Chapter 1

General introduction
Introduction

When people listen to music, they often wiggle or tap in synchrony with the musical beat. Soldiers march to music and dancers swing to it. This so-called auditory-motor synchronization has long been thought to be specific for humans only (Patel et al., 2005). Recently, however, Nature news (Ball, 2008) reported that Snowball – a famous YouTube cockatoo\(^1\) – boogied on Backstreet Boys’ *Everybody*. Interestingly, Snowball also rocked to Queen’s *Another one bites the dust*\(^2\) and even adjusted his bopping to match variations in the speed or tempo of the music (i.e., *Everybody* at 106, 125, and 130 beats per minute\(^3\); Patel et al., in press). In sports, the beat and tempo of the music often also set the pace for spinning and aerobics while in running stride frequency and respiration may become synchronized to the musical meter. Beneficial effects of a strong musical beat have been demonstrated in sports (e.g., Simpson & Karageorghis, 2006), with one of the clearest anecdotic examples being the indoor 2000m World record by the Ethiopian athlete Haile Gebreselassie – the current World-record holder of the marathon – in Birmingham 1998, synchronizing his running pace to the fast beat of *Scatman*, a rhythmic song by the late American performer Scatman John.

---

\(^1\) http://www.youtube.com/watch?v=N7IZmRnAo6s
\(^2\) http://www.youtube.com/watch?v=cJOzZ2ZfdCw
\(^3\) See http://www.nature.com/nature/newsvideo/Snowball_106_BPM.mov, */Snowball_125_BPM.mov, and */Snowball_130_BPM.mov, respectively.
Sensorimotor synchronization

The aforementioned examples have in common that bodily rhythmic movements become synchronized with external acoustic rhythms. In general, synchronization can be regarded as “an adjustment of rhythms of oscillating objects due to their weak interaction” (Pikovsky et al., 2003). If two non-identical oscillators (e.g., Gebreselassie’s running and Scatman’s beat) having their own frequencies $f_1$ and $f_2$ are coupled together, they may start to oscillate at a common frequency. Whether synchronization actually occurs depends on the strength of the interaction between two oscillators (coupling strength) and the initial frequency mismatch between them (frequency detuning, $\Delta f = f_2 - f_1$).

Synchronization of movements to external acoustic rhythms can be defined as auditory-motor synchronization. In acoustically paced walking, running, or bopping, both the actor and the acoustic stimuli are oscillators capable of generating their own rhythms. When put together, the actor may adjust his or her own cadence or boppi ng rate (within a certain range of frequency detuning) to the beats per minute set by the acoustic rhythm (e.g., Arias & Cudeiro, 2008; Howe et al., 2003; McIntosh et al., 1997; Patel et al., in press; Styns et al., 2007). In auditory-motor synchronization, the interaction or coupling is informational (i.e., acoustic stimuli are picked up by the actor’s auditory system) and unidirectional in nature because only the movement rate can be adjusted to changes in beats per minute of the acoustic rhythm but not vice versa.

Synchronization of bodily movements is not limited to external acoustic rhythms but has also been observed with external rhythms of visual (e.g., Huys et al., 2005; Lee & Thomson, 1982; Peper & Beek, 1998; van Wegen et al., 2006a; Wimmers et al., 1992) and haptic/kinesthetic (e.g., Ridderikhoff et al., 2005; van Wegen et al., 2006b) modality. In general, one speaks of sensorimotor synchronization to indicate synchronization with external rhythms of any modality4. Given the ubiquity of sensorimotor synchronization, perhaps the

---

4 Although the focus of the present thesis is on unidirectionally coupled sensorimotor synchronization, it is important to realize that sensorimotor synchronization may also occur under bidirectional coupling, that is, in situations where both oscillators can adjust their movements to each other (cf. Schmidt et al., 1990). An example of gait synchronization with a bidirectional coupling was recently reported by van Ulzen and colleagues (2008) who studied the coordination between two walkers with different preferred cadences walking side-by-side. Synchronization was observed by cadence adjustments of both walkers. Note that the coupling in side-by-side walking is also informational, being of auditory (sounds corresponding to footfalls) or visual (motion of the legs) modality. The coupling can also be “mechanical” in case the two walkers are physically coupled, for example, in walking while holding hands (see also Zivotofsky & Hausdorff, 2007).
question is not so much whether bodily rhythms may become synchronized to external rhythms, but rather

i) How are rhythmic movements coordinated with external rhythms? and

ii) How can these external rhythms be optimally exploited or utilized to enhance the execution of rhythmic movements?

The work presented in this thesis addresses these broad questions and derivatives thereof. The first, more fundamental question requires an in-depth examination of task-specific perceptual information used in the control of sensorimotor synchronization. Answering this question is important for well-motivated and theory-driven implementations of external rhythmic stimuli in applied settings, such as sports, physical therapy, and rehabilitation. The second, more applied question is, in part, inspired by clinical practice, where rhythmic acoustic stimuli proved beneficial for pathological gait of patients with stroke, Parkinson’s disease, Huntington’s disease, and cerebral palsy (see Thaut, 2008 for a state-of-the-art overview). Nonetheless, how those rhythms are best applied, and why, remain open questions. For successful clinical applications, it is necessary to translate the results of basic research and basic insights to clinical research and settings.

**Translational approach**

Translational research is currently booming, yet it means different things to different people (Woolf, 2008). For many, translational research refers to the bench-to-bedside enterprise: “Effective translation of the new knowledge, mechanisms, and techniques generated by advances in basic science research into new approaches for prevention, diagnosis, and treatments of disease is essential for improving health” (Fontanarosa & DeAngelis, 2002). A typical endpoint for this area of research is a demonstration of the clinical effect of a promising new treatment, adhering to the strict criteria for clinical evidence (e.g., randomized clinical trials). This branch of translational research has been labeled T1 (Sung et al., 2003). For others, translational research refers to translating research into practice: in this case, the clinical effect of a certain treatment is only the starting point and research is aimed at ensuring that new treatments and research knowledge actually reach the patients or populations for
whom they are intended, using indices of health care and health as primary outcome measures. This branch of translational research has been labeled T2 (Sung et al., 2003).

In the Research Institute MOVE of VU University Amsterdam, where the research presented in this thesis was conducted, the notion of translational research is interpreted as an integrative research approach aimed at a bidirectional integration (or translation) of fundamental and applied knowledge at different levels of analyses and across different disciplines. According to their annual report, MOVE emphasizes translational research in which i) clinical implications of fundamental scientific findings and insights are sought, and ii) clinical practice guides and inspires basic research. This is reminiscent of the processes implied by T1 research where basic scientists provide clinicians with new tools for use in patients and clinicians make novel observations stimulating or calling for basic investigations. It is also consistent with the definition employed by the Dutch Advisory Council on Health Research (‘Raad voor Gezondheidsonderzoek’; Dutch acronym: RGO), which considers “translational research as a phase in the knowledge chain. It comprises all steps from the identification of possible leads (in patients or patient material) for diagnostics, prevention or treatment, up and including early application in clinical practice. Research questions may originate from clinical practice as well as from the laboratory” (RGO, 2007).

This thesis follows this bidirectional integrative translational research approach by aiming to understand how bodily movements are coordinated with external rhythms and how those rhythms can be exploited to enhance impaired movements. This endeavor was inspired by the clinical observation that external rhythms (or rhythmic cueing, cf. Nieuwboer et al., 2007 for a definition) can be used to improve the execution of impaired movements (e.g., Lim et al., 2005; Nieuwboer et al., 2007; Thaut, 2008; Thaut et al., 1993, 1997, 2007; van Peppen et al., 2004; Whitall et al., 2000).

In the first part of the thesis, a basic understanding of rhythmic sensorimotor synchronization is gained centered around the notion of anchoring, to be introduced in the next section. In the second part, this understanding, and corresponding findings and (laboratory) methods, is translated to gait rehabilitation practice. The purpose of this ‘move from theory to therapy’ is not only to assess the effects of external rhythms on various aspects of impaired gait, but also to better understand how impaired gait is adjusted to those external rhythms.
rhythms and possible (individual) deviations therein. Although this type of research does not satisfy the strict criteria for clinical evidence, the so-obtained insights are deemed important for streamlining future effect studies in terms of formulating inclusion/exclusion criteria, constraining intervention parameters, optimizing its apparatus or protocol, et cetera. It may be seen as an important first stride in improving the outcome, validity, and efficacy of the far more costly and time-consuming randomized clinical trials, establishing the desired clinical evidence (T1 endpoint), and determining the feasibility and limitations of a given intervention in rehabilitation practice (an important T2 constraint).

**Anchoring**

A central aspect in the basic understanding of rhythmic sensorimotor synchronization is to unravel which sensory information is used in synchronizing motor events. The notion of anchoring seems particularly well-suited to address this issue given that this type of information is often of a discrete nature, such as the beats of a metronome. In his study of the dynamics of juggling, Beek (1989) suggested that rhythmic movements are often organized around certain spatial locations serving as intentional attractors or organizing centers within and for the movement cycle. That is, by timing or consistently orienting the movement to particular points in the movement cycle, the cyclical activity as a whole is timed. Such control points in the movement cycle are called anchor points (Beek, 1989; Carson et al., 1994), which are often characterized, and hence identifiable, by a local reduction of variability in the movement cycle (Beek, 1989; Byblow et al., 1994, 1995; Carson et al., 1994; Fink et al., 2000; Maslovat et al., 2006). Beek (1989) conjectured that at, or around, anchor points critical task-specific information is available for organizing a cyclic act.

According to this conjecture, manifestations of anchoring in movement trajectories may thus hint at points or regions in the sensorimotor-synchronization workspace where the actual synchronization or control takes place. Sometimes such manifestations are trivial, for example, when participants are instructed to tap to the beat of a metronome. In this case, it is obvious that the actual tap will be synchronized with recurring metronome beats, serving as the anchor or control point for the movement cycle (cf. Peper et al., 1995). Both
the movement and the external rhythm are then composed of discrete events (taps and beats, respectively).

At other times, however, rhythmic sensorimotor synchronization and concomitant control or anchor points are less trivial. On the one hand, the rhythmic movements may be produced in a more continuous or harmonic manner, such as for rhythmic wrist oscillations or circle drawing. On the other hand, the external rhythm may be more complex (e.g., music) or presented in a continuous manner (e.g., an oscillating light display). In this case, rhythmic movements and external rhythms are not composed of a series of salient recurring discrete events rendering it less obvious how sensorimotor synchronization is instantiated. Here local compressions of variability in the movement cycle may reflect control or anchor points (Beek, 1989; Byblow et al., 1994, 1995; Carson et al., 1994; Fink et al., 2000; Maslovat et al., 2006) and contain clues, in relation to concurrent aspects of the external rhythm, regarding the task-specific information used for sensorimotor synchronization.

It is important to stress at this point that anchoring can also occur without external pacing (Beek, 1989; Byblow et al., 1994). Anchoring basically implies that rhythmic movements are consistently oriented at a particular point in the movement cycle. In other words, the movements become discretized. In this sense, intentionally emphasizing or accentuating a specific aspect of the movement cycle may thus also lead to local reductions of trajectory variability, irrespective of whether it is synchronized to an external rhythm. This illustrates that there may be other factors or constraints besides information pickup that determine or evoke anchoring phenomena, such as intentional constraints. Also mechanical constraints may lead to anchoring. Sometimes those mechanical constraints are immediately evident, such as physical contact with a surface in tapping. In other cases, the influence of mechanical factors is more covert, such as when gravitational aspects interact with movement production, or when movement execution is influenced by viscoelastic joint properties, movement rate, or amplitude (see e.g., Esposti et al., 2005, 2007). All these factors may induce local compressions of movement variability and potentially hamper interpretation as points where task-specific information is available.

What has been lacking so far in this line of research are systematic, well-controlled investigations of the factors influencing anchoring behavior. As a consequence, the notion of anchoring is still more descriptive than explanatory, despite its face validity. As it stands, the crux of this approach – using signatures
of anchoring to identify the information used in task execution – has not been rigorously tested and systematically investigated. The work presented in this thesis aims to fill this lacuna and to deepen, in so doing, the understanding of anchoring such that successful clinical applications come into reach.

**Coordination dynamics and pattern stability**

The notion of anchoring arose and was elaborated further in the dynamical systems approach to rhythmic coordination, also called coordination dynamics (e.g., Beek et al., 1995; Haken et al., 1985; Kelso, 1995; Kugler et al., 1980; Scholz, 1990). This approach offers a generic theoretical framework and accompanying tools to investigate sensorimotor synchronization in a broad variety of tasks. In particular, coordination dynamics provides an expedient means for studying the stability properties of rhythmic coordination in all its manifestations, including bimanual finger and hand movements (Haken et al., 1985; Kelso et al., 1984; Yamanishi et al., 1980), pendulum swinging (Kugler & Turvey, 1987), juggling (Beek, 1989), visuomotor tracking (Wimmers et al., 1992), tapping (Peper, 1995), bimanual circle drawing (Carson et al., 1997) or crank circling (de Poel et al., in press), hula-hooping (Balasubramaniam & Turvey, 2004), playground swinging (Post et al., 2007), and interpersonal coordination (Schmidt et al., 1990). The coordination dynamics framework was also successfully translated to study intersegmental coordination in the gait of stroke patients (Kwakkel & Wagenaar, 2002; Wagenaar & Beek, 1992), prosthetic patients (Donker & Beek, 2002), and patients with chronic low back pain (Lamoth, 2004).

In terms of empirical and theoretical development, rhythmic interlimb coordination constitutes the core subject of coordination dynamics. The seminal studies of phase transitions in finger and hand movements by Kelso and colleagues (Haken et al., 1985; Kelso, 1981; Kelso et al., 1984) have shown that only two bimanual coordination patterns can be stably performed with limited practice. One is the in-phase coordination pattern, where both limbs flex and extend together and the other is the antiphase pattern, where the limbs flex and extend alternately (for a different position, see Mechsner & Knoblich, 2004). The coordination is characterized by means of the relative phase between the limbs, being around 0° and 180° for in-phase and antiphase coordination, respectively. The stability of those coordination patterns can be assessed by
quantifying the variability of the phase relation (Kelso et al., 1984; Post et al., 2000; Schöner et al., 1986). Alternatively, pattern stability can be probed by perturbing the phase relation between the limbs (de Poel et al., 2007; Post et al., 2000) or by increasing the frequency of oscillations (Kelso, 1981; Kelso et al., 1984; Yamanishi et al., 1980). Antiphase coordination is generally less stable than in-phase coordination (Haken et al., 1985; Kelso et al., 1984; Yamanishi et al., 1980), as evidenced by higher relative phase variability, longer recovery to restore coordination following perturbations, and transitions to in-phase coordination when movement frequency is increased.

In studies of bimanual coordination, pattern stability is often probed by gradually increasing the frequency of a metronome setting the pace for movement production. The influence of this metronome on the execution of bimanual patterns is often neglected or underestimated (cf. Byblow et al., 1994; Fink et al., 2000; Jirsa et al., 2000, for notable exceptions) despite findings of systematic local and global effects of these external stimuli on movement coordination. Byblow and colleagues (1994), for example, observed metronome-related local adjustments of specific events in the bimanual supination-pronation cycle, i.e., manifestations of anchoring, affecting the stability of bimanual coordination (see also Cabaj et al., 2008; Carson et al., 2000). Fink and colleagues (2000) found that antiphase flexion-extension movements between index fingers of both hands could be maintained longer under double than single metronome pacing (i.e., pacing both reversal points in the movement cycle as opposed to one). The latter finding indicates that bimanual coordination can be stabilized by means of external rhythms, which is an important insight in light of the second question to be addressed in this thesis, i.e., how can external rhythms be best used to enhance motor performance? Furthermore, the findings highlight that the external rhythms are, literally speaking, not external but interfere with the dynamics of bimanual coordination. This is in itself not surprising given that similar differential stability features were observed\(^5\) for unimanual movements that were explicitly coordinated with external stimuli, such as in auditory-motor coordination (Kelso et al., 1990) and rhythmic visuomotor tracking (Byblow et al., 1995; Wimmers et al., 1992).

Note, however, that when rhythmic bimanual movements are paced by external stimuli, the focus should not only be on the stability of interlimb coordination, as is often the case (e.g., Fink et al., 2000; Maslovat et al., 2006),

\(^5\) The same tools and concepts of coordination dynamics were applied, testifying to its generic applicability.
but also on stability properties of the coordination of the movements with the external stimuli (just as for the unimanual sensorimotor coordination studies of Kelso et al., 1990 and Wimmers et al., 1992). These are different and unrelated quantities, which are sometimes confused. For example, one can perform interlimb coordination very stably without showing a stable frequency or phase relation with the external rhythm. In other words, the required bimanual coordination pattern was performed, yet at a frequency deviating from that set by the external rhythm (see, e.g., Maslovat et al., 2006).

**External rhythms to improve gait after stroke**

External rhythms, mainly of auditory modality, are often used in physical therapy practice simply by clapping the hands, snapping the fingers or counting out loud, for example to assist or facilitate rhythmic stepping of impaired gait (stroke, Parkinson’s disease, Huntington’s disease, cerebral palsy). There is growing evidence for the effectiveness of the use of external rhythms during rehabilitation for improving gait after stroke, in particular gait speed and stride length (Thaut et al., 2007; van Peppen et al., 2004). Furthermore, external auditory rhythms can improve gait parameters like gait symmetry and the fluency of gait after stroke (see Thaut, 2008, for an overview). External rhythms thus constitute an affordable, effective, and easy-to-use tool for gait training after stroke in physical therapy practice.

In spite of these merits, it is still largely unknown why auditory cueing works and how it can be exploited to achieve the greatest improvement in gait after stroke. This is mainly due to the fact that the adjustment of gait events to those external rhythms has never been systematically examined in stroke patients. Hence, it is largely unclear which aspects of gait after stroke are modifiable through external rhythms and whether, for example, steps or strides should be paced for optimal gait improvement. This thesis systematically examines the adjustment of gait events to the external acoustic rhythm to be able to address those issues.

The focus is on improving gait after stroke, which is usually slow, unstable, and asymmetric (e.g., Brandstater et al., 1983; Olney et al., 1994;  

---

6 External acoustic rhythms are also applied in training the organization of rhythmic arm movements (e.g., Luft et al., 2004; Whittal et al., 2000), with extensions to clinically effective training paradigms in for example stroke patients (e.g., so-called BATRAC: bilateral arm training with rhythmic acoustic cueing). Furthermore, external acoustic rhythms, often in the form of music, have also been used with success in speech and language rehabilitation as well as in cognitive rehabilitation (cf. Thaut, 2008, for an overview).
Turnbull et al., 1995). Although previous studies convincingly demonstrated the efficacy of external acoustic rhythms in improving stroke patients’ gait speed and stride length, the reported positive effects of acoustic pacing on gait symmetry may have been confounded by concomitant changes in gait speed. In other words, it is not known whether the observed improvement in gait symmetry was a direct effect of the external acoustic rhythm as such or rather an indirect effect of the pacing-induced increase in walking speed. In order to be able to conclude that acoustic rhythms enhance gait symmetry it is important to control gait speed when assessing its effect, for example by using a treadmill.

Moreover, not only is the gait pattern of stroke patients usually impaired, they also typically show a reduced ability to adjust gait to changes in the environment, as evidenced for example by a greater difficulty in avoiding obstacles (e.g., den Otter et al., 2005) and reduced ability to modulate cadence (Bayat et al., 2005; Nakamura et al., 1988). The ability to adjust gait is very important for everyday ambulation, for example when walking in a crowd, as the lack of this ability may elevate the risk of falling (e.g., Weerdesteyn et al., 2006). Interestingly, by manipulating the external rhythms (changing its frequency or perturbing interbeat intervals) and analyzing gait adjustments in relation to the external rhythm, the efficacy of acoustic rhythms to induce gait modulations after stroke can be evaluated. In this way, external rhythms may not only be used to improve stroke patients’ gait pattern but also to evaluate, and ultimately train, their ability to adjust gait in gait rehabilitation. These possibilities will be examined further to gain insight into the feasibility of the application of external rhythms in gait rehabilitation practice and clinical gait research, as well as the underlying perceptual-motor processes.

**Part 1: Delineating the underpinnings of anchoring**

In Chapters 2, 3, 4, and 5 of the thesis, the notion of anchoring, as advanced and elaborated in coordination dynamics, is systematically scrutinized and tested. In Chapter 2 the co-occurrence between regions of information pickup and anchor points is evaluated empirically in a task in which the sensory system itself acts as a pointer for the information it senses. Specifically, participants were invited to track with their hand a sinusoidally oscillating visual target signal under different feedback and instruction conditions. Gaze direction was monitored and participants were free to look wherever they wanted. This study examined the
Chapter 1

hypothesis that gaze direction reflects the task-specific visual information used in the control of tracking by comparing gaze direction to identified local reductions of movement variability. The manipulations of movement-related feedback served to determine how external feedback (de)stabilizes visuomotor coordination and plays into the pickup of task-specific information through anchoring. In the studies reported in Chapters 3, 4, and 5, informational, mechanical, and intentional constraints were manipulated to assess their effects on anchoring including possible interactions. In a similar visuomotor tracking task as in Chapter 2, participants were invited to track the visual target under systematic manipulation of gaze direction and wrist position (Chapter 3). The obtained insights into musculoskeletal constraints were subsequently used in Chapter 4 to neutralize confounding anchoring phenomena to be able to study the precise informational underpinnings of anchoring in rhythmic visuomotor tracking. In Chapter 5, the effect of intention on anchoring was manipulated via carefully formulated task instructions. In brief, participants were instructed to perform rhythmic wrist oscillations while synchronizing either peak flexion, peak extension, or both movement extrema to the beat(s) of an acoustic metronome. These four well-controlled, more basic experiments were conducted to examine whether at, or around, anchor points critical task-specific information is available for organizing a cyclical act (Beek, 1989), or whether those points reflect other task-specific constraints that may be exploited in rhythmic movement execution. Collectively, those experiments aimed to provide detailed basic knowledge on how rhythmic movements are coordinated with external rhythmic stimuli to pave the way for successful translation of the notion of anchoring to clinical settings.

Part 2: Moving from theory to therapy

In Chapters 6 and 7 the efficacy of external acoustic rhythms to improve gait coordination and its ability to modulate gait is examined in stroke patients. Chapter 6 entails a systematic study of the effects of external acoustic cueing on gait coordination after stroke while controlling for possible confounding effects of walking speed by using a treadmill. Furthermore, the relative phase (and its variability) between footfalls and metronome beats was determined separately for the paretic and non-paretic side to examine the stability of the coupling of auditory-motor synchronization and potential anchoring-related differences
Chapter 1

therein between sides (Chapters 6 and 7). In this manner, the efficacy of external rhythms in assisting stroke patients to modulate their gait can be evaluated. Specifically, in Chapter 6 the frequency of the acoustic rhythm was manipulated around each individual’s observed cadence during unpaced walking to evaluate whether external pacing is an effective method for immediately eliciting changes in stride frequency. Chapter 7 focuses on the question how acoustic external rhythms can be best administered in rehabilitation practice, motivated theoretically from the notion that a stable coupling of footfalls to the acoustic rhythm may increase its facilitating and modulating effect. Specifically, the stability of the auditory-motor coupling in acoustically paced walking after stroke was examined under manipulation of the metronome, pacing either steps or strides, and a more stable coupling was expected for the double metronome condition. The coupling strength was not only assessed via pattern variability but also directly using perturbations of the rhythm. Swifter recovery to the initial phase synchronization was expected for more stable auditory-motor coordination patterns. The obtained insights regarding the benefits of external rhythms to improve and modify impaired gait are translated to rehabilitation practice by developing a therapeutic tool to administer external rhythms to patients. Chapter 8 describes the development and validation of an instrumented treadmill for everyday use in gait rehabilitation practice. Specifically, with this device gait events are detected online using a single large force platform embedded in a treadmill, allowing for automatic presentation of visual or acoustic rhythms contingent upon a patient’s gait and to provide feedback on gait performance. Finally, Chapter 9 – the epilogue – summarizes the main theoretical findings of this thesis in relation to the notion of anchoring and proposes directions for the integration of these basic insights in future T1 translational research and T2 practical implementation.