

RHYTHM-BASED REGULATION/MODIFICATION OF MOVEMENTS IN HIGH-PERFORMANCE ROWING AND NEUROLOGIC REHABILITATION

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ABSTRACT

Research over the past two decades has revealed a rich physiological connection between the auditory and motor system across a variety of cortical, subcortical, and spinal levels. Entrainment accrues due to the fast and precise processing of temporal information in the auditory system. Results in high performance sports and neurologic rehabilitation showed significantly improved movement-execution and stabilized temporal motor control with provided external acoustic information due to rhythm-based auditory-motor-synchronization.

1. INTRODUCTION

Auditory rhythm is described as an ordered structure of discernible events in time that recur regularly. It plays an essential part for the learning, development, and performance of cognitive and motor functions [1], [2]. Rhythm formation requires complex cognitive operations and motor transformations as a result of processes on basic levels of sensory perception and motor entrainment. The ability to perceive and volitionally produce rhythm is unique to the human brain [3].

Rhythm serves as an anticipatory and continuous time reference on which movements are mapped within a stable temporal template [4]. This becomes observable when humans easily move in time with acoustic rhythms and effortlessly adjust their movements to rhythmical acoustic elements such as beat and tempo. Research in neuroscience over the last two decades has revealed a rich physiological connection between the auditory and motor system across a variety of cortical, subcortical, and spinal levels [5],[6]. Researchers have demonstrated that rhythm processing and production are distributed throughout the cortex, subcortex and cerebellum [7]. It was suggested, that entrainment accrues due to the fast and precise processing of temporal information in the auditory system. There is now evidence that rhythmic information provided audibly supports the timing of movement-execution subliminally [8],[9].

Investigations in sports science have provided empirical evidence for the effects of using sonification (as an audible representation of data) that is given as acoustic feedback (AF) on perception accuracy, reproduction and regulation of movement-patterns [10],[11]. There is growing evidence that sonification of movements has beneficial functions on motor control and learning, which can be enhanced by concordant multimodal information presentation [12],[13]. These findings underline the potential of enhancing perception-accuracy of

human movement due to the use of audible information by sensitizing the listener/athlete to the time-dynamic structure of the acoustic event.

Results in high-performance rowing and neurologic rehabilitation underline these findings by showing significantly improved movement-execution and stabilized temporal motor control with additional provided external acoustic information as the result of rhythm-based auditory-motor-synchronization.

Since it is known, that acoustic stimuli have a profound and direct effect on the motor system, it is used as external presented acoustic feedback to modulate and refine the execution of movements in training processes of high performance rowing [14] as well as in rehabilitation and in neurologic rehabilitation [15]. It is the time-base of rhythmic information particularly, that affects the motor system and enforces motor reactions by providing regular reference points. The fast-acting physiological entrainment mechanisms that exist between rhythm and motor responses serve as coupling mechanisms to stabilize and regulate movement patterns. Rhythm affects listeners' attention by guiding the focus of auditory perception to important aspects and sequences within the movement for which cyclical movements are particularly suited due to their regular repetition in time. Thus, rhythm provides an anticipatory and continuous time reference for the mapping of movements within a stable temporal template [8].

This paper describes how acoustic stimuli can be used as an effective entrainment stimulus and physiological template to cue the control of movements. On the basis of previous findings, assorted results from investigations in high-performance rowing and from neurologic rehabilitation were presented exemplarily.

2. HIGH-PERFORMANCE ROWING

An AF-concept for on-water training in high-performance rowing was developed for supporting and improving the technique training and was implemented into the German Rowing Association [14],[16]. By sonifying a kinematic parameter of the boat motion and presenting it as AF, it was aimed at enhancing the athletes' perception for the movement execution by providing assistance for the development of a feeling for the movement. Finally it was aimed at increasing mean boat velocity, assuming that AF has an effect on the time structure of the rowing cycle. In particular, on the recovery phase that is critical for the boat run as there is no propulsion by the blades. In addition, the crew slides on the seats in the direction opposite to the boats' forward motion during this

phase, and thus, the whole system is decelerated [14]. AF can provide detailed information about the athletes' movements and their execution during the recovery as well as for the time needed for execution of the reversal points (catch/finish turning points in the rowing cycle).

2.1. Methods

The German National Rowing Team (juniors, seniors $N=47$) in 12 boats as well as the German National Adaptive Rowing Team ($N=6$) was examined with the AF-system *Sofirow*. The system was developed in cooperation between engineers from BeSB Berlin [17] and scientists from the University of Hamburg [18]. *Sofirow* measures boat acceleration (a_B) with a MEMS-sensor ($\geq 125\text{Hz}$) and boat velocity (4-Hz-GPS) as kinematic parameters of the boat motion, sonifies the data of the boat-acceleration-time trace using parameter-mapping and provides the sound sequence as audible data information online during rowing. In doing so, every acceleration data was mapped to a specific tone on the musical scale whereas 0m/s^2 was set at 440Hz as the general tuning standard for musical pitch. During rowing, the sound sequence thus changed as a function of the boat acceleration.

AF was presented via in-board mounted loudspeaker and in blocks that consisted of sections with and without alternately over a minimum of 3 training sessions and a total of 5 blocks per boat. All boat classes took part in the investigations from the single sculls up to an eight. In detail, the procedure was the following: after obtaining a baseline (section with no sound), AF was presented. Subsequently, a section without AF was conducted, that was followed by a section with AF and a section without AF. Each section had the duration of 3 minutes. Athletes were instructed to row at a constant stroke rate (max. variation of 0.5 strokes per minute). In order to meet the correct stroke rate, athletes used a stroke count device.

For the statistical analysis, 30 rowing cycles per section were averaged using the special analysis software *Regatta* [19] for each boat to get a mean acceleration curve. In order to rate the size of one factor, partial eta-squared (η_p^2) was calculated as the parameter of effect size. It describes the effect size on the dependent variables according to the classification according to Cohen [20].

Intra-cyclical analysis was realized via curve sketching in relation to the phase structure of the rowing cycle and of athletes' movement. An analysis of variance with repeated measures was used to establish differences between the sections with AF and without presentation. In addition, standardized questionnaires assessed the athletes' impressions during rowing with AF as well as the coaches' valuation of the concept in terms of being beneficial for technique training.

2.2. Results

Results of the ANOVA showed significant main effects for AF for all squad-levels with high values of effect-size (η_p^2). No difference was found between the boats. Mean boat velocity was increased in the sections with AF compared to the baseline-section at the training intensity of 20 strokes per minute whereas the velocity decreased during the sections without. The effects occurred immediately when AF was presented. Table 1 provides an overview of the results of inner-subject effects of the factor AF for the mean boat velocity found for the different squad-levels.

Intra-cyclical analysis revealed qualitative changes in the boat-acceleration structure for its propulsive-sensitive phases (recovery and front reversal), and a reduction of variations in boat acceleration during the recovery.

Squad-level	N (Boats)	df	F-value	p	η_p^2
Seniors	4	4	5.41	0.003	0.47
Juniors	8	4	12.66	0.000	0.38
Adaptives	1	1	10.33	0.015	0.60

Table 1. Test of inner-subject effects of the factor AF for the mean boat velocity; degree of freedom (df), F-value, level of significance (p) and partial eta-squared (η_p^2)

For illustrating the changes in the acceleration curves that were found for all boats, Figure 1 shows the individual curves of the Men's double sculls (M2x): baseline section vs. section with AF. It becomes obvious that the time structure of the acceleration curves changed as the time period of positive acceleration during the recovery was extended and the deceleration of the boat was reduced (#1 in the Figure). The movement phase at the end of one rowing stroke and the transition phase to the next rowing stroke are referred to as the front reversal (#2 in Figure 1). The results showed that the time needed for the front reversal was reduced as well as the area of marked negative acceleration (#2).

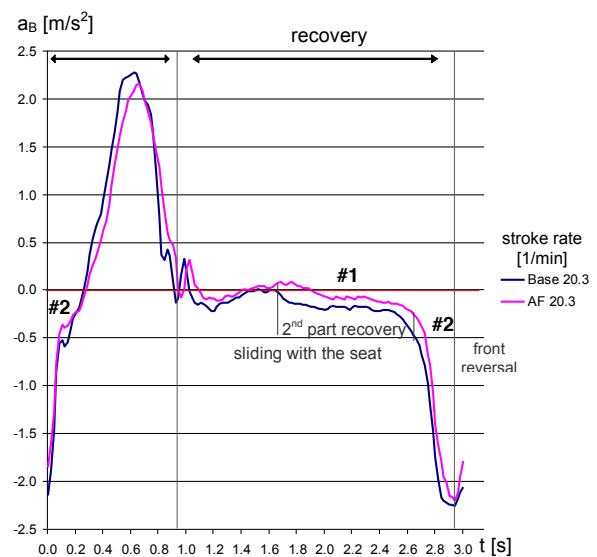


Figure 1. Boat-acceleration-time traces averaged for the 30 rowing cycles each; Baseline vs. section with AF measured with the Men's double sculls (M2x).

Replying to the questionnaires, AF was perceived as functional and supportive for the movement execution from the athletes. The sound provided a stable reference for the timing of single movement-parts within the rowing movement by audibly representing characteristic phases. Athletes perceived changes in tone-pitch within the rowing cycle. In particular during propulsive-critical phases, the acoustic mapping demonstrated "... audibly very clear the deceleration of the boat during the slide-movement". According to the answers, the sound result stayed in correlation with athletes' inner-sensation (kinaesthesia) of the rowing movement and thus, variations were possibly being controlled directly.

Overall, the results showed high acceptance of the AF-concept among athletes and coaches in all squad-levels and it was rated as a functional training aid for on-water rowing training.

3. NEUROLOGIC REHABILITATION

In neurologic rehabilitation, three techniques in motor therapy for patients were developed: (1) rhythmic auditory stimulation for gait (RAS), (2) patterned sensory enhancement (PSE) for upper extremity and full body coordination, and (3) therapeutic instrumental music playing (TIMP) mapping functional movements onto percussion and keyboard instruments. The techniques have become standard in neurologic music therapy (NMT) [5]. RAS, PSE, and TIMP involve the use of rhythmic sensory cuing of the motor system and are based on entrainment models in which rhythmic auditory cues synchronize motor responses into stable time relationships. TIMP in addition uses auditory feedback for successful movement completion. Multiple studies have demonstrated the therapeutic benefits of rhythmic entrainment via RAS, PSE, and TIMP in motor therapy, most extensively with patients post Cerebrovascular accident (CVA) and Parkinson’s disease (PD).

3.1. Methods

Investigations in gait rehabilitation were realized with patients (1) post CVA (experimental-control-group) over a 6-week ($N=20$) and 3-week daily training program ($N=78$) and, (2) with Parkinson’s disease ($N=37$) over a 3-week at-home based exercise program (30min. daily). All patients were pre- and post-tested the day before commencing and the day after concluding the training. Pre- and post-tests were carried out without RAS. In RAS-groups, patients trained their walking daily for 30 minutes with a therapist blinded to study purpose by using a metronome or specifically prepared instrumental music tapes (CD, portable CD player, headphones, music in renaissance genre, pitch range 2.5 octaves) with embedded metronome. Metronome frequency was matched to the baseline step frequency at initial training and then incrementally increased (see studies for training protocol details).

Stride timing was recorded at a sampling rate of 500 per s with a computerized foot sensor system consisting of 4 foot contact sensors (heel, 1st and 5th metatarsal, big toe) embedded into shoe inserts, a portable microprocessor to record data, and computer interface and data analysis hard and software.

Stride parameters of 5 stride cycles were used to assess improvement in gait ability with regard to velocity, stride-length, and swing-symmetry. Symmetry was calculated as the time ratio between the swing times of 2 successive steps using the longer step as the denominator. Percentage change scores for all stride data were computed for each subject and averaged across groups for statistical analysis.

3.2. Results

Results in PSE and TIMP studies have shown significant reductions in variability of arm trajectories and significant increases in functional arm motor tests in hemiparetic arm rehabilitation [21].

Gait studies showed significantly improved velocities with increases in stride length and cadence for the RAS groups vs. control groups. Using the entrainment paradigm as the basis for a six-week gait therapy investigation with persons with hemiparetic stroke, long-term training effects with rhythmic stimulation were reported that were significantly higher in all gait parameters except cadence than for conventional gait therapy without rhythmic sensory cues [22]. Besides improvements in kinematic gait parameters such as smoothing of knee angles and reductions in medio-lateral displacement of center of mass, a central physiological effect of auditory rhythm on EMG patterns was found in reduction of amplitude variability of the gastrocnemius muscle. These data were replicated in a study employing the same design, however, over a 3 week training period. Overall improvements were smaller than in the 6 week study, but differences between RAS and neurodevelopmental treatment (NDT)/Bobath training were proportionally the same. All gait parameters were significantly higher for RAS (Summary of training results in Figure 2).

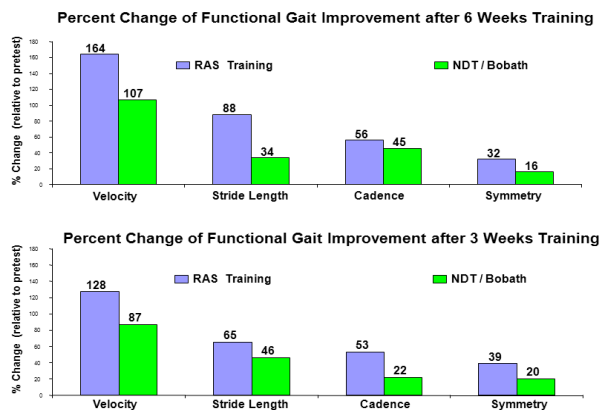


Figure 2. Percentage change from pretest and posttest between RAS and control group for velocity, stride length, symmetry and step cadence over 6-weeks [22] and 3-weeks Training [23].

In experiments with PD patients concerning the immediate rhythmic entrainment effect on gait patterns, without extended training periods, it was found that PD patients were able to synchronize their step patterns to metronomic and musical-rhythmic cues in time-coupling ranges to a degree very similar to healthy elderly persons [25].

Interestingly, the essential synchronization patterns were retained when PD patients went off dopaminergic medication for forty-eight hours, although variability in all gait parameters had increased. Significant training effects for RAS were established for the first time by Thaut et al [24]. In a 3 week daily training study RAS cued training led to significantly higher velocity, stride length, and cadence compared to self-paced gait exercise training.

The positive effect of RAS on PD gait has been since then confirmed by a large number of research groups [e.g. 31]. In-depth physiological analysis of EMG patterns showed significantly decreased muscle shape variability and asymmetries for RAS and thus, more stable gait patterns [26].

4. DISCUSSION

Results showed how the temporal structure of acoustic stimuli can be used as a physiological template to cue the control and temporal regulation of movements. This paper described a possible theoretical background for the impact of acoustic stimuli on the human motor systems on the basis of investigational findings in neuroscience and sport science, and provides empirical evidence with assorted results from investigations in high-performance rowing and neurologic rehabilitation.

In high-performance rowing, AF affected the mean boat velocity in on-water rowing training of elite athletes immediately and as soon as it was presented. Due to the data-to-sound-mapping, the functional attribution of tone-pitch here is a function of changes in acceleration that makes the sound particularly informative; detailed information about velocity and periods of acceleration and deceleration were conveyed as a result of the parameters and the instantaneous states of the objects in contact (boat, athletes' movements and water resistance). The characteristic profile of the rowing cycle was represented in the periodic patterns of tone-pitch and intensity which are caused by the boat acceleration. Thus, the sonified boat motion reflected the rhythm of the rowing cycle by providing detailed information of its characteristic phases. The dynamic relationship of tone-pitch to acceleration facilitated an intuitive understanding of the sound that corresponds to experiences in everyday situations. In this way, the physics-based algorithm which was used to create the movement defined sound sequences, simplified and abstracted the complex parameters and made the sound data intuitively comprehensible to and applicable by the athletes. Due to the presentation of AF, athletes' attention was driven to the time-dynamic structure of the rowing cycle which enabled them to regulate its critical phases more precisely. The data-based sound sequence supported the feeling for the movement execution and improved coordination among the athletes, yielding to improved crew synchronization.

In neurologic rehabilitation, RAS demonstrated a strong facilitating effect on gait performance in several patient groups with gait deficits (CVA and PD) and also improves positional and muscular control. The initial understanding of rhythm in motor control was as a timing cue entraining the motor system into higher frequencies and velocities of movement. However, by studying the underlying velocity and acceleration profiles during movements, a very important insight into understanding the effect of auditory rhythm on motor control was developed. There had been very strong evidence that non-temporal movement parameters, such as stride length in gait or movement trajectories of upper and lower limb joints (e.g., wrist, knee), improved during rhythmic cuing. One basic conclusion was that enhanced time stability across the duration of the movement during rhythmic cuing—by way of rhythm providing a continuous time reference based on its period information—also enhanced spatial-positional control of movement. However, a conceptual link to connect temporal cuing to spatio-dynamic parameters of motor control was missing. Analyses of the acceleration and velocity profiles of joint motions during rhythmic cuing offered an intriguing explanation by linking the different parameters of movement control into an interdependent system that could be accessed and modulated by time.

The consistent evidence for the smoothing of velocity and acceleration profiles of joint motions during rhythmic cuing suggests that rhythm enhances the control of velocity and acceleration by scaling movement time [8]. Velocity and acceleration, however, are mathematical time derivatives of the spatial parameter of position. Thus, in working our theory backward, we reasoned that by fixating time through a rhythmic interval, for a movement from point A to point B the subject's internal timekeeper now had a precise reference interval, with time information present at any stage or moment of the movement. This time information allows the brain to map and scale smoother parameters of position change (i.e., velocity and acceleration) across the entire movement interval (e.g., heel strike to heel strike in gait, reaching target points in space for arm movements, etc.).

Changes in velocity and acceleration profiles, however, must be reflected in the position-time curves of the movement. This can be described mathematically as an optimization problem. If we assume that the brain uses some optimization strategy to control movement, it is possible to show, in certain cases, that such optimization implies scaling of the resulting movement over time. The immediate consequence of this assertion is that matching the period of a cyclical movement to the period of an external timekeeper will result in the regulation of the entire movement trajectory. Once the time constraint has been added, the brain is presented with a well-defined optimization problem: how to move from point A to point B in a fixed time interval while maximizing precision and minimizing some objective cost function for the body associated with making the movement [27].

The findings in both, sports as well as in neurologic rehabilitation showed that rhythm affected the timing of movement. More specific findings indicate that auditory rhythmic cues add stability in motor control immediately (within short period of stimuli presentation) rather than through a gradual learning process [5], [14]. Facilitation and immediacy of effects presumably occurred due to the close neural connection between auditory and motor areas and happened at subliminal levels of sensory perception [28]. There is evidence for the existence of audio-motor pathways via reticulo-spinal connections on the brain stem-level [4]. The rich connectivity between the auditory rhythm and movement interfaces in distributed and parallel fashion throughout the brain. Using sound cues and musical rhythms, it was possible to demonstrate priming and timing of motor responses via the audio-spinal path [29]. Results of other investigations that addressed the motor-synchronization of finger-tapping to tempo shifts in metronome cues indicated a spatial and temporal neural coding process for rhythmic time measurements which is located in primary auditory cortex [30].

On the basis of these research findings, it was concluded, that acoustic stimuli uses multiple auditory-motor pathways to access and entrain central motor processors that are coupled to rhythmic time information. The conceptual understanding converged on an oscillator-entrainment model where rhythmic processes in neural motor networks become entrained to rhythmic timekeeper networks in the auditory system. These timekeeper networks are driven peripherally from rhythmic inputs. It thus was suggested, that the interaction stabilized the internal rhythm generating system and reintegrated timing networks [31] independent of specific participant groups.

5. CONCLUSIONS

Using AF in high-performance rowing opened new possibilities to assist the technique training by providing the feedback information via the sense of hearing and thus, to facilitate the development for a feeling of the rhythm in racing boats. The AF-concept has been successfully integrated into the technique training of elite athletes and the preparation for the World Championships as well as for the Olympic and Paralympic Games.

RAS is a promising tool for improving gait performance in neurologic rehabilitation. Rhythmic cues as a predictive time constraint can result in the complete specification of the dynamics of the movement over the entire movement cycle. It thus not only cue speed and timing of movement but also can regulate comprehensive spatiotemporal and force parameters in restoring motor function in brain rehabilitation.

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