

Listen to the boat motion: acoustic information for elite rowers

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ABSTRACT

Presenting information acoustically has become increasingly interesting for technique training and control in elite sport. In rowing, acoustic feedback is a new and promising application to optimize the boat motion. By taking advantage of auditory perception, which is particularly sensitive to temporal resolution, the physics-based movements are mapped to acoustic parameters using Parameter Mapping Sonification (sonified) and was transmitted to the athletes as acoustic feedback in order to sensitize them to the time-dynamic structure of movements; assuming that this yields to an increased boat velocity. Listening to the sound of the boat motion enables athletes to detect small variations and deviations in movement execution and improves effectiveness in interaction without distracting the athletes' focus of attention. Indications for the existence of an "action-listening"-mechanism [1] in humans support the assumption that movement execution and effectiveness in interaction are improved which is perceived as a side-effect.

This paper describes a potential version of acoustic information which represents the movement-relevant information of the boat motion for rowing and its implementation as a real-time acoustic feedback for elite rowers during on-water training sessions. The first significant results were encouraging and support the intention to implement the acoustic information regularly into training processes for elite athletes.

Keywords: Interactive Sonification, auditory information, acoustic feedback, on-line feedback training, motion perception, movement optimization, elite athletes, rowing.

1. INTRODUCTION

The inextricable relationship between acoustic events and human movements has been known since the era of the ancient Greeks and has influenced social functions in all cultures [2]. The genesis of music goes so far back in history that it finds expression in the primal mythology of different national cultures. It was assumed that music evolved as a cooperative method for the coordination of actions and promotion of group cohesion [3].

Music is described as "organized sound" and sound as "a mental image created by the brain in response to vibrating molecules" [4]. So the alliance between sound and movements is constituted in their physical nature which is an inherent time structure: both are results of a temporal (chronological) sequence of events. Consequently, all kinds of movements produce sounds in various frequency ranges (ranges of vibrations in cycles per second). Human movements are

normally below the audible human frequency range (which is located between 20 Hz and 20 000 Hz) [5] except those sounds accompanying movements as a result of the interaction of materials. In sport situations, the contact phase between sports equipment with a surface evokes sport specific sounds (e.g. in tennis, where the impact-sound of the ball reflects the velocity and impact-force). Similarly, in rowing, the boat's forward motion creates a sound like splashing and flowing which plays an important role especially for elite rowers [6]. They rely on the boat-specific sounds to obtain feedback about the boat's forward motion and they are able to assess their rowing strokes as more or less successful. This acoustic feedback can effectively convey information in real-time about different attributes such as the amount of velocity and force applied to the system per rowing stroke. Actually, the rowers perceive solely the basic elements of the sound (like loudness, pitch, duration or rhythm, tempo, timbre, spatial location, etc.). It is the translation and organization of this information by the brain into higher level concepts [4] which gives the rowers the necessary information.

Besides the advantage of perceiving multiple attributes at one time, athletes' focus of attention can be guided by the rhythm to specific sections in the sound without distracting their focus of attention and without occupying the audio sensory channel, which can analogously be the case when feedback is displayed visually [7]. Available perception capacities enable augmented information gathering and interpretation of simultaneously perceived information streams. Moreover, the sound increases the awareness of every athlete in the boat, rather than only that of a single athlete.

Results from neuroscience research [8] confirm the processing of acoustic stimuli as a solid, precise and subliminal process which proceeds at different neuronal levels. The resulting neuronal impulse affects directly the human motor system, which is extremely sensitive for acoustic information. During the process, rhythmical-temporal templates were generated which are responsible for the temporal sequence of actions. Movement 'follows' sound because of the strong connection between sensory input and motor output' [9]. Thus, music -and therewith sound- seem to be ideal synchronization devices because of its' unique influence on humans to drive rhythmic and metrically organized motor behaviour [10]. The interaction between auditory stimuli and motor reaction becomes evident when people intuitively (and often spontaneously), tap or clap to the rhythmic pattern of a musical piece. This reaction only occurs in the presence of acoustic stimuli - there is no comparable effect for visual stimuli. The metrical organized structure of an auditory stimulus enables the listener (and performer) to anticipate future occurring events and may contribute to motor prediction [11].

Thus, acoustic feedback systems become a powerful tool for the training processes of elite athletes. The sonification of the boat motion aims to guide athletes' attention to those specific sections in the rowing cycle that critically cause the boat to slow down (like the recovery phase and the front reversal (for details see section 3, results)) by taking advantage of the properties of the auditory perceptual system with its high temporal resolution. By listening to the sound of the boat motion, the athletes' feeling for the rhythm of the boat motion can be sensitized.

This paper describes a potential version of acoustic information which represents the movement-relevant information of the boat motion for rowing and its implementation as a real-time acoustic feedback for elite rowers during on-water training sessions. The first significant results were encouraging and support the intention to implement the acoustic information regularly into the training of elite athletes as an attention-guidance system.

2. METHODS

2.1. Subjects

The subjects who participated in the study were male and female elite junior athletes ($N=30$): Male ($n=21$) aged 17.8 years (± 0.8), body height 190.6cm (± 7.2), body weight 83.9kg (± 8.9); Female ($n=9$) aged 19.0 years (± 2.1), body height 172.6cm (± 5.5), body weight 63.8kg (± 7.1).

2.2. Test design

The intervention took place at the race course in Berlin-Gruenau during the preparation phase for the junior world championship in June 2009. Test runs in different stroke rate (sr) steps (18, 20, 22, 24, 30, 32, 36 strokes per minute) were measured for different sections (500m sections) and for the overall duration of 30 rowing strokes. The average stroke rate of a regular extensive training session (represented by the lower stroke frequencies) as well as the average race pace frequency (represented by stroke rate 32 and 36) have been considered.

To identify the effect that the acoustic information had on the boat motion, three measurement sections during a training run of a Men's Junior 2x (JM2x) were chosen at five different measurement times compared to the baseline: "without" sonification (baseline), "with" sonification (section 1), "without" (section 2), "with" (section 3), "without" (section 4) and again "without" sonification (section 5). The sections were analyzed for the factors that determine the boat motion: boat velocity (v_{boat}), stroke rate (sr) and the distance traveled by the boat (s_{boat}). Each section had a total of 30 rowing strokes. The test was conducted 13 times during the training session of the JM2x.

Additionally, athletes were asked to answer standardized questionnaires to investigate athletes' experiences with the acoustic information and the acceptance of the sound result in particular among (German) elite junior athletes.

Statistical analysis of the data based on an ANOVA with repeated measures. Mean differences, standard errors, significance and F-value were listed.

2.3. Measurement system

In order to create the acoustic information, the training and measurement system Sofirow was developed in cooperation with engineers from BeSB GmbH Berlin. Sofirow measured the kinematic parameters of the propulsive boat motion: boat acceleration (a_{boat}) with a piezo-electric acceleration sensor (sampling rate: 100 Hz) and boat velocity (v_{boat}) with GPS (4 Hz). Figure 1 showed the position Sofirow is located on top of the boat.



Figure 1: *The training and measurement system Sofirow (developed by BeSB GmbH Berlin and University of Hamburg) located on top of the JM2x.*

Sofirow converted the acceleration-time trace into acoustic information in real-time and transmitted it to the athletes in the boat as on-line sound feedback via loudspeaker and earplugs. To control the time for and duration of the acoustic information, the sound could be selectively switched on or off by remote-control from the accompanying boat of the coach. Acoustic transmission was controlled by the scientist after talking to the coach who could receive the same sound information simultaneously with the real-time feedback into the motorboat.

2.4. Sound design

In order to convert the acceleration-time trace into a meaningful and audible sound result, the sonification method of Parameter Mapping [12], [13] was chosen, which is regularly used to render sonification from data. Therefore, the data of the acceleration-time trace were attributed to specific tones on the musical tone scale and related to tone pitch. Every defined decimal midi-number equates to a specific semitone. Data were multiplied by the factor k (spread of the acoustic sound) and displaced with an absolute term h on the midi-scale (pitch of sound). The middle C on the western musical tone scale represented the point of zero acceleration, so that positive acceleration varies above this pitch and negative below: as the acceleration increased the pitch of the tone increased, and as the acceleration decreased the pitch decreased as well. As an outcome of this, the sound result (as the melody of the boat motion) changed as a function of the acceleration-time trace. Accordingly, every change in the boat motion was acoustically represented and thus, even those changes, that were not visible by solely watching the motion of the boat could be detected. The direct mapping of the boat motion and its changes or reverses of the boat's momentum (such interruptions in the boat's forward motion) became especially apparent in videos of several training sessions which were synchronized with the sound of the boat motion.

3. RESULTS

3.1. Data

To analyze the movement-relevant information, it was important to detect characteristic movement patterns in the rowing cycle and qualitative changes in the boat motion (phases in which the boat motion increased or decreased). Therefore, the cyclic motion sequence of a rowing stroke was separated into its four characteristic and repetitive sub-phases that consists of the drive (d) phase, recovery (r) phase, front (fr) and back (br) reversal (also known as the catch and finish turning points).

The acceleration trace of a rowing cycle, with its characteristic and repetitive patterns, begins at the moment of zero acceleration followed by a distinctive increase during the catch and the drive phase to the point of maximum acceleration. During the back reversal, the moment when the oars were lifted out of the water, the boat was decelerated. Positive acceleration then occurs just before the recovery phase begins, followed by the next rowing stroke that starts again with a deceleration of the boat during the front reversal.

Figure 2 shows the acceleration-time trace for one selected rowing stroke in which the curve characteristics became evident.

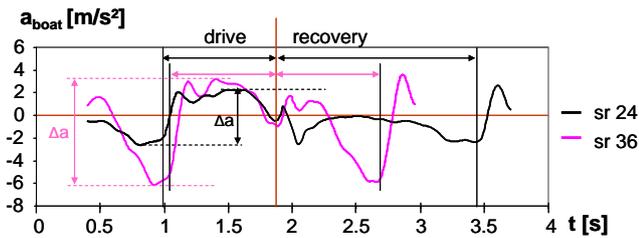


Figure 2: Acceleration traces of one complete rowing cycle at stroke rates 24 and 36 strokes per minute with drive and recovery phase and characteristic curve(s).

The greatest acceleration changes were measured during the catch and finish turning points: during the front reversal as a deceleration and then an acceleration of the boat and the back reversal by temporary negative and positive acceleration peaks reflecting the deceleration and acceleration of the boat. The main positive propulsive acceleration occurred during the drive phase.

Table 1 shows six selected stroke rate steps at different measured intensities (18-36 strokes per minute).

Table 1: Selected stroke rate steps: stroke rate (sr) and boat velocity (v_{boat}).

sr-step	sr [strokes/minute]		v_{boat} [m/s]	
	mw	sd	mw	sd
18	20.6	0.3	3.9	0.5
20	21.1	0.9	4.0	0.5
22	21.8	0.9	4.2	0.6
24	23.8	1.6	4.4	0.6
30	29.3	2.1	5.0	0.8
36	35.1	1.0	5.4	1.0

Mean boat velocity clearly increased (3.9 – 5.4m/s) with the measured stroke rate increments (20.6 – 35.1 strokes per minute). Thus, the acceleration trace characterized the rhythm of the rowing cycle according to the intensity which was statistically confirmed with significant differences between the several stroke rate steps ($p=0.00$).

With this requirement fulfilled, characteristic phases of the rowing cycle were represented and its rhythm was audibly differentiated in the sound result. The information contained in the measured data were displayed acoustically, audibly perceivable and, for our purposes even more important, audibly distinguishable from each other.

To identify the effect that the acoustic information had on the boat motion, the five sections studied were referred to as section 1 (“with”) in which the sonification was presented to the athletes, section 2 (“without”) in which no acoustic information was given, section 3 (“with”), section 4 (“without”) and section 5 (again “without”) in relation to the baseline (fig.3).

Figure 3 shows the differences in increase of the boat velocity (v_{boat}) for the five sections of a Junior Men’s 2x (JM2x).

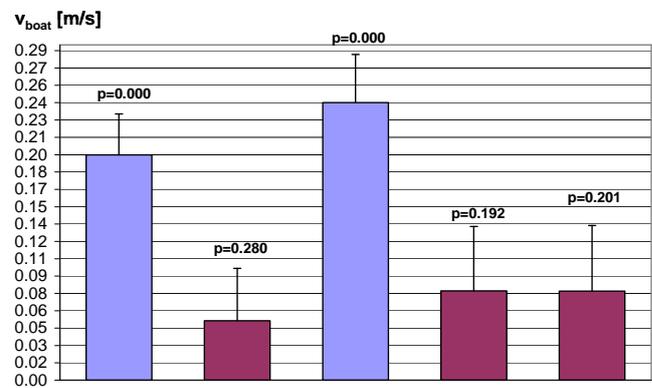


Figure 3: Mean differences and standard errors of the boat velocity (v_{boat}) for the five measurement times compared to the baseline for a JM2x each with 30 rowing strokes over a total of 13 tests.

The data showed an overall significant effect of the sound information on the boat velocity ($F=18.94$; $p=0.00$). Section 1 and 3, in which the sonification was used, showed a significant increase in the boat velocity compared to the baseline (without sonification) (section 1: $F=30.42$ and section 3: $F=32.96$; both $p=0.000$). Section 2, 4 and 5 (without sonification) showed no significant differences (section 2: $F=1.28$, $p=0.280$; 4: $F=1.91$, $p=0.192$ and 5: $F=1.83$, $p=0.201$) compared to the baseline. The greatest mean boat velocity was measured in section 3 with sonification (with 4.23 m/s) (table 2). Therewith, the sonification increased the average boat velocity in this instance about 2.4 ± 0.04 m/s.

In contrast to the significant effect of the acoustic information on the boat velocity, there was no significant effect on the stroke rate ($F=1.26$; $p=0.291$). Consequently, the several sections with and without sonification showed no significance (fig. 4). But it is worth to mention, that the sonification decreased the average stroke frequency about 0.06 ± 0.10 strokes per minute.

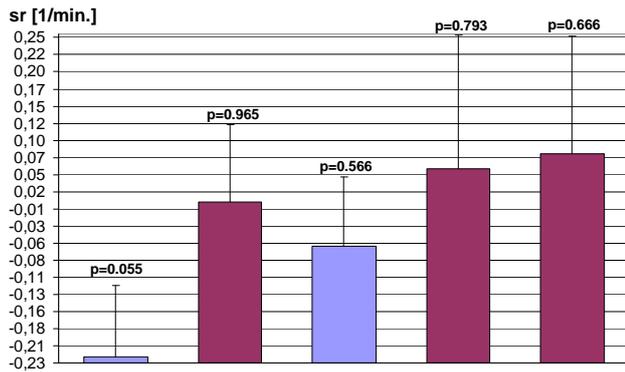


Figure 4: Mean differences and standard errors of the stroke rate (sr) for the five measurement times compared to the baseline for a JM2x each with 30 rowing strokes over a total of 13 tests.

The data for the measured distance traveled by the boat showed a significant effect of the sonification ($F=16.35$; $p=0.000$). Section 1 and 3, with the sonification, differed significantly to the baseline (section 1: $F=36.71$, $p=0.000$ and section 3: $F=23.32$, $p=0.000$). The sections without the sonification (2, 4, 5) showed no significant increase in the traveled distance compared to the baseline (section 2: $F=0.88$, $p=0.367$; section 4: $F=0.76$, $p=0.402$ and section 5: $F=1.60$, $p=0.230$) (fig. 5).

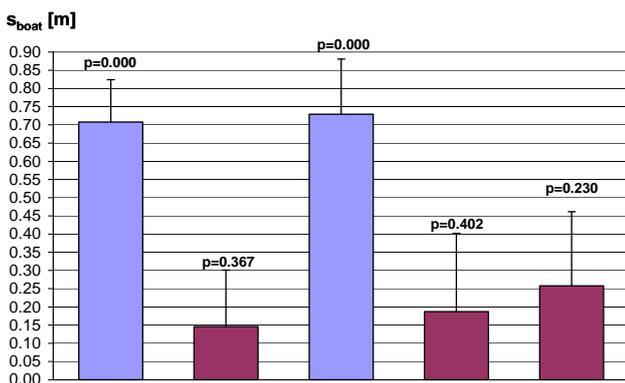


Figure 5: Mean differences and standard errors of the distance traveled by the boat (s_{boat}) for the five measurement times compared to the baseline for a JM2x each with 30 rowing strokes over a total of 13 tests.

The greatest mean distance traveled by the boat was obtained in the sections with sonification (1 and 3) with 12.28 m (table 2). As a consequence of this, the average distance traveled by the boat increased in this instance about 0.7 ± 0.15 m per stroke.

Table 2 shows mean values and standard deviation for the boat velocity (v_{boat}), stroke rates (sr) and the distance traveled by the boat (s_{boat}) for the baseline and the five measurement times with (J) and without the sound information.

Table 2: Mean values and standard deviation for the boat velocity (v_{boat}), stroke rates (sr) and the distance traveled by the boat (s_{boat}) for the baseline and the five measurement times.

	v_{boat} [m/s]		sr [1/min]		s_{boat} [m]	
	mean	sd	mean	sd	mean	sd
baseline	3.97	0.2	20.8	0.9	11.48	0.6
section 1 J	4.18	0.1	20.5	0.7	12.28	0.4
section 2	4.02	0.2	20.7	0.9	11.66	0.5
section 3 J	4.23	0.2	20.7	0.7	12.28	0.4
section 4	4.05	0.2	20.8	0.9	11.69	0.5
section 5	3.89	0.2	20.8	0.8	11.23	0.7

3.2. Questionnaire

Athletes' overall answers were positive regarding the acoustic feedback experienced and its support in on-water training sessions. The reproduction of the boat motion was recognizable to 100%* and athletes could focus their attention on various movement sections inside the rowing stroke. Characteristic sub-phases of the rowing cycle were distinguishable as represented for 87.5% of the athletes. 75% would appreciate a provision of acoustic feedback for their on-water training sessions as a promising training-aid and for 50% the sound result did not interfere with the perception of the surrounding environment and the usual perception of the athletes (fig.6).

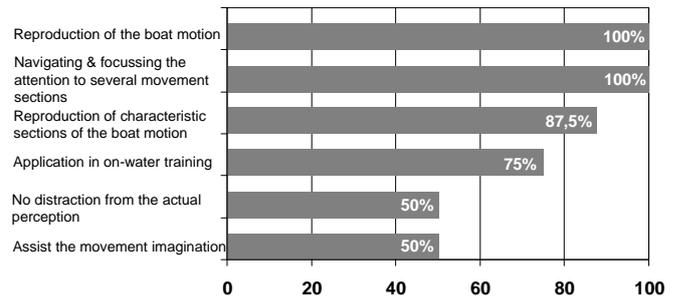


Figure 6: Percentages of athletes' answers.

An assortment of individual responses of the athletes for selected questions is listed below.

Question: How was the feeling with the additional sound while you were rowing?

"The feeling was good. I was encouraged to accelerate backwards and when implemented I've received a positive feedback." (1x)¹

"The sound pointed to things that we have not been aware before and the movement became more consciously." (2x)

"The sound helped us to better synchronize us." (4x)

"Everybody was more concentrated." (8+)

"The boat run is enhanced." (8+)

Question: Are the different movement intensities mapped clearly (by the several stroke rate steps)?

¹ Terms used for the classification of the different types of boats: 1x: single scull; 2x: double scull; 4x: quad (or quadruple) scull; 8+: eight (always coxed).

“During the drive phase there was a high pitched sound whereas during the recovery phase the sound was low pitched and, just before the blades touched the water it sounded very low pitched.”

“You recognized the sound getting higher and shorter at higher frequencies.”

“You recognized the shorter recovery phase at higher stroke frequencies in the sound.”

Question: Is it possible to hear variations of successful and less successful strokes (e.g. if a stroke didn't feel successful, but another one did)? We mean variations between single strokes of the same stroke rate step.

“Especially a break at the front reversal (catch) was very good perceptible.”

“I could hear the moment of the front reversal (catch) very precisely. The sound of the drive phase was different from the sound of the recovery phase.”

Question: If yes, what especially can you hear?

“I perceived very well the moment of the highest sound during the drive phase. So you can try to keep the sound high pitched as long as possible and let it get lower pitched after the stroke was finished.”

“I heard changes: the better the acceleration the higher was the sound.”

Question: Is it possible to navigate and focus attention on several movement sections because of the sound to adjust and regulate movements?

“You can concentrate to the sound especially for the moment before the oar blades enter the water: trying not to decrease the sound too much to get the best boat acceleration.”

“Especially at the finish position it was possible to ‘play with the sound’: you can try to keep the decrease of the sound as minimal as possible.”

“You try to accelerate backwards to minimize the decrease of the sound before the catch.”

“You can try to extend the rising sound at the end and keep it high pitched before the oar blades entered the water.”

“Mistakes were easier detectable and become more distinctive. Furthermore it is possible to concentrate on specific movement sections.”

4. DISCUSSION AND CONCLUSIONS

This paper described a potential version of acoustic information which represented the movement-relevant information of the boat motion for rowing and its implementation as a real-time acoustic feedback for elite rowers during on-water training sessions in order to optimize their movements. The training and measurement system Sofirow was developed and underwent preliminary testing during which the boat motion was analyzed and described acoustically (sonified) for the purpose of making the measured differences in intensity between several stroke rate steps audibly perceivable and distinguishable. The resulting acoustic information was sent to elite junior rowers in real-time

with the objective of helping them to improve the boat's forward motion by, for example, extending the propulsive phase of the rowing strokes. First significant results were encouraging and support the intention to implement the acoustic information regularly into the training of elite athletes as an attention-guidance system.

The training and measurement system Sofirow produced a sound output in real-time that represented the boat acceleration trace acoustically and characterized (differentiated) the rhythm of the rowing cycle, related to tone pitch, or expressed mathematically: the sound result changed as a function of the boat motion. Specifically, the more the boat was accelerated, the higher tone-pitched was the acoustic result. The sound example of a sonified rowing sequence of a junior Men's Four (JM4-) synchronized with a video [14] demonstrated clearly the phase in which the boat was accelerated (drive phase) and the phase in which the boat was decelerated (recovery phase). The high tone pitched sound result represents a high rowing stroke frequency of 38 strokes per minute which is equal to the average stroke frequency in rowing races. Therewith, the sound result, synchronized with the video of the rowing sequence, demonstrates aspects of the movement acoustically that would not have been perceived visibly or at least less precisely. The sound definitely supported and facilitated the perception.

Defined as “the perceptual correlate of periodicity in sounds” [15], tone pitch by its nature occurs in waveforms which repeat in a time period that is comparable to the characteristics of the periodic rowing cycle. Athletes perceived the rowing cycle as a short sound sequence that repeated with its characteristic phases (like the refrain in a piece of music) with every rowing cycle. The periodic recurrence of characteristic sections (as a sub-part of the total rowing cycle) awakened a sensitivity for details in the sequence which did not need to contain any explanation. Awareness of the structure emerged solely from the knowledge of the movement and audio-visual interaction. Changes in tone pitch represented and characterized variations inside the rowing cycle that also repeated variably with every rowing stroke. Listening to the boat motion, the sound data became intuitively comprehensible to and applicable by the athletes. It helped them to improve their feeling for the time duration of the movement for the single rowing stroke as well as for the series of rowing cycles.

Results from earlier empirical studies in motor learning have already proved effective for enhancing the process of learning new movement techniques [16].

Further indications for an “action-listening”-mechanism [1] in humans confirmed initial results that multi-sensory information (audio-visual feedback) facilitates movement execution and regulation, as well as movement reproduction and simulation can even support motor learning processes [17] and group cohesion [18]. Action listening takes place during human interaction with the world and their regular daily activities associated with sounds such as a clicking sound when a light switch is pressed or the sound of a glass filling with water. Most probably, the sound is recognized, the brain simulating the action [19].

Also, when people observe another person performing an action, cross-modal neural activity in the brain is evoked that produces activity similar to that which would have been produced if the person himself had moved. This system of neurons becomes active when people execute movements themselves, watch others or listen to something [20].

As a result of this, perception (sound) and action (movement) become coded in the same modality [21]. In other words: sounds were associated with specific movements and their execution. Therewith, the specific sound of different stroke rate steps gets associated with the respective movement intensity and can be thought of as an acoustic footprint of the particular movement pattern. That indicates that the auditory modality can access the motor system [11]. Hence, the rhythm and duration of the movement experienced creates a feeling for the sound of the desired outcome that remains in relation to kinesthesia and movement performance [22].

There is evidence for a responding mechanism in the brain that creates a neural basis for the coherence of sounds [4]: for every component in the sound a neuron in the auditory cortex exist that responds with a firing rate that corresponds to the frequency rate of the sound [23]. Therewith, the vibrating rate of the sound and the firing rate of the neurons get synchronized one with another. And as a result of the acoustic feedback, the components of the movement became synchronized for both, the interpersonal (measured rhythm of the boat) as well as the intrapersonal (subjectively perceived by athletes) rhythm and a common team rhythm evolved with its characteristically communicative, compulsive and intoxicative effects. Athletes' individual rhythm became automatically subordinated to the rhythm of the team [22].

The structure of an auditory stimulus is organized metrically and with the regularly recurring (rhythmical) cue it can create expectations for the likelihood of future events. Therewith, the listener (and performer) can accurately anticipate the next temporal event and can, for example, tap to the beat or synchronize several movement sections such like the moment when the oar blades enter the water all at the same time. Therewith, perception and actions can be tightly coupled, suggesting that there is an inherent link between auditory and motor systems in the context of rhythm [24].

From a psychological-physiological point of view, rhythm is transferred as a result of the phenomenon of the 'ideomotor effect' (also known as the carpenter effect). Due to the observation (and less strongly to the imagination) of a specific movement by another person, motor reactions occur involuntarily (and often unconsciously) that are in principle not distinguishable from the executed real movement [22].

The sound result represented the rhythm of the boat motion as a real-time monitoring and feedback system with the potential to increase athletes' awareness of the rhythm and duration of movements [25]. It supported the feeling for synchronization and, hence, improved coordination. Therewith, the sound result represented the boat motion audibly in a way that seems to be perceptually and cognitively meaningful. With the positive attributes of the sound it is possible to implement acoustic feedback into training processes of elite athletes in order to optimize their movements.

The results of the questionnaire showed basic agreement among the athletes regarding the acceptance and effectiveness of the sound result which was reflected in their answers and confirmed the initial assumptions. Apart the accordance among the athletes, the individual perception of the sound result differed from athlete to athlete, because every athlete has his own way to experience the feeling of rowing and thus, realizes rowing technique differently. Presenting acoustic feedback can not affect every athlete in the same way; one athlete may find the

sound result more helpful than another athlete apart from the aesthetic perception [26]. However, it can help in acquiring an enhanced feeling for the rhythm and duration of the movement and can bridge the gap between coach and athlete in their psychological interaction: the sound result as the information presented to the athletes, is consistent with the physical movement as its cause and thus, it is conveyed by the same modality of senses [27]. With it, the sound result is, in contrast to verbal instructions, intelligible to all and has furthermore the possibility to form an idea of the movement based on earlier experiences. Thus, expectations developed from those ideas can be satisfied by the received sensory information while executing the movement [1].

In conclusion, the sound result presented here tried to contribute to existing feedback system with an expansion into the audible range for the information presentation. The first results showed that acoustic feedback helped the athletes to adjust their strokes with an increase in boat velocity and the distance traveled by the boat. The sound result also was understandable for every athlete without extra explanation. And with the sonification that offers in general an abundance of applications [13], acoustic feedback systems seems to be a promising training aid for elite athletes that offers new possibilities especially for motor control and motor learning as well as for rhythmic education in racing boats. Moreover, reproduction of several movement patterns is facilitated and monitoring is eased.

But however, there is still a lack of practical experience. To get the desired benefit, it is important to use the sound information effectively in training. Therefore, further studies will examine its effectiveness and validity in on-water training sessions.

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* Percentage descriptions must be interpreted in relation to the small number of tested subjects.