the action in cracking a whip. The tip of the stick is held about an inch above the drumhead and the stick is flicked *upwards* and then 'cracked' downwards till it strikes the head, which will, by its elasticity, throw the stick back

> again in an upward direction. The whole movement is made *as one* and as the stick is thrown back after striking the head it is so to speak caught and held steady to prevent a second and subsequent 'bounce' on the drum." [3] (Shivas, 1957)

The rebound of the stick can be both an advantage and a problem, depending on how loud the following stroke is to be played. Generally soft strokes will be played with the hand in a resting position 10-20 centimeters above the drumhead and the drumstick barely rising above it, *tapping*. Before a strong blow, the hand needs to lift the drumstick after the preceding tap. Here the rebound from the drumhead is a welcome assistance when the hand and drumstick need to rise to a higher position *upstroke* (or *pull-out*) from where the stroke is delivered. When strong strokes are repeatedly played the stick is usually allowed to bounce up to full height, *full* (or *free*) *stroke*. If the following stroke is to be a soft tap the stick must end up in the suitable lower position, *downstroke* (or *control stroke*).

These terms, tap, upstroke, downstroke, and full stroke, are commonly used to help the performer plan and carry out the right movements (see e.g. Moeller, 1956; Famularo, 1999). Using these basic strokes the player can execute sequential strokes of different heights. This is a prerequisite for playing various combinations of strokes at different dynamics, including accents. An example of their use for the playing of an accented stroke is shown in Figure 1, Paper I.

In a three-dimensional tracking of drumming movements, Trappe (1998) found differences between non-drummers, beginners, students and professional drummers. The motion patterns of the professionals were found to be flexible and whip-lash-like. The students showed similar patterns, but the calculated angles between segments (drumstick, hand, lower and upper arm) showed less control of the stick compared to the professionals. Compared to the drummers, the wrist movements of the non-drummers were stiffer and less flexible.

Acquiring relaxed and flexible movements is one of the main issues in learning drumming techniques. With a cramped grip the drumstick does not have enough freedom to move and accelerate. As a result the command 'Relax!' frequently occurs in instruction manuals.

[3] The subsequent 'bounce' is of essential use when playing fast rolls.

Chapter 2

Contributions of the present work

The three papers presented in this thesis take up (and partly overlap) four aspects of percussion performance: (1) The preparatory movements for unaccented and accented strokes in drumming, (2) the timing of single strokes involving accents, (3) the information on grouping inherent in the timing patterns, and (4) emotional expression through movement cues in performances on marimba.

2.1 The preparation of a stroke (Papers I and II)

Four percussion players' strategies for performing an accented stroke were studied. The main objective was to investigate what kind of movement strategies the players used when playing interleaved accented strokes, the hypothesis being that accented strokes would be initiated from a height greater than for unaccented strokes. Other questions addressed were whether there would be any differences in movement patterns or striking velocities depending on playing conditions; dynamic level, tempo, or striking surface.

Method. Three professional percussionists and one amateur played on a force plate with markers on the drumstick, hand, and lower and upper arm. The movements trajectories were recorded using a motion detection system (Selspot), tracking the displacement of the markers at 400 Hz. The rhythmic pattern - an ostinato with interleaved accents every fourth stroke - was performed at three dynamic levels (pp, mf, and ff), at three tempi (116, 160, and 200 beats per minute), and on three different striking surfaces on top of the force plate (soft, normal, and hard).

The analysis was concentrated on the vertical displacement of the drumstick at the initiation of a stroke, the *preparatory height*, and the vertical velocity before impact, the *striking velocity*. Both these measures were extracted from the vertical displacement of the marker on the drumstick.

The *metric location* of a stroke, that is, the position of the stroke in the measure was of special interest. The mean values were therefore calculated and presented with respect to the metric location.

Results. The analysis showed that the four players prepared for the accented stroke with their own movement strategies. The movements were maintained consistently within each player, but the movement trajectories differed considerably between players (see Figure 2.1). All subjects raised the stick to a greater height before the accented stroke. In Figure 2.2 the average preparatory height for the four subjects are seen. The figure shows how the players increased the preparatory heights with increasing dynamic level and in preparation for the accented stroke (beat No. 4).

The characteristics of the players' individual movement patterns were reflected in the striking velocities. The observed preparatory heights corresponded well to the striking velocities. The most influential condition on the movement patterns was the dynamic level, resulting in higher striking velocities at higher dynamic levels. When comparing the striking surfaces, the players tended to increase striking velocity when playing on the soft surface, but to decrease striking velocity for the hard surface.

Both the preparatory heights and the striking velocities showed that the main difference between the playing styles of the drummers was the emphasis on the accented stroke as compared to the unaccented stroke. For instance, players S1 and S2 produced similar average striking velocities for the unaccented strokes, but while S1 played the accented strokes on average with a velocity 1.5 times higher than for unaccented, the striking velocity for S2's accented stroke was almost five times that for unaccented.

Figure 2.3 shows a comparison between how players S1 and S2 emphasized the accented stroke compared to the unaccented, at different tempi and dynamic levels. The figure shows a linear plane fitted to the measured striking velocities for all unaccented strokes (stroke No. 2, bottom plane), and the accented strokes (stroke No. 4, top plane) for the two players performing on the normal surface. As illustrated by the different inclination of the planes in the figure, tempo and dynamic level have different influences on the players' emphasis on the accented strokes.

Discussion. The movement patterns of the players were clearly reflected in the striking velocities. It is likely that the differences between the players' movement strategies and emphasis on the accented beat compared to the unaccented beat could be related to the different backgrounds of the players. Player S1 and S3 are mainly active in the symphonic and military orchestral traditions, while S2 and S4

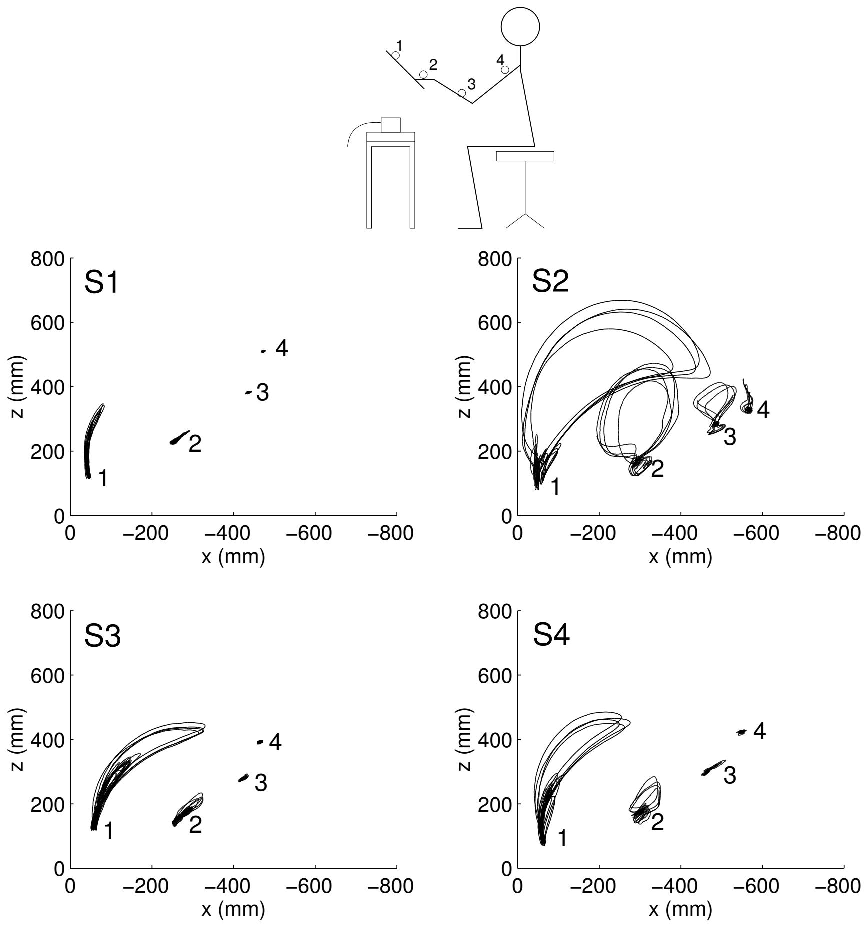

Figure 2.1. Movement trajectories captured from four markers: on the drumstick, and on the subjects' hand, lower, and upper arm. Side view from the players' left side; vertical direction (z-axis) vs. horizontal direction (x-axis). Subject S1 (top left), S2 (top right), S3 (bottom left), and S4 (bottom right). Each panel includes approximately four measures at mf, 200 BPM, played on the normal surface. The preparatory movements for the accented stroke can be seen as a larger loop compared to that of the unaccented strokes. The players' drumstick, hand lower and upper arm are involved to different extent in the movements.

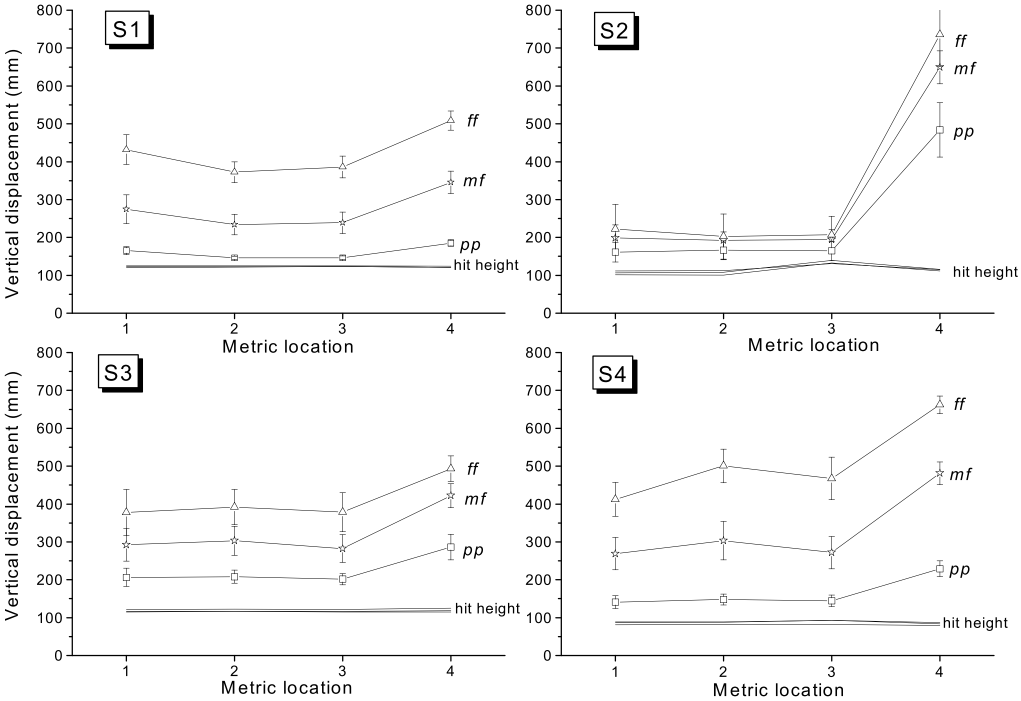

Figure 2.2. Average preparatory heights and hit heights for the four subjects playing on the normal surface. Each panel shows the preparatory height and hit height for the three dynamic levels (pp - mf - ff), averaged across each of the four metric locations. The error bars indicate standard deviations. The subjects increased the preparatory height with increasing dynamic level. The panels reflect the individual strategies of the subjects, shown in the movement trajectories (Figure 2.1).

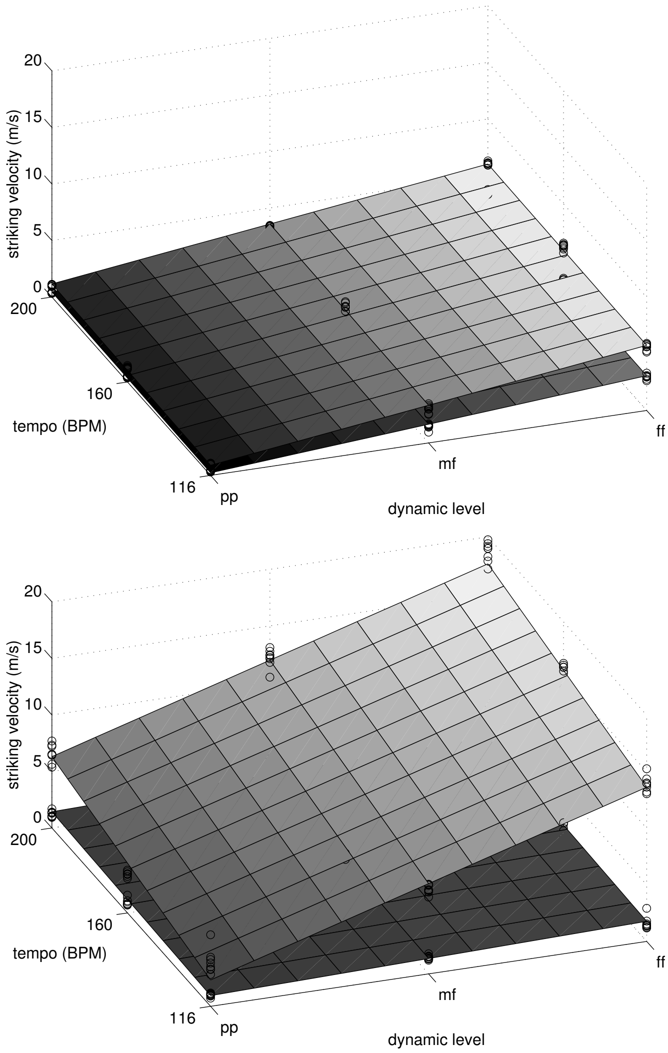

Figure 2.3. Striking velocities for player S1 (top panel) and S2 (bottom panel) playing at three tempi and three dynamic levels on the normal surface. The graphs show a linear plane fitted to the measured striking velocities for an unaccented stroke (stroke No. 2, bottom plane), and the accented strokes (stroke No. 4, top plane). The measured data points are indicated by circles. The fit of a linear plane to the data is not optimal, but made to simplify comparisons.

mainly play the drum set in the Afro-American music tradition. In orchestral playing, an accent, although emphasized, should not be *over* emphasized. In contrast, many genres using drum set playing often encourages large dynamic differences between accented and unaccented beats. In fact, unaccented notes are sometimes played as soft as possible; “ghost notes”.

2.2 The timing of strokes (Papers I and II)

With regard to the percussionist as time keeper, the timing of the strokes ought to be of special concern when studying playing strategies. If we hypothesize that one of the reasons for the preparatory movement prior to the accent is to deliver the accented stroke “on time” a natural question is how did the subjects perform in timing.

Method. The subjects and procedure were the same as described in the previous section (2.1). None of the subjects were informed that their timing performances would be analyzed.

The analysis concentrated on the strokes recorded by the force plate, and their separation in time, the *inter-onset intervals (IOI)*. Inter-onset interval number n is defined as the interval between stroke number n and $n+1$ The average IOI across a whole sequence is denoted by IOI_{avs} , and normalized IOIs as $\mathrm{IOI}_{rel} = \mathrm{IOI}/\mathrm{IOI}_{avs}$

Results. All subjects displayed both long-term changes in tempo (drift), and short-term variations between adjacent IOIs. Among the short-term variations, recurrent cyclic patterns could be observed. In general there was a lengthening of every fourth interval, i.e. the one beginning with the accented beat.

An example of the timing performance in one of the recorded sequences can be seen in Figure 2.4 (top sequence). The figure shows a tendency for intervals to be lengthened, when beginning with an accented stroke (marked with filled symbols). Which strokes that the players displaced in order to contribute to the lengthening differed. Subject S1 and S2 on average shortened the first two intervals and prolonged the last two, while subjects S3 and S4 on average shortened all the first three intervals and prolonged only the accented interval. The average lengthening across all subjects and playing conditions reached 3 %. The lengthening of the fourth interval frequently appeared in the form of cyclic patterns. The more pronounced cyclic patterns usually only appeared for three to four measures at a time (see for instance intervals No. 36-50, Figure 2.4).

Some of the recorded sequences showed a drift in tempo that was either increasing or decreasing (see Figure 4, Paper I). The drift was estimated as linear and typically amounted to 0.2 %/measure, or 0.05 %/interval, when normalized relative to the initial IOI of each 20 s sequence.

The standard deviations for the first 8 measures of all recorded sequences ranged from 2 % to about 7 % (normalized to the mean IOI across each sequence). The

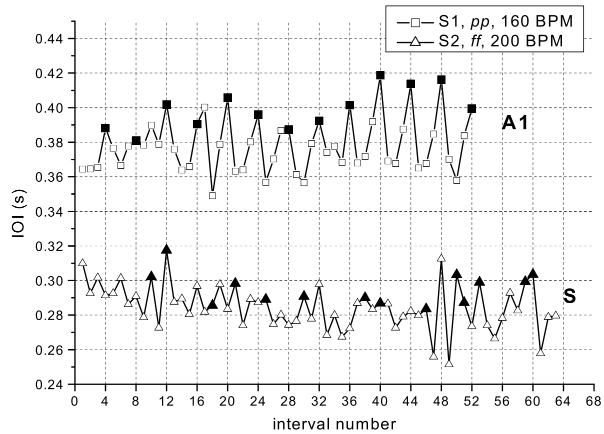

Figure 2.4. Example of timing performance for accents occurring regularly (top) and irregularly (bottom) in two sequences used in a listening test (see section 2.3). The accents are indicated by filled symbols. In sequence A1, (S1 pp, 160 BPM on the normal surface) cyclic patterns, with every fourth interval prolonged can be discerned, most clearly seen in the intervals No. 36-50. Sequence S (S2, ff, 200 BPM on the normal surface) is played with irregular accents.

spread in IOI compares rather well to that reported by Madison (2000), considering that the influence of the lengthening due to the accent in the rhythm is included. In general the standard deviations in IOI_{rel} decreased with increasing dynamic level. For some subjects also tempo had an influence on the spread in IOI_{rel}, with higher standard deviations at a higher tempo.

On average the differences between adjacent IOIs across sequences ranged between 10 and 14 ms. Occasionally these differences were substantial. In the topmost sequence in Figure 4, Paper I, the difference between successive intervals reached 65 ms, or 12 % of the associated tempo.

Discussion. The tendency for lengthening every fourth interval, the accented note, was evident for all four players. It is worth noting that it is not the interval involving the preparatory movement before the accented stroke that is prolonged, but the following interval. Although the preparatory movements used for the accented strokes are larger (sometimes much larger, like when player S2 involved the whole arm), the accented stroke arrives on time. It is the following stroke (the first stroke in the next measure) that is delayed. The lengthening not only emphasizes the accent, but also allows the oscillations of the rebounding stick to decay. Recurrent cyclic patterns could be discerned in the timing data, but usually only appeared for three to four measures.

2.3 Grouping based on timing information (Paper I)

The appearance of the lengthened fourth intervals in cyclic patterns was seldom maintained throughout a whole 20 s recording. The question thus emerged whether these patterns still could convey some information on the grouping of strokes to listeners. To resolve this question a listening test, including modified and synthesized sequences, was set up.

Method. Four of the recorded sequences with an interleaved accent were used in the test (sequence A1 is shown in Figure 2.4, top, A2, A3, and A4 in Figure 7, Paper I). A performance where irregular accents were played (sequence S in Figure 2.4, bottom) was also included. All sequences were notated in 4/4 measure.

In order to isolate the timing aspects of the recorded sequences, the original strokes were replaced with a standardized stroke. The measured IOIs for the recordings were used as timing templates and a recorded stroke was repeatedly pasted in. In this way differences in striking force between strokes and overall dynamic level were removed, leaving only timing information.

In addition to the stimuli based on the recordings, two fully artificial files were synthesized; one completely isochronous (sequence I), and one with every third interval prolonged by 7 % (sequence W). A detailed description of the seven stimuli used in the test can be found in Paper I, Table 1.

Two groups of listeners participated in the listening test: 10 professional percussionists or advanced students ("percussionists"), and 10 listeners without any musical training ("novices"). The listeners were asked to sort the stimuli sequences according to the perceived grouping of strokes; groups of 2, 3, and 4 strokes, or no grouping at all. When sorting the stimuli, listeners could also indicate how confident they were in their sorting.

The expected result was that sequences originating from the recorded accented 4/4 rhythm (A1, A2, A3, and A4) would be perceived as groups of four strokes, that the synthesized sequence W would be perceived as groups of three strokes, and that sequences without pronounced cyclic patterns (S and I) would be perceived as no grouping.

Results. In general the listeners sorted the stimuli as had been expected (see Table 2 and 3, Paper I). Sequence A3 was repeatedly placed in the 4 group (93 % of times by percussionists and 77 % by novices). By contrast, sequence A4, was placed in the 4 group as well as in the 2 group. The differences reflect the cyclic patterns that can be discerned in the sequences. While every fourth interval in A3 is clearly and consistently prolonged throughout the sequence, A4 displays two kinds of cyclic patterns: prolongation of every fourth interval (intervals No. 1-16), or every other interval (No. 24-32).

Figure 2.5 show the percussionists' (top) and the novices' (bottom) ratings in their placements. The figure shows the mean ratings for the seven stimuli files in each category. The 95 % confidence intervals are indicated by vertical error bars. The listeners' ratings follow the relative occurrences of placements well, but with somewhat lower values. The percussionists seem more confident in their placements than the novices.

Discussion. Sequence A3, with the most persistently maintained cyclic pattern was placed in the 4 group with the highest occurrence and confidence in the listening test. However, it does not seem to be necessary for the players to consistently maintain the patterns throughout the 20 seconds in order to convey grouping to listeners. Also sequences A1, A2, and A4 were repeatedly placed in the same group, although the two latter also appeared in other groups – quite in line with the timing patterns. An unexpected result was that the fully artificial sequences I and W were sorted into the "wrong" category to some extent. Even the percussionists repeatedly placed the artificial sequences in categories other than what was expected.

2.4 The perception of players' movements (Paper III)

The communication of expressive intentions through movements in performances on the marimba was investigated. The objective was to explore (1) to what extent the movements conveyed the intended emotions, (2) if certain parts of the player's body were more important than others in the communication, and (3) what movement cues were used by observers to discriminate between expressions.

Method. A professional percussionist was video recorded when performing a short piece of music with the intentions Sadness, Anger, Happiness and Fear. From the video recordings, stimuli clips were generated showing different parts of the player in four *viewing conditions*: *full* (showing the full image), *no-hands* (the player's hands not visible), *torso* (the player's hands and head not visible), and *head* (only the player's head visible). The clips were shown without sound, and edited so that facial expressions would not be visible.

Twenty subjects watched the videos individually and rated the emotional content on a scale from 0 (nothing) to 6 (very much) for the emotions Fear, Anger, Happiness, and Sadness. The subjects were also asked to mark how they perceived the movements. The ratings were done on bipolar scales (from 0 to 6) for the cues:

Amount:	none	-	large
Speed:	fast	-	slow
Fluency:	jerky	-	smooth
Distribution:	uneven	-	even

Results. The ratings for the emotions showed that the intentions Sadness, Happiness, and Anger were successfully conveyed, while Fear was not (see Figure 2, Paper

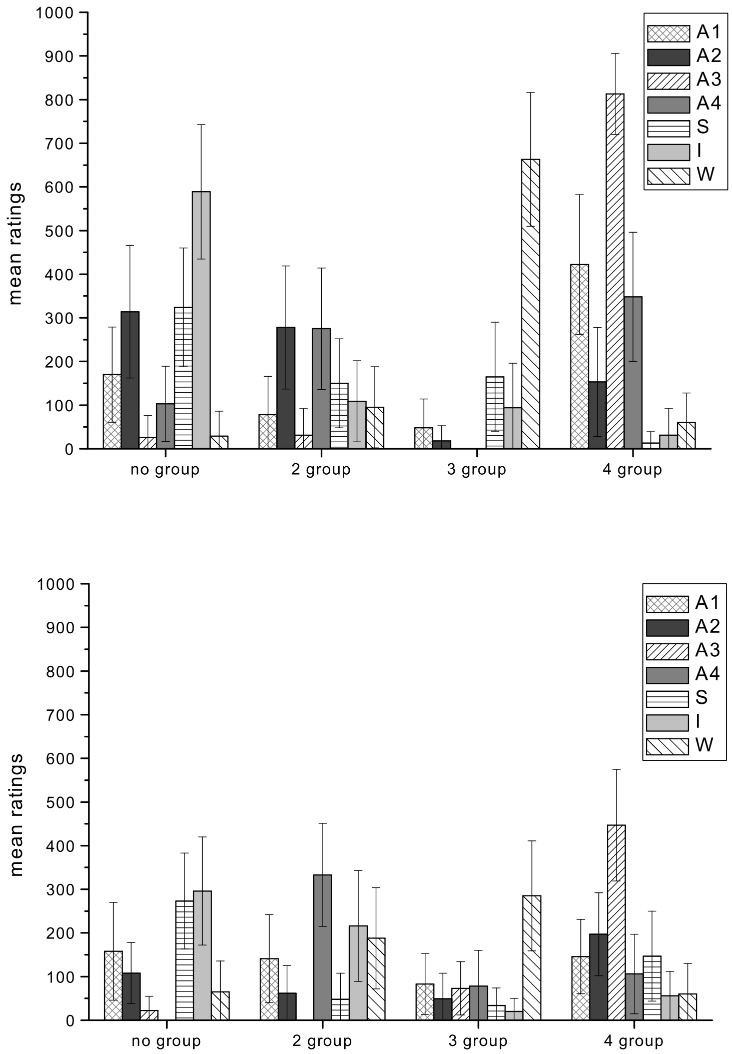

Figure 2.5. Mean ratings for the ten percussionists (top) and ten novices (bottom) in the listening test. For each of the seven stimuli (A1-A4, S, I, and W) the mean ratings for the four possible responses (no group, 2, 3, or 4 group) are shown by bars. A value of 1000 would correspond to a case in which all 10 subjects were fully confident on their placement of the sequence in one category. The vertical error bars indicate the 95 % confidence intervals.

III). The influence of viewing condition proved to be surprisingly small. However, whether the head of the player was visible or not seemed to play a key role in some cases. The Sad intention received the highest correct identification in terms of sadness ratings. For this intention all the conditions where the head was visible were rated high (means from 4.3 to 4.6), while the torso received much lower ratings (mean 3.1). The low torso ratings appeared in both performances of the Sad intention.

The ratings for movement cues showed that for the three recognized emotions Sadness, Anger, and Happiness, there were movement cues similar to audio cues found for music performances. Anger was characterized by large, fast, uneven, and jerky movements; Happiness with large and somewhat fast movements, and Sadness with small, slow, even, and smooth movements.

Discussion. The influence of viewing condition on the observers' ability to recognize the intentions was surprisingly small. In the cases where there was an effect of viewing condition, the main differences in ratings were either the head or the torso conditions. For the Sad intention, the viewing condition 'head' was actually identified as Sad to a higher degree than was the 'full' condition. One explanation for this surprising observation could be that the actual playing movements of the hands and arms had a distracting effect on the body language visible with regard to the head. Some support for this can be found in an earlier study. Davidson (1994) measured the head and hand movements of a pianist performing the same piece as "deadpan", "projected", and "exaggerated". She found that the extent of head movements differed significantly between performance conditions, while the extent of the hand movements was about the same.

Interestingly a marimba player clearly does not *have* to move in different ways between performances with different intentions – then why do it? A tempting answer is that these movements facilitate the interpretation of different moods in some way. A possible support for this hypothesis is that the movement cues, as rated by the observers in the viewing test, indeed show strong similarities to the acoustic cues used for the same emotions in music performances. Another, more straightforward, explanation is that the player, entering the mood she is trying to convey, moved accordingly. The movement cues that were used by the marimba player resemble the cues that children used to portray different emotions in a study by Boone and Cunningham (2001). For instance, reportedly the children used more force and rotation when portraying Happiness and Anger than they did for Sadness and Fear.

2.5 Summary and conclusions

The papers in this thesis deal with mainly two aspects of percussion performance: first the execution and interpretation of a single musical element (the accent), and second, the interpretation and communication of specific emotional intentions.

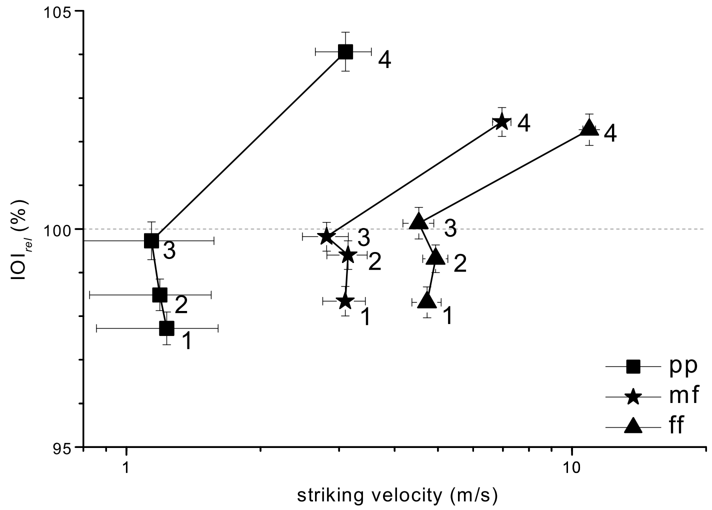

Figure 2.6. The relation between striking velocity and IOI_{rel} for the different metric locations and dynamic levels. The figure shows the grand average for the metric locations (numbered 1, 2, 3, and 4), at pp (squares), mf (stars) and ff (triangles), across all subjects and playing conditions. Each data point represents 288 analyzed strokes. The 95 % confidence intervals are indicated by error bars. As seen in the figure, the increase in striking velocity for the accented stroke is by about a factor of 2 for all the dynamic levels. The lengthening in IOI_{rel}, however decreases with increasing dynamic level.

While the first aspect deals with a structural element on the micro-level, the latter focuses on high-level performance characteristics. A common aspect, however, is the need for the player to execute the correct movement at the right moment in time.

The accent receives a lot of attention in percussion training, although it is a simple element in music. From the results presented in Papers I and II it is clear that the players have acquired a playing technique that allows them to produce an accent at the right time. However, it is also clear that players interpret the accent very differently. A possible explanation for the different performances can be sought in the musical context the players are used to performing in (symphonic orchestras, military bands, and jazz and rock bands). Despite the differences in playing styles there are some common features. First, the accented stroke was always initiated from a greater height, which was in direct correspondence with the striking velocity for the stroke. Second, the interval beginning with the accented stroke was prolonged, primarily by delaying the following stroke. Figure 2.6 illustrates the impact of the accent on striking velocity and IOI_{rel}. The figure, in which each data point is averaged across 288 strokes, shows the average IOI_{rel} vs striking velocity for each metric location and dynamic level.

The aspects on a higher performance level addressed in Paper III concern how different parts of the body contribute to conveying a specific emotional intention to an observer. The movement cues used by observers to distinguish performances with different emotional intentions from each other have clear similarities to the audio cues found in music performances. Interestingly enough there were only small differences between the viewing conditions, both for the ratings of emotions and for the ratings of movement cues. In the cases where one viewing condition received significantly different ratings than the others that viewing condition was either the torso or the head. The results from this study suggest that the head is especially important for conveying the intended emotion.

In summary, the papers in this thesis show that percussion players follow well-defined strategies in their performance of an interleaved accent. Furthermore, body language alone may serve as an efficient way of communicating different emotional intents.

2.6 Acknowledgements

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This is not the end of the story, hopefully there will be another thesis coming up and I expect to fill pages with the many dear persons around me that I haven't thanked properly here. Still, there are some people that have to be mentioned, simply because without your support and aid the past years I would not be here to write this. I think you know why. **Tack för att ni finns**

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Giampi
♡

Bibliography

Abernethy, B., Kippers, V., MacKinnon, L. T., Neal, R. J., and Hanrahan, S. (1997). *The biophysical foundations of human movement.* Champaign, Ill.:Human Kinetics.

Behrens, G. A. and Green, S. B. (1993). The ability to identify emotional content of solo improvisations performed vodally and on three different instruments. *Psychology of Music*, 21:20–33.

Billon, M., Semjen, A., and Stelmach, G. E. (1996). The timing effects of accent production in finger-tapping sequences. *Journal of Motor Behaviour*, 28:198–210.

Boone, R. T. and Cunningham, J. G. (2001). Children's expression of emotional meaning in music through expressive body movement. *Journal of Nonverbal Behavior*, 25(1).

Clarke, E. F. (1988). Generative principles in music performance. In Sloboda, J. A., editor, *Generative processes in music*, pages 1–26. Oxford: Clardendon Press.

Cooper, G. and Meyer, L. B. (1963). *The Rhythmic Structure of Music.* University of Chicago Press.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed skill. *Ergonomics*, 2:154–165.

Davidson, J. W. (1994). What type of information is conveyed in the body movements of solo musician performers? *Journal of Human Movement Studies*, 6:279–301.

Davidson, J. W. and Correia, J. S. (2002). Body movement. In Parncutt, R. and McPherson, G. E., editors, *The science and psychology of music performance. Creative strategies for teaching and learning.*, pages 237–250. Oxford University Press.

Deutsch, D., editor (1999). *The Psychology of Music.* Academic Press, 2nd edition.

Dittrich, W. H., Troscianko, T., Lea, S. E., and Morgan, D. (1996). Perception of emotion from dynamic point-light displays represented in dance. *Perception*, 6:727–738.

Drake, C. and Botte, M.-C. (1993). Tempo sensitivity in auditory sequences: Evidence for a multiple-look model. *Perception & Psychophysics*, 54(3):277–286.

Drake, C. and Palmer, C. (1993). Accent structures in music performance. *Music Perception*, 10:343–378.

Famularo, D. (1999). *It's Your Move. Motions and Emotions.* Warner Bros. Publications.

Fitts, P. M. and Posner, M. I. (1967). *Human performance.* Belmont, California: Brooks/Cole.

Friberg, A. and Battel, U. (2002). Structural communication. In Parncutt, R. and McPherson, G. E., editors, *The science and psychology of music performance. Creative strategies for teaching and learning.*, pages 199–218. Oxford University Press.

Friberg, A. and Sundberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *J. Acoust. Soc. Amer.*, 98(5):2524–2531.

Friberg, A. and Sundström, A. (2002). Swing ratios and ensamble timing in jazz performance: Evidence for a common rhythmic pattern. *Music Perception*, 19(3):333–349.

Gabrielsson, A. (1974). Performance of rhythm patterns. *Scandinavian Journal of Psychology*, 15:63–72.

Gabrielsson, A. (1999). The performance of music. In Deutsch, D., editor, *The Psychology of music*, pages 501–602. Academic Press.

Gabrielsson, A. and Juslin, P. N. (1996). Emotional expression in music performance: Between the performer's intention and the listener's experience. *Psychology of Music*, 24:68–91.

Guettler, K. (1992). Electromyography and Muscle Activities in Double Bass Playing. *Music Perception*, 9(3):303–310.

Hart, M. and Stevens, J. (1990). *Drumming at the edge of magic.* Harper San Francisco.

Juslin, P. N. (1997). Perceived emotional expression in synthesized performances of a short melody: Capturing the listener's judgment policy. *Musicae Scientiae*, 1:225–256.

Juslin, P. N. (2000). Cue utilization in communication of emotion in music performance: Relating performance to perception. *Journal of Experimental Psychology: Human Perception and Performance*, 26(6):1797–1813.

Juslin, P. N. (2001). Communicating emotion in music performance: A review and theoretical framework. In Juslin, P. and Sloboda, J. A., editors, *Music and Emotion*, pages 309–337. Oxford University Press.

Juslin, P. N., Friberg, A., and Bresin, R. (2002). Toward a computational model of expression in performance: The germ model. *Musicae Scientiae*, (Special issue 2001-2002):63–122.

Juslin, P. N. and Madison, G. (1999). The role of timing patterns in recognition of emotional expression from musical performance. *Music Perception*, 17:197–221.

Juslin, P. N. and Sloboda, J. A., editors (2001). *Music and Emotion*. Oxford University Press.

Kaladjev, S. (2000). *Ergonomi i musikutbildningen. Ergonomiska och kognitiva aspekter på instrumentalspel.* Published doctoral dissertation, Kungliga Musikhögskolan i Stockholm.

Laukka, P. and Gabrielsson, A. (2000). Emotional expression in drumming performance. *Psychology of Music*, 28:181–189.

Lerdahl, F. and Jackendoff, R. (1983). *A Generative Theory of Tonal Music*. MIT Press, Massachusetts Institute of Technology, Cambridge, Massachusetts 02142, 1st edition.

Madison, G. (2000). Rhythm perception and production. In Desain, P. and Windsor, L., editors, *On the nature of veriability in isochronous serial interval production*, pages 95–113. Lisse: Swets and Zeitlinger.

Madison, G. (2001a). *Functional Modelling of the Human Timing Mechanism*. Published doctoral dissertation, Uppsala University, Sweden.

Madison, G. (2001b). Variability in isochronous tapping: Higher order dependencies as a function of intertap interval. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2):411–422.

Michon, J. A. (1967). *Timing in temporal tracking*. Assen, the Netherlands: Van Gorcum.

Moeller, S. A. (1956). *The Moeller book*. Ludwig Music Publishing Co.

Parncutt, R. (In press). Accents and expression in piano performance. In *Systemische Musikwissenschaft. Festschrift Jobst P. Fricke zum 65. Geburtstag*. Frankfurt:Peter Lang.

Paterson, H. M., Pollick, F. E., and Sanford, A. J. (2001). The role of velocity in affect discrimination. In *Proc. of the Twenty-Third Annual Conference of the Cognitive Science Society, Edingburgh*, pages 756–761.

Pollick, F. E., Paterson, H. M., Bruderlin, A., and Sanford, A. J. (2001). Perceiving affect from arm movement. *Cognition*, 82(2):B51–B61.

Repp, B. (1992). Diversity and commonality in music performance: An analysis of timing microstructure in schumann's "Träumerei". *Journal of Acoustical Society of America*, 92:2546–2568.

Shivas, A. A. (1957). *The art of the tympanist and drummer.* London: Dobson Books.

Trappe, W. (1998). 3-d measurement of cyclic motion patterns in drummers with different skill. In *Proc. of the Fifth International Symposium on the 3-D Analysis of Human Movement.*, pages 97–99, Chattanooga: Tennessee.

Walk, R. D. and Homan, C. P. (1984). Emotion and dance in dynamic light displays. *Bulletin of Psychonomic Society*, 22:437–440.

Wanderley, M. M. (2002). Quantitative analysis of non-obvious performer gestures. In Wachsmuth, I. and Sowa, T., editors, *Gesture and Sign Language in Human-Computer Interaction*, pages 241–253. April, Springer Verlag.

Wickstrom, R. L. (1983). *Fundamental Motor Patterns.* Lea & Febiger, Philadelphia, 3rd edition.

Wickstrom, R. L. (1990). *Biomechanics and Motor Control of Human Movement.* New York: John Wiley & Sons, 2nd edition.

Wing, A. M. and Kristofferson, A. B. (1973). The timing of interresponse intervals. *Perception & Psychophysics*, 13(3):455–460.

Winold, H. U. (1984). High speed photography of cello playing. In Roehmann, F. L. and Wilson, F. R., editors, *The Biology of Music Making*, pages 180–182. Proceedings of the 1984 Denver Conference.

Part II

The papers