

AN INTERACTIVE SONIFICATION SYSTEM FOR SWIMMING EVALUATED BY USERS

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ABSTRACT

This paper presents a novel setting for the measurement, real-time processing and interactive acoustic representation (sonification) of hydrodynamic pressure induced by the interaction of hands of swimmers and the water mass, causing propulsive momentum changes. The sound is presented in real-time both to the swimmer, via in-ear waterproof headphones, and to the coach. The setting was used in a first empirical test concerning the symmetry of hand actions during breaststroke swimming. The swimmers were asked to attend to the sonification and in case they perceive asymmetry they should try to enhance their interaction, interactively. The use of the setup was judged positively by the swimmer. In combination with the actual motion and body perception the functional sounds were judged to be a supportive tool to change hand-water-interaction.

1. INTRODUCTION

Elite swimmers are masters in displacing water mass at low energy costs resulting in high swimming speeds. To increase the mastership of self-induced locomotion it is advantageous to dispose a specialized cognitive control transmission tool, the “swimmer’s talent of feel for water”. A communication about this intimate interplay is hardly possible between coach and swimmer or between swimmers due to lack of a measurable comparison of this particular perception. Yet this is a key prerequisite for the *Cognitive control* of self-induced interaction in aquatic space, demanding coupling of self-perception of limbs’ actions and perception of displaced water mass.

An experienced swimming coach of elite swimmers motivated this interdisciplinary approach bringing together researchers from biomechanics, mechatronics and sonification. The coach wanted to know how the communication with elite swimmers concerning the “feel for water” could be improved in order to better bridge the gap between biomechanical analysis and internal information transmission, which governs the necessary fine motor control to adapt to changing conditions, whether they are internal (fitness) or external (open water swimming). He pointed out that in his opinion the pressure difference of the flow around the hands would be the decisive parameter when asked what would be the representative agent of the feel for water. He wondered if the flow sensing understood from studies of fish movement might benefit elite swimmers and enhance other human aquatic space activities.

Indeed, the displacement of water mass can be felt and measured. Self-induced interaction simply means the transfer of metabolic energy via limbs action to the energy field of a unit of water volume. This change is represented by the term *pressure*¹. The meaning of the term *liquid pressure* is not equivalent to the term pressure used in solid physics since water gives way to solid objects. Hence the measurement of hydrodynamic pressure² in currents differs from the pressure term used in solid body physics. Studies on flow sensing in fish swimming revealed that pressure differentials [11] or pressure gradients [10] are the relevant agents that stimulate neuromasts to produce and send signals aiding to detect the aquatic world as well as self-induced stream characteristics – also used to distinguish the foreign fish from self-induced flow.

Considering these measurable parameters and that physics of sound and hydrodynamic pressure wave are similar [6] the idea arose to represent the hydrodynamic pressure changes due to swimming actions by audible sound. By the sound another feedback channel is used by the swimmer. As beneficial side effect, for the first time people outside the water can better learn what happens in detail. [8] presented the acoustic mapping of some kinematic variables representing the wrist and ankle location in relation to the pelvis per breaststroke cycle; they concluded that motor performance and perception of movements may be enhanced.

Sonification transforms information systematically from a data space to the auditory space [3], in this case the data space is the change of hydrodynamic pressure values due to displaced water mass. The method to convert data into sound is independent of the method to measure data. The selection of the optimal mapping and sound domain is not yet decided [1]; it can be ecologically oriented (e.g. sounds like falling water) or a purely free selected functional synthetic sound to accentuate an aspect. Hermann [4] in 2012 introduced the sonification of hydrodynamic pressure starting from data that were recorded and published by Toussaint [16] in 2002; they used – among others – a parameter-mapping sonification by which the change of the pressure to suction (during the outswEEP of the hand action in crawl stroke) was perceptually emphasized.

Considering the effects of unsteady flow aspects [9,16,7] the focus on changes in hydrodynamic pressure is justified, as it represents the origin of the physical *work* done on the water [18]. Kinematics of limbs actions is no indicator of flow effects since the effect of interaction with water mass is not

¹ energy change per unit volume and hydrodynamic pressure are measured in Pascal, respectively

² also named static pressure.

considered: drag does not explain the interaction effects even if repeatedly stated [7]. Unsteady flow means that time-average methods cannot be applied since static pressure varies locally and with time (body undulation) while so-called engineering turbulence can be treated by time-average equation [12].

Referring to the coach’s practical claim, a tool is required to allow for real-time sonification of pressure data as an audible immediate feedback for the swimmer and the coach, simultaneously. For the time being the use of functional sound representing invisible effects due to interaction of limbs and displaced water mass requires the selection of tools like pressure probes, pressure sensors, a sonification program, loudspeakers and equipment to be combined into a new setting that enables the measurements at the deck of a 25 m pool. The general objectives for this first test are to investigate how sonification can affect symmetry while swimming, which requires (a) a symmetry operationalization on the basis of pressures, (b) to measure the local flow-induced pressure changes, (c) real-time sonification and (d) to check different test situations with and without auditory feedback, finally (e) to receive the swimmers’ feedback using a questionnaire.

The current paper introduces a novel sonification system and method and focuses on the results from the questionnaire: Section 2 introduces the design of the whole measurement / sonification system; Section 3 explains asymmetry, and why it was chosen for these studies; Section 4 presents the sonification designs (direct and task-oriented mapping); Section 5 shows the design and execution of the experiments, whose results are presented in Section 6 together with a discussion; finally Section 7 concludes the paper.

2. SYSTEM DESIGN

The static¹ pressure component of water is sensed with the “piezo-probe” method, which uses an open hole on a large surface, over which fluid can flow. Electronic measures of such pressures are obtained with a set of 4 differential analog pressure transducers attached to 4 elastic plastic tubes with the open end. The open ends are placed as “piezo-probes” between the fingers of the two hands of the swimmers as depicted in Fig. 1.

The system setup, depicted in Fig. 2, is composed of 4 probes, 4 sensors, a microcontroller, a USB connection, a Notebook running GNU/Linux and SuperCollider sound synthesis environment and stereo speakers / earphones. A new measurement system was developed since an existing measurement system, the Aquanex [6], a device by which palmar-dorsal static pressure data are normalized to a unit area before being presented graphically, represents a closed structure that does not allow to process them in real-time, but only acquire data offline, thus impeding interactive real-time sonification. To transform hydrodynamic pressure into electric signals 4 differential pressure sensors (Freescale MPX5010DP) are used, connected to the Analog-to-Digital ports of an 8 MHz microcontroller (Atmel ATmega32). The chip, running a self-written firmware, samples the sensors at a frequency of 640 Hz

¹ Static pressure is not related to solid physics. Indeed, regarding flow physics, together with dynamic pressure (related to the speed of the flow), it is ‘the other’ component of the omnidirectional static pressure.

and performs a 10:1 averaging filter, providing a filtered stream of data at rate of 64 Hz to the application on the PC. SuperCollider, running on Linux Operating System on the PC, processes the incoming data and implements both data logging and sonification.

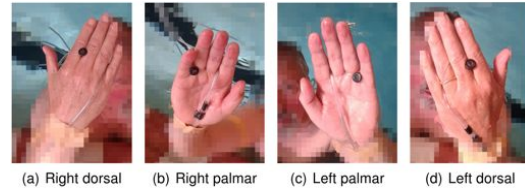


Figure 1: Positioning of the probes on the two hands

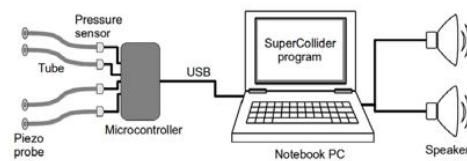


Figure 2: Setting modules and information flow.

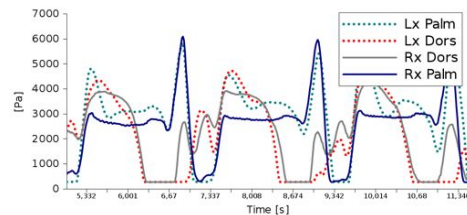


Figure 3: The hydrodynamic pressure over three breaststroke cycles for the four measuring points.

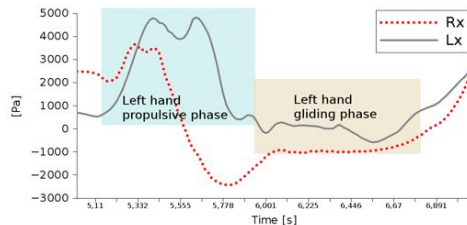


Figure 4: The hydrodynamic pressure-difference over one breaststroke cycle for each hand.

Figs. 3–4 show selected data segments acquired using the sensor system. The raw data quality is good, i.e. the signal-to-noise ratio is 34 dB (also thanks to the averaging filter implemented on the microcontroller). The data are qualitatively and numerically comparable to data reported in existing literature [14]. Fig. 3 shows a plot of the data for all four probes of three breast swimming cycles. Fig. 4 shows a plot of the data for the palmar-dorsal pressure difference for a single breast swimming cycle. From a perceptual point of view all subjects (authors included) that tested the system reported that latency between action and auditory feedback is negligible. The delay can be estimated to 20–30 ms (depending on the actual PC hardware and operating system).

3. SYMMETRY IN SWIMMING

In order to evaluate the methods and system a specific task was selected to (a) shape the sonification to provide task-relevant information, (b) give study-participants a clear goal optimization task, and (c) more easily evaluate the effect of the sonification. In particular the objective is to attend to and enhance symmetry of hidden effect of hand-water interaction while performing breaststroke swimming.

Breaststroke swimming, according to rules in competition, demands that the hands move simultaneously and on the same horizontal plane. Judges control it via visual inspection. The level of symmetry of hydrodynamic pressure while swimming is unknown. Measuring pressure-changes during simultaneous hand action, respectively, is a means to detect the level of symmetry. Pressure changes in a flow in general are the relevant stimuli to control the action cognitively. As a matter of fact the pressure changes are the cause of momentum change and if the pressure fields are not equal on both sides a resultant yaw will disturb the body locomotion.

3.1. Asymmetry Measures

The first step in the direction of enhancing symmetry is to define what exactly is meant by asymmetry and thus to operationalize the term in form of a mathematical expression. In fact, symmetry can be understood from different perspectives, e.g. that the *geometric shape* the fingers of left and right hand exhibit over time (when observing the swimmer from above) are axial symmetric to the body axis; or that the turning points (i.e. local maxima and minima) of the hands' velocity occur at the same time (independent of the actual value). In fact, symmetry has many facets. As the importance of hydrodynamic pressure was emphasized, here a definition is proposed and adopted for asymmetry from the time-variant net pressures of left and right hand (i.e. palmar minus dorsal pressure). The instantaneous asymmetry is thus defined as

$$\text{asym}(t) = P_l(t) - P_r(t).$$

The overall asymmetry can be computed over larger time intervals such as a complete breast swimming cycle, or over a 25m lap by integrating the absolute value $|\text{asym}(t)|$ of the instantaneous asymmetry over time. Note that the adopted definition of asymmetry is structurally identical to [5], yet here applied to pressures.

4. SONIFICATION DESIGNS

The sonification design process was started on the background of past experiences with sonifying offline data of the same type as introduced in [4], which were, however, created on the basis of 5 sensors attached to a single arm. In this current setup, two pressures (dorsal/palmar side) of each hand (left/right) are measured, leading to reconsider the mappings, and in particular the use of spatial information in sound.

A principle which remains plausible and which thus did not change is the *excitatory* mapping, which means in this case that the amplitude of the sound scales with the amount of activity. The underlying rationale is that the sound should fade into silence once the action stops. As pointed out in Sec. 3,

starting from the pressure difference $P_r(t)$, $P_l(t)$ between the palmar and dorsal piezo probes, resulting in zero values independent of the depth of the hand below water level¹. In consequence, the pressure values $P_r(t)$, $P_l(t)$ can be taken to represent activity or *energy transfer* on the water. Instead of a direct mapping of these values to amplitude, they are fed into leaky integrators $y[n] = (1-\lambda) y[n-1] + \lambda x[n]$, where x is the input and y the output at sample n . Thus the excitatory mapping is a linear mapping from y to the amplitude of the sound streams. The leak rate λ is manually tuned to get a half-time of approximately 0.5 seconds.

For this study the following two sonification designs, that represent different conceptual approaches were created.

4.1. Baseline: Absolute Continuous Sonification

A non-parametric baseline and direct sonification is chosen, with an analogue representation of $P_r(t)$ (resp. $P_l(t)$) as pitched tone, thus mapping the pressure exponentially from $[0, 5000]$ (hPa) to frequencies in the range of $[350 \text{ Hz}, 2637 \text{ Hz}]$ ². Dealind with activity of the left (resp. right) body side, a spatial mapping is highly intuitive. In result two continuous sound streams – with amplitude and frequency mapped as explained before – are played on the corresponding left and right sound channel of a stereophonic sonification.

The mapping was subjectively tuned to be appropriate in sound level and audible using in-ear headphones worn under a bathing cap. The sonification is highly direct, and a well-established baseline/benchmark sonification, familiar from auditory graphs and many other sonification applications in sports. Concerning the symmetry, users can extract information about the instantaneous asymmetry both from a displacement of the stereo position from the center position, as well as from attending to the pitch difference between the left and right channel. The latter is, however, difficult to pick up as the tones change rapidly in time. Tests were carried out also with mappings that are continuous in time but discretized and quantized in pitch (either on a semitone scale or even higher intervals such as minor thirds), yet the baseline continuous mapping was chosen for its simplicity.

A sound example for breaststroke swimming sonification is provided online³. Therein you can hear that the breast swimming cycle becomes a distinct auditory gestalt, whose shape varies between instances, but is clearly reproduced. A second swimmer exhibits basically the same structure but is quite different in the details, showing that the sonification is capable to convey structural differences as auditory shape. In the remainder of the text the direct mapping will be called S1.

4.2. Task-oriented Asymmetry Sonification

This sonification is particularly optimized to convey specifically and explicitly guiding information to experience and minimize asymmetry of hydrodynamic pressure between

¹ and thus the hydrostatic pressure.

² Corresponding to the MIDI notes 65 to 100, spanning roughly 3 octaves.

³ Listen to S1 on www.techfak.uni-bielefeld.de/ags/ami/publications/CHU2014-AIS/

the hands while swimming. As explained in Sec. 3.1. the adopted the definition of asymmetry is

$$\text{asym}(t) = P_r(t) - P_l(t).$$

To acknowledge that the asymmetry is a continuous and steady variable, the sonification is continuous, using a pitched, spectrally shaped and spatially panned single sound stream whose timbre is controlled by a brightness parameter. Specifically a continuous formant-filtered periodic signal using the SuperCollider UGen Formant is used:

```
SynthDef(\form, { |freq=540, amp=0.3, pan=0, bright=0|
  var sig;
  sig = Formant.ar(freq, 2*freq,
    freq*(0.1+bright)*10,
    5*amp*((0.1+bright)**0.8));
  Out.ar(0, Pan2.ar(sig, pan));}.add;
```

The fundamental and the formant frequency are coupled to achieve a pitch-dependent spectral shape. The brightness affects the bandwidth, and also the amplitude as the filtering otherwise perceptually affects the audible level. Amplitude is adjusted empirically. Given this synth, the following mapping was chosen to create an asymmetry-dependent sonification:

- the absolute asymmetry value $|\text{asym}(t)|$ is mapped to the brightness, so that higher instantaneous symmetry deviations become more salient as a spectrally richer sound;
- the average signed value, starting from the most recent zero crossing of the $\text{asym}(t)$ function is mapped to the spatial panning, so that the spatial location guides to the body side where more action is required to ‘symmetrize’ the activity;
- the average unsigned value is mapped to the frequency of the formant synthesizer in a narrow range, so that pitch does not dominate the perceptual effect compared to the other variables. The higher the pitch gets, the more relevant the asymmetry is.
- Given that it is generally preferable that sound fades without ongoing action, the absolute immediate pressure value $|P_r(t)| + |P_l(t)|$ is mapped to the amplitude of the sound.

A sound example for this breaststroke asymmetry sonification is provided online¹. In the remainder of the text the task-oriented mapping will be called S2.

5. EXPERIMENT

With the described setting a first time study has been carried out, while its evaluation needs different steps due to the complete novelty. In a first step, a questionnaire was presented in order to evaluate different aspects of acceptability to use sonification as a tool of intervention, and whether trends exist that are to be considered in further operations of the setting.

The aim of the study is to assist the swimmers in the task, to harmonize the effects of hand-water-interaction provided they detect asymmetries between left and right hand due to the functional sounds while swimming breaststroke.

Hypotheses: Swimmers alter the pressure-time curves that result from by the simultaneous interaction of each hand with the water respectively, in the sense of harmonization, if asymmetry-focused sonification is used as a feedback tool.

Study design: The new setup is used in a first field test concerning the symmetry of effects of hand-water interaction during breaststroke swimming. The data are acquired and the functional sounds are processed for each hand separately. Two different sonification mappings (S1 and S2) are provided. The swimmers are asked to attend to the sonification and in case they perceive an asymmetry between the sounds they should try to enhance their interaction, interactively.

Tests execution: The test design was composed of 4 different tasks with minor pause at turning points. (1): swim 2×25 m fully equipped without feedback, (2): swim 4×25 m fully equipped and feedback by S1 (S2), then (3): 4×25 m fully equipped and feedback by S2 (S1) and finally (4): 2×25 m fully equipped without feedback. In task 2 and 3 the swimmers were asked (a) to make their own judgment if the sounds per hand signalize asymmetry and (b) to decide whether to execute the cycle differently. No hints were given on how to change the effects of the interaction, because the 14 participants were merely recreational swimmers.

Swimmers (S&S): 14 swimmers (7 female, 7 male) aged 25.8 (± 7.78) years gave written consent to participate; 4 participants named themselves to be active swimmers since 11.2 (± 5.75) years at regional level, and 8 participants claimed to be familiar with the gliding variant in breaststroke. Nobody experienced in interactive sonification test before, S&S just know of a few examples, that sonification exists. The investigators could not present auditive examples of underwater interactive sonification of flow before the tests, since there were not yet any functional sounds worldwide.

Evaluation Method: A questionnaire is fundamental to figure out aspects concerning the setting, the sound acceptance, and whether the setting is a supportive tool to harmonize the effects of hand-water-interaction. The proof if this setting is a relevant feedback tool is not only a technical issue because the individual acceptance is also a matter of fitting, listening and finally cognition.

It was possible to refer to a questionnaire that had been proven successful in another study with Interactive Sonification [13]. The paper-based questionnaire is composed of several parts, statements and questions, whereby the answers to questions used a 7-point Likert ordinal scale ranging from 1 (totally disagree) to 7 (totally agree). The swimmers answered the questions directly after the 4 tests.

The questions asked included the influence of the tubes for the measurement of the pressure on hands or wearing the in-ear headphones, the audibility of the sounds, the emotionality of the sounds, the perceived effectiveness of the sounds as well as questions related to the attitude for further use of interactive sonification with the intention to adapt the planning and further execution of actions by S&S. Since two sounds were offered to the S&S, the question of the more accepted sound was obvious. The question most frequently asked by practitioners was whether the S&S swam faster using this type of intervention could not be checked in the questionnaire.

6. RESULTS

All 14 S&S filled out the questionnaire. They knew that the scale value (4) applies to "not know" or "no decision

¹ Listen to S2 on www.techfak.uni-bielefeld.de/ags/ami/publications/CHU2014-AIS/

possible" and is (1) for "totally disagree" of a statement, and (7) for "totally agree". Trend statements are based on means of the individual scale values per statement. Given the novelty of the test content and the inexperience of the S&S to deal with tasks focusing on water motion perception for the purpose of changing the hand-water interaction no clear trends in the rating of statements were hypothesized. The results of the questionnaire are presented in figures 5, 6 and 7, all showing Means. .

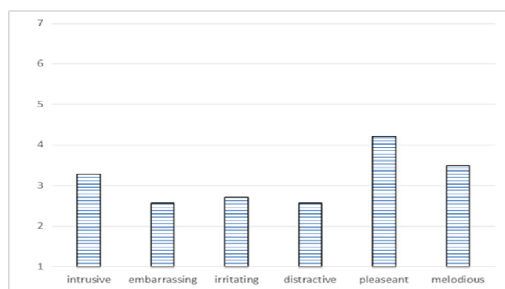


Figure 5: Evaluation of emotions of sound 1: 1 = totally disagreed and 7 = totally agreed.

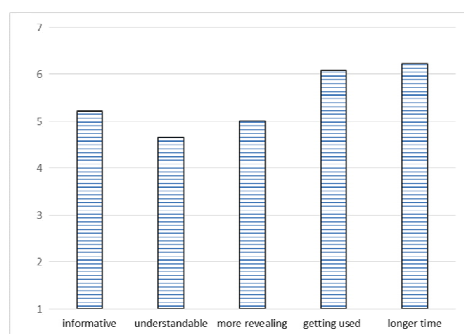


Figure 6: Evaluation of acceptance of sound 1: 1 = totally disagreed and 7 = totally agreed.

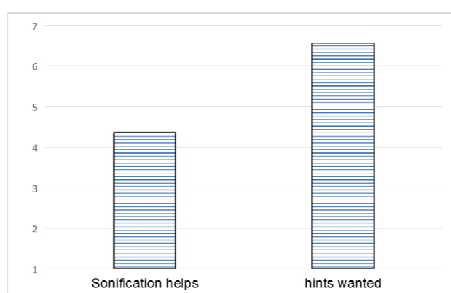


Figure 7: Evaluation of sound 1 as a relevant tool of intervention and rating "Hints wanted": 1 = totally disagreed and 7 = totally agreed.

The question on the preference of sound 1, the continuous baseline mapping, with respect to sound 2, the

task-oriented mapping, was answered by only 8 S&S, and the mean value of 4.0 can be interpreted as an expression of general uncertainty. Thus, for simplicity, the following trend statements concentrate on sound 1 only. The ratings for Sound 1 are related to emotional evaluations (Fig. 5): the statements "melodious" or "pleasant" were neither rejected nor accepted while negative attributions were rated "weakly rejected". Concerning statements "informative", "understandable", "more revealing", "getting used" and "longer time" the trend is conclusive that this sound should be represented in the future, supported by ratings as "weakly agreed" to "agreed" for the statements "longer time" and "getting used" (Fig. 6). The question "Did sonification help to work on symmetry of hand-water-interaction?" was generally "weakly agreed" and thus the sonification may be regarded as a potentially helpful intervention tool. The statement "I would like to know more about what I could do to prepare the intended symmetry" scored an average 6.5 showing strong support from all inexperienced swimmers. It is not inconceivable that this awareness will affect the other ratings. Therefore, a conservative trend prediction for statements is required, which should be respected by the researchers for any further investigation, also in the light that most of the mean rating values were hardly different from "weakly agreed" (Fig. 7). As a concluding remark, the noises due to pool situation were not considered to create problems to listen to the sounds. While swimming there is a natural perception of flowing water and the swimmers' judgment if the sounds match with that individual feel for water is just above "don't know the answer".

7. CONCLUSION

A new measurement setup for the interactive sonification of effects of hand-water-interaction was presented. The setup combining the measurement of the change of hydrodynamic pressure with functional sound mapping, was used for real-time feedback on the symmetry of effects of hand-water-interaction using two sonifications. Listening to the sounds while swimming breaststroke, swimmers tried to meaningfully merge sound and their own perceptions of the action, striving for a higher symmetry of effects of hand-water-interaction. It can be assumed that the novel sonification design making the asymmetry information perceptually available to swimmers is a welcome tool to enhance the effects of swimming actions. The sonification design is excitatory meaning that without ongoing interaction the sound fades into silence or by following a guidance paradigm, i.e. the spatial location of the sound indicates what body side requires more action to yield a symmetric activity. Different aspects of asymmetry are conveyed via perceptual variables like brightness and pitch.

It is noteworthy that, although the perception of the continuous baseline mapping (sound 1) seemed not to be an easy affair there was a promising agreement that the cyclic sound characteristic were in accord with the feel for water supported by the positive trend "sonification helps". In future, the swimmer will hear sound examples and will have the possibility to discuss adjustments before the tests. Moreover,

the swimmers who were initially less interested in the "secrets" of the determination of the hydrodynamic pressure became very curious about the internal relationship of hand-water-interaction. Presumably the situation when stroking and listening is happening simultaneously differs from just listening to the sounds. It would be a promising aspect for future applications. Furthermore, the selection of sounds should not overstretch the S&S. The setup can further be used, because no complaints were registered, i.e., the swimming movements were not hindered and the sounds were good to hear. It can be assumed that the sounds act as an intervention tool stimulating the S&S to change the hand-water-interaction. Finally, a familiarization to the sound can be expected after a few cycles, and also an outlasting curiosity using this tool during training.

For completeness it should be mentioned that only one other study has been undertaken elsewhere in the world: Chollet et al (1992) introduced a sonification feedback into crawl stroke, to shorten the swim times over 100 m after several days of training. To register only the palmar pressure, the swimmers had to wear paddles, which hindered the self-perception of change of hydrodynamic pressure in general around the hand; a sound was elicited when a predetermined threshold was exceeded. As a statistical result, the group receiving feedback simultaneously as sound and also about the pace swam the 100 m distance in comparably shorter time (no real values reported). As a reason a "finer correction of the propulsive distance of the hand" was introduced. In the study described here, no feedback on the current speed was given to the students. The researchers are working on the integration of speed into the auditive real-time feedback. Whether the students' judgment regarding assistance through interactive sonification, which they judged with a weak agreement, is true, will be examined yet on the basis of comparison of the pressure time-curves per stroke and per test.

Finally, initial analyses of the results curves for hydrodynamic pressure under different feedback situations reveal two trends: (a) it is likely that some of the swimmers did adapt to the feedback and (b) the asymmetry in the post test was more remarkable compared to pre test. Further research is required to clarify whether this asymmetry increase is due to fatigue or the intermediate use of sonification. As often, a study opens up more questions than it answered. The gained information encourage to continue the quest towards increased communication (and training) means for swimmers / coaches. It is regarded as particularly important to establish this new setup for regular training of few swimmers in a longitudinal evaluation, hoping to better understand the benefits and the potential of interaction sonification in swimming sports.

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