SONIFICATION OF PRESSURE CHANGES IN SWIMMING FOR ANALYSIS AND OPTIMIZATION

Thomas Hermann[1], Bodo Ungerechts[2], Huub Toussaint[3], Marius Grote[2]

[1] Ambient Intelligence Group, CITEC, Bielefeld University
[2] Neurocognition and Action Group, Faculty of Psychology and Sport Science, Bielefeld University
[3] Human Movement Science Group, VU University of Amsterdam

thermann@techfak.uni-bielefeld.de

ABSTRACT

This paper introduces the sonification of pressure sensor data measured while executing crawl stroke swimming. Swimming research aims at better understanding the flow conditions in detail to adapt swimming strokes to achieve maximal speed with minimal energy consumption. The fact that a pressure field is induced during the interaction of body and water is rarely considered. Any aquatic self-induced locomotion needs a *mediator* to cause a reaction in terms of body motion since there is no solid object a swimmer can push off from. The mediator function is taken over by the pressure field caused by the swimmer's actions. With our sonifications of the mediating hydrodynamic pressure – measured at 5 positions along one arm – we turn the hydrodynamic situation into a complex sonic rhythmical motive. These motives become auditory gestalts and we can identify differences and variations between patterns. We present six alternative sonification methods and discuss the resulting sounds in their ability to bring different patterns to attention. Our future goal is to help swimmers to optimize their motions by real-time sonification.

1. INTRODUCTION

Sonification allows to combine multiple data channels into a single sound stream, enabling listeners to understand coherences in the data that could otherwise be overseen. Similar to our ability to perceive simultaneously playing orchestra instruments as a musical piece, yet also to focus on a single instrument, we can benefit from multi-stream sonifications on different levels, such as for process monitoring, data analysis or diagnosis.

A particularly promising application field is the use of sonification to understand and support the coordinated movements of the human body, e. g. in dance, while playing a musical instruments, or during sports such as rowing [1], swimming [2], speed skating [3] or German wheel training [4].

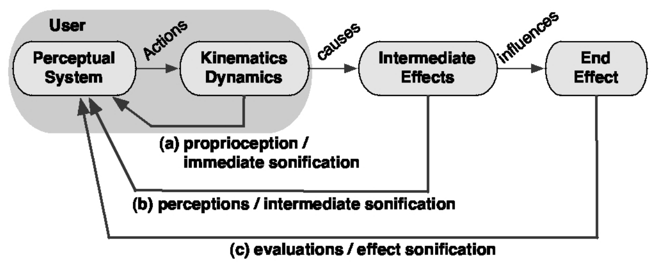

Figure 1: Sonification as Auditory bio-feedback: sonification can provide information from (a) the immediate state, (b) the intermediate effects, and (c) effect information. We suggest that the intermediate level may offer valuable information as a scaffold for learning.

The main benefits of sonification in the area of swimming research discussed in the paper are that (i) sound is accessible without demanding visual attention (which would be difficult underwater), that (ii) our auditory perception has a high temporal resolution, allowing tightly closed interaction loops in online applications, and (iii) we are highly sensitive to rhythms and changes of rhythms, and these patterns occur frequently in repetitive coordinated body movements.

1.1. Sonification of Intermediate Levels

Most sonification approaches in movement research research start from body postures and sonify the kinematic information to understand or support the execution of movements (few selected references are [2, 5, 6, 7]). On the other side, there are sonifications that represent the overall task-specific effect (such as the intracyclic fluctuation velocity in rowing [1]) as the source for sonification. Both feedback types enhance the better perception of the users' actions and their effects. However, we suggest that complex goal-driven actions can be regarded as a chain (as illustrated in Fig. 1) or even better as a continuum that have *intermediate* processes between the users' actions and the ultimate task-specific effects. Intermediate processes are all physical processes between the actions and their intended effect. Direct feedback on the behavior (e.g. kinematics, or the deviation from a nominal movement) may help to induce a specific motion pattern, yet this will not necessarily guarantee the wished total effect. On the other side, a mere feedback of the effect variable (e. g. the overall speed) may lack suitable information for the users how to refine their motion to achieve better results. Here we suggest to sonify the *intermediate effects* which are caused by the actions and in turn influence the end effect. It might indeed be difficult or impossible for a user to integrate an intermediate feedback for the self-regulation in the actual movement execution, but if the movement is a repetitive pattern, the user might be able to explore how the own actions systematically relate to sound changes and refine the movements for the subsequent repetitions.

This paper takes swimming sonification as an example for intermediate effect sonification. In contrast to former sonifications of swimming actions focusing on the distance of hands from the body [2], in this paper sonification represents the intermediate effect of hand actions that displace water and thus induce flow pressure. Specifically, we focus on flow patterns in sport swimming.

1.2. Sonification of swimming

According to elite swimmers' saying, effective swimming is a matter of "feel for motion of water mass" controlling the interaction of water mass and body limbs. However, little is known how to communicate this kinesthetic wisdom. Mostly swimming actions are studied via the kinematics of the external gestalt, leaving out the motion of water mass. Motion of water mass, however, induces hydrodynamic pressure and together with the pressure of the water column the entire interaction is represented by measuring the total pressure. The transformation of pressure signals into force-time-data may inhibit information because force is finally not a kinesthetic valuable, e.g. muscle tension. Our starting hypothesis is that the sonification of pressure offers a helpful new channel to support the communication about flow and on the sensation of flow, respectively.

Our primary goal in this paper is to develop and introduce sonification methods that allow to investigate the patterns of total pressure that occur during crawl stroke swimming using previously recorded data sets and videos. Thus we offer different methods to make patterns accessible as sound, we sonify data from different crawl speeds, and listen to the sounds to characterize the sonification methods in their ability to uncover relevant structures. In a future step these methods may serve as the basis for future online sonifications to be developed as a new teaching and training instrument, also to be used by swimmers in the water for self-regulation. Practically this can be done for instance by using underwater loudspeakers[1] or available swimming solutions for earphones. The latter do not only enable stereo sound projection, they also reduce the level of external sounds such as water splashing [2]. For sound rendering a belt-mounted mobile phone with underwater protection may be used.

—

The paper starts with an introduction to swimming research followed by some explanations of the relevant phenomena and the origin of the data. Section 3 introduces the selected data sets and explains the features to be used for the sonifications. Section 4 presents six sonification methods, explains why and how they have been selected and illustrates them with sound examples. We then discuss what auditory patterns stand out or surprise. The paper concludes with a discussion of the results and an outlook on future work.

2. SWIMMING RESEARCH – APPLIED HYDRODYNAMICS

This paper is about the sonification of water, set in motion by hand actions during crawl stroking. Whatever is said about the aquatic effect of hand actions, the origin of propulsion is still a matter of discussion. In most cases the kinematic aspects of body actions are emphasized. The hand action during crawl stroking is a cyclic 3D event in aquatic space and can be described using functional analysis whereby the following nodes (BACs)[3] are used: (1) Fingers enter water, (2) Hand moves forwards, (3) Body rolls to side of action, (4) Hand moves downwards, (5) Prolonged pronation of the hand, (6) Hand moves upwards, (7) Body rolls back, (8) Slicing hand moves outward, (9) Breathing in, (10) Hand moves forward. The duration of action below waterline is approx. 70–85% and above is 15–30% per cycle. In most cases the kinematic aspects of these body actions are emphasized. However, without regarding the interaction between hand and water mass the story is incomplete like the description of applauding with one hand. In the field of biomechanics of swimming, the conditions of self-induced locomotion is still a matter of discussion. Traditionalists emphasize the application of steady flow physics as used e.g. in ship construction. But the effects of hand actions cannot be limited to a question of forces since forces do not explain their origin.

Meanwhile the change of body form (per cycle) and the creation of unsteady flow conditions are recognized as a central aspect. Unsteady flow in the vicinity of a body is characterized by changes of flow velocities in time and space. In particular three agents are involved to generate effects: the body (i.e. the propelling parts like hands and feet) moves water mass while a pressure field is induced.

[1] e.g. Ocean Engineering Enterprises "OCEANEARS" (DRS-8)

[2] e.g. `http://www.h2oaudio.com/store/flex-waterproof-all-sport-buds-super-hero-blue.html`

[3] BAC = basic action concepts, see [8]

The term pressure in flowing water can be distinguished into hydrostatic, static and hydrodynamic pressure. Hydrostatic pressure depends on the mass of water and column height which represents the potential energy. Static pressure is like normal stress elementary to particles (mass and volume) at rest or streaming with others due to exerting pressure in all directions (like compression). Hydrodynamic pressure is an induced component due to the (local) flow velocity, representing kinetic energy. The sum of all is called total pressure. When the water is displaced by a body the total pressure is of particular interest. Displacement of streaming particles demands some pressure work (on a certain volume of water) which is an amount of work to force some mass m of a volume V from a certain pressure p_0 in a space with the pressure p_1. Due to this, the mass transfers some of the potential energy into kinetic energy by means of a third energy, the pressure work. Those locally altered pressure components induce "proto-vortices" [14] which contribute to locomotion whereas pressure drag is not a major player. Hand motion, starting from the water line where the hydrostatic pressure is small, is directed to a deeper level accompanied by increasing total pressure and finishes at the water level again. Continuous displacement of water mass by the hand induces a change of hydrodynamic pressure.

The secret to maximally propel the body forward per cycle is to move the hand continuously along a curved 3D line shaped like a crescent bowl, starting from (BAC 3) until (BAC 8). This movement makes use of the change of potential energy to kinetic energy by means of pressure work. This is what makes swimming so exhausting, except when a jet stream is created due to vortex-like flow structures, as they occur in tornados as a matter of the pressure distribution.

Swimming research is documented by a series of "International Symposium of Biomechanics and Medicine in Swimming" organized every four years since 1970. During these decades several studies related to pressure measurements were presented as well. Van Manen et al. [13] expect that wrong hand positions can be explained when unusual pressure graphs occur. Takagi and Wilson (1999) [11] put forward that without pressure no propelling force will be produced and a pressure differential method is potentially a useful means in stroke analysis.

Toussaint et al. (2002) [9] studied the pressure along the extremity of elite swimmers executing crawl stroke to investigate the axial flow component. Waterproof pressure sensors have been attached to different body point (shoulder, elbow, wrist, dorsal and palmar side of one hand, see Fig. 2) and calibration was done by measuring the hydrostatic pressure at different depth in water. Total pressure signals were recorded and low-pass filtered at 25 Hz while swimming at slow, intermediate and sprint speed. The key assumption is that flow effects act predominantly perpendicular to the local measuring point. Comparing total pressure–time-curves of

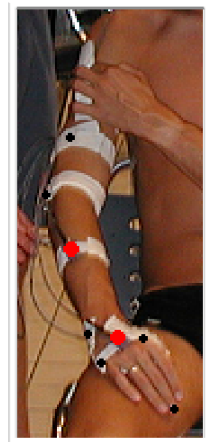

Figure 2: Sensor setup used to measure the pressure data at hand palm, hand back, elbow and shoulder.

all measuring points at sprint speed globally they show individual shapes and data were highest at the palm, at the dorsal side of the hand and at the elbow approx. 60% less, and at the shoulder lowest, approx. 80% less relative to palmar pressure, before all curves descend and turned remarkably to suction during the last 1/3 of the cycle period. Since dorsal pressure drops much more, the hand does not act like a paddle. When the pressure at the dorsal side of the hand is lower than the pressure at the shoulder this is completely opposite to what is hypothesized when taking the effective water column into consideration: the hand is deeper than the shoulder). A local pressure drop near the fingertips will induce an axial fluid flow along the arm and hand towards the fingertips which lead to an increased propulsion (pumped-up propulsion) and it suggests that swimming faster is more a matter of decreasing the pressure at the dorsal side of the hand than augmenting the palmar pressure. How these results can be used in practical questions such as teaching or self-regulation needs still to be evaluated.

Loetz et al. [12] point out that pressure-time recordings are an "essential complementary information". In search of communicating this information the sonification of pressure data might be a promising tool, not only because pressure waves and sound waves are alike. Since the link between kinematics of the hand and the resulting pressure or propulsion is not fully understood, a better communication between swimmers/experts is needed. Our vision is to give feedback to the swimmer directly – probably in conjunction with an effect variable such as the intracyclic velocity-variation – and to support the communication about flow and the sensation of flow between all experts. A necessary first step is to examine how sonification can be used for making a pressure field audible. For this first step the data of an experimental study published in a peer-reviewed journal by Toussaint et

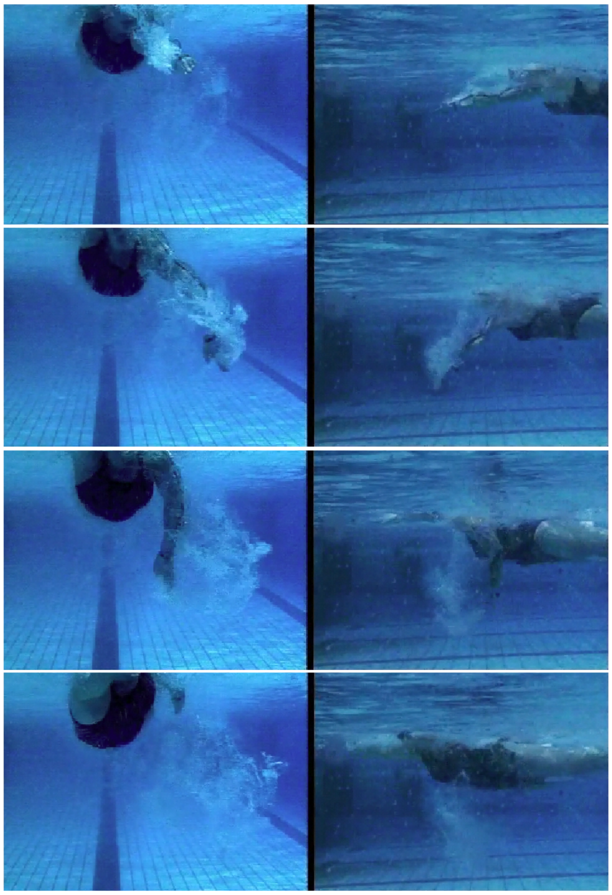

Figure 3: Key frames of a crawl stroke from front (left frame) and side (right frame): the air bubbles allow to understand the 3D trajectory. The video was recorded by the 3rd author and corresponds to the condition 'faster' shown in Fig. 4.

al. in 2002 [9] were used in this paper.

3. DATA AND FEATURES EXTRACTION FOR SONIFICATION DEVELOPMENT

For the development of the sonification methods we start with pre-recorded sensor data measured at different points along the upper limb of an elite swimmer in a study done by the co-author [9]. Fig. 2 shows the sensor setup attached to the arm of the swimmer. Selected video key frames of a crawl-stroke in the data set 'faster' are depicted in Fig. 3. Fig. 4 depicts the data sets for 4–5 crawl-strokes at slow, somewhat faster, faster, and sprint performance. The flat plateau between the strokes around a pressure of 0 Pa represent the intervals where the hand has left the water. While visual inspection allows to discover certain patterns such as the acceleration of the rhythm or the decrease of pressure below 0 Pa for the back of the hand at sprint, it is more difficult

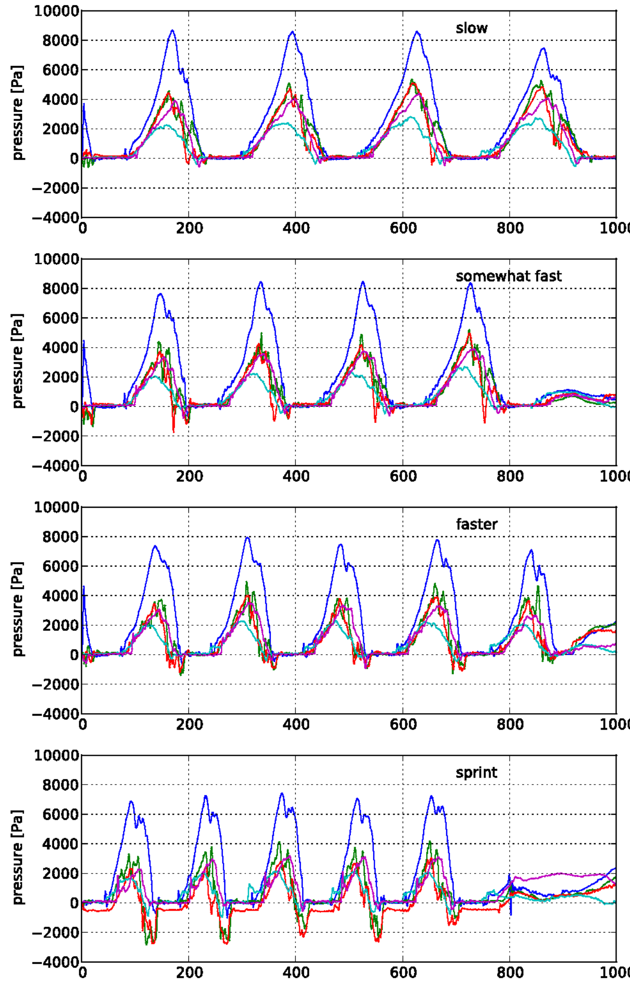

Figure 4: Pressure data at selected points of the one arm: shoulder (cyan), elbow (magenta), 1/3-elbow(red), palm of hand (blue), back of hand (green) as function of time for different crawl-velocities. The data are recorded at 1000 Hz, filtered to 25 Hz and down-sampled to 100 Hz.

to understand temporal patterns that involve all 5 time series from visual inspection alone.

We started from basic direct sonifications and gradually advanced towards task- and analysis-specific auditory displays that render features more salient that are expected to be relevant for understanding the phenomena. In this section we summarize data features and their computation as they are needed in the following section to specify the mappings.

Polarity: Firstly, we see that the data is ordinal with a defined zero value. To better perceive the polarity of a time series, it makes sense to use a feature $f_p(t) = \mathrm{sgn}(x(t))$. This feature, however, would exhibit many value changes when the pressure oscillates around 0 Pa so that a modified feature is superior which returns 0 if the value is below a threshold θ_0. A suitable value is around $\theta_0 = 150\,\mathrm{Pa}$.

Slope: The gradient can be computed by

$$f_g(t) = \nabla x(t) \approx (x(t) - x(t-\tau))/\tau \qquad (1)$$

where τ is 1/sampling rate. Since the data are low-pass filtered, this feature is quite stable and will be used for excitatory sonifications.

Local Maxima/Minima: for event-based sonification, local optima as well as zero crossings are candidate time points. Since the time series is low-pass filtered, a 3-point criterion provides a suitable condition to detect extrema:

$$\begin{aligned} f_{\min}(t) &= (x(t-\tau) > x(t)) \wedge (x(t) < x(t+\tau)) \\ f_{\max}(t) &= (x(t-\tau) < x(t)) \wedge (x(t) > x(t+\tau)) \end{aligned}$$

4. SONIFICATION METHODS

A data set is basically a 5-dimensional time series and there are manifold possibilities to sonify them, starting from a naive time-variant frequency modulation to task-specific designs. We document the development cycle and report six selected sonifications that provide gradually different 'sonic views' of the data. Please note that in this first design stage we are primarily interested in the sort of sound patterns that emerge when sonifying the data – we do not consider the aesthetics or the compatibility with environmental sounds here, yet we acknowledge that for any practical applications these are major factors for subsequent optimization. All approaches demand the manual selection of parameters (e.g. frequency ranges, level ranges, etc.). Most of them have been subjectively adjusted, and thus depend on personal design experience and taste. Limited space prohibits to discuss all choices in detail. Certainly, such parameters are subject to swimmer-specific personalization, should a method be selected for further consideration. Since we consider the sonifications as preparation for future real-time/online use, we map the real time to the sonification time throughout all methods. For detailed analysis, however, we provide 1:3 slowed down sonifications.

4.1. Standard oscillator bank mapping

As the data is in essence a multivariate time series, the first approach was to sonify the data in the most direct and naive way, using a simple mapping of the values to a bank of 5 sine oscillators. This provides a rough first sketch of the dynamics that is to be expected from the sonification. The mapping spreads the channels equally in spectrum, from upwards from shoulder, elbow, 1/3-elbow, via hand back to hand palm, one octave per channel. The pitch range is 9 semitones, ranging from the minimum to maximum values in the time series. Listening to sonification examples (see website[4]) S1a (slow), via S1b (somewhat fast), S1c (faster), S1d (sprint) allows to perceive the rhythm and the speed. Interestingly a different timbre is audible at the 'zero-pressure breaks' where the hand is above the water. This is because the mapping maps the min/max pressure range to the min/max pitch range, causing different pitch values for the zero-pressure values. The increasing pitch indicates that negative pressure (suction) increases on average with crawl-speed. An interesting pattern is, that the higher pitched tone leads (or preceeds) the change in the pitch wave. This pattern becomes even more salient in the following sonifications. Finally sound example S1e is a 1/3 slow-motion sonification of the first two crawl-strokes of the sprint data. We find that this slower pace makes it much easier to attend to patterns for analysis and learning, yet we think that with increasing familiarity with the features, real-time interactive use will be feasible.

4.2. Excitatory Oscillator Mapping

The naive mapping has the disadvantage that the sound remains equally audible independent of the activity. Therefore in this approach we create a sonification that remains soft to inaudible when the signals are constant. Practically, this is achieved by mapping the absolute value of the derivative $|f_g(t)|$ of each time series to the level of a white noise signal which is fed into a subtractive synthesis with controllable ring time and center frequency. Pitch depends on the value just as before, so low-pitched sounds correspond to the shoulder, high-pitched sounds to the hand. Yet now the polarity of the signal is additionally mapped to the spatial panning. In result negative pressures (which are here of particular interest) become salient as they are represented by sounds from the left audio channel.

The sound examples S2a, S2b, S2c, S2d are sonifications for the different speeds (slow, somewhat faster, faster, sprint). The emphasis of change makes activity audible and particularly it can be heard that a high-pitched action preceeds the larger sound wave. For faster speeds, it becomes audible that there is a distinct pitch curve at the end of each crawl-stroke, related to the negative pressures. It sounds like the high-pitch actions (hand) 'frame' the overall stroke. This becomes even better audible in the 1/3-slow motion sound example S2e.

4.3. Single-stream multi-parameter mapping

Multi-parameter mapping is an approach that binds different channels more tightly together into holistic perceptual units than the above multi-stream approaches. The time series is mapped to different parameters of a *single* continuous sound stream. The only problem is to find a good motivation

[4]see `http://www.techfak.uni-bielefeld.de/ags/ami/publications/HUTG2012-SOP`

for the specific selection of which time series controls what parameter, which may appear quite arbitrary. Yet once the mapping is defined and kept constant, it may just be learnt by heart and understood implicitly and then the sounds may be useful nonetheless. Specifically, we used a formant filter synthesis with pitch, level, center frequency, bandwidth, and panning as the 5 different parameters. The detailed mapping is as follows:

hand back	[min, max]	→	freq	[80 Hz, 120 Hz]
hand palm	[min, max]	→	cf	[200 Hz, 800 Hz)
1/3 elbow	[min, max]	→	bandwidth	[100 Hz, 1000 Hz]
shoulder	[min, max]	→	panning	['right', 'left']
elbow	[min, max]	→	level	[-40 dB, -6 dB]

We received a first opinion from the swimmer whose data has been recorded for the sonification who felt that the sound reminded her of a 'tortured cat'. Clearly such issues need to be considered once a design is to be optimized for sustained use. Concerning the patterns, the sounds allow the listener to follow the roughness of the wave around its maximum, and it becomes audible that there is an increasing roughness (in brightness and pitch) at the main wave with increasing crawling speed.

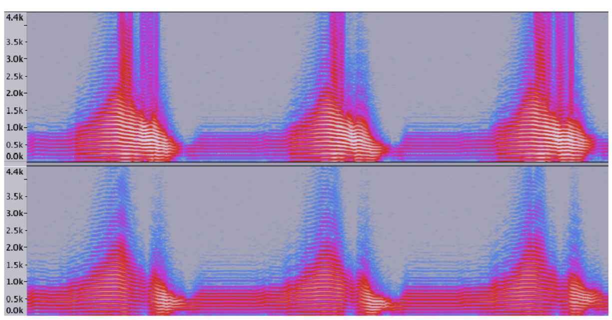

Figure 5: Spectrogram of the single-stream sonification: upper plot shows the left stereo channel. 3 strokes and subtle changes in level, brightness, and panning can be observed. This plot depicts the beginning of sound example S4a.

4.4. Harmonic Series mapping

Timbre is a multidimensional parameter, and while timbre itself may be difficult to characterize and memorize, timbre changes can be quite salient and characteristic. This motivates a variation of the previously demonstrated single-stream approach where now an additive model is used so that the different pressure variables control the activation of different harmonics. In result, the *timbre* – characterized by the amplitudes in the harmonic series – changes according to the pressure in the channels. A continuous playback, however, causes the harmonics to separate into different sound streams. For that reason we added an LF pulse to chop the signal into segments. Thereby we get a coherent onset in all harmonics which enhances timbre perception and differentiation. The pulse rate itself is a very salient parameter, and here it is used to represent the total pressure, while the hand back pressure is mapped to the fundamental frequency, but using only a small pitch variation, so that the timbre change achieves a balanced saliency.

Sound examples S4a–S4d are sonification for the different speeds from slow to sprint. S4e is, as above, the 1/3 slow-motion sonification. The sound supports the observation made above that activity in some channels (here: higher harmonics, hand) frame the major pressure wave.

4.5. Event-based Mapping

While all previous approaches started from a continuous representation of the time series, this approach follows the idea that continuous sonic information may deliver overly detailed information – in fact a condensation of the detailed values to 'key frames' of the pressure curve may not only leave the sonic signal easier to process, but we expect that this makes slight differences in synchronization between the different channels much better perceptible since they lead to changing patterns in the sequence of events. Practically we consider zero crossings (in both directions) and minima/maxima as the most relevant event types. For both minima and maxima, the actual value and the level value to the previous extremum of the other type are variables that can be used to parameterize details of the events. Sonification examples S5a–S5d start with the representation of zero crossings. The slope at the zero crossings is mapped to level and the sign of the slope determines spatial position, i.e. left/right stereo channel. Thus zero crossings from pos. to neg. (neg. to pos.) become audible on the left (right) channel.

As we listen to the sound examples with the intention to uncover rhythmical patterns between the four crawl-stroke speeds, we find that there is a characteristic distribution of pitches over strokes: they begin with high pitched tones and have mainly low-pitched events at the end. This corresponds to the palm getting far away from zero-pressure early and not returning near 0 pressure for the whole time, while other arm parts experience pressure around 0 Pa, particularly the shoulders. So again, the sonification emphasizes different features than those other approaches bring into the fore.

4.6. Task-specific mapping optimizations

Finally, we present a task-specific optimized sonification that invests a bit more knowledge from the domain experts into the design. Since the pressure polarity is one of the key variables for the swimming researchers, it makes sense to represent it by a very salient parameter such as pitch. Pitch, however, is also very useful to separate and distinguish the different channels. Thus in this sonification, the sign of the pressure is responsible for a 1–2 semi-tone shift of the 5 well separated channel-tones. The pitch values have been selected so that different combinations of polarities induces the perception of differently colored musical chords. Specifically the palm pitch (pos., neg.) was assigned to (g', a'), the tones for the hand back is (c', h), the 1/3-elbow to (g, g#), the elbow to (e, f) and the shoulder to pitch (c, H). So the hand, which is here of highest interest is assigned the highest pitch and pitch is systematically lower towards the shoulder. Sound level of these tones is an excitatory mapping from the absolute value of the derivative, and thus loud sounds indicate strong changes of pressure over time. The brightness of the timbre (i. e. bandwidth of the formant) is driven by the actual pressure value so that this information remains audible, yet appears slightly more in the background of this sonification.

Listening to the series of crawl-strokes from slow speed (sound example S6a) to sprint (S6d), we find a distinct pattern to emerge, namely that the highest pitch signal preceeds the other signals the faster the stroke becomes. Also, we become aware of harmonical patterns that correlate with the phases of the hand/arm actions. Since we cannot yet explore the sonifications in a closed interaction loop we cannot figure out what tone selections would be most suitable to turn characteristic pressure profiles for more effortless propulsion into a pleasant harmony or motif. If this should be possible, swimmers could simply be asked to attend to the motif and try to make it more harmonic. Such experiments are on our roadmap for ongoing research.

5. DISCUSSION

The paper explores the sonification of pressure data from swimming research. The presented methods contribute in different ways to understand patterns in the data, as discussed in the previous section. This section aims to look at the design and cooperation cycle from a meta level.

The different methods have been developed in the order of presentation and demonstrate various 'sonic views' on the same data. From method to method, various aspects are explored: the first approach is very generic and starts from minimal explicit knowledge; subsequent approaches invest particular domain- and task-oriented context, e.g. to turn the sonification more ergonomic for interactive use by using excitatory mappings. We found different things interesting while listening to the different sonifications, yet a lack of 'direct experience', i.e. to listen to the sonifications while swimming, makes it difficult to optimize the mappings further. So we regard these first explorations more as preparation to get a clearer feeling how to proceed once we can sonify pressure changes for the swimmer in situ. In one example, we synchronized the sonification to a video animation, and immediately felt that this makes it much easier to connect movement actions and (pressure / audible) effects.

The sonifications have not yet been optimized for aesthetics or compatibility with the soundscape of swimmers. This will become important not only for any practical use in teaching and training, but also much before, when trying to convince sportsmen and funding agencies to invest in this idea. It is, however, of lower interest if the main purpose is scientific discovery, e.g. to discover unknown relevant patterns in the data.

6. CONCLUSION

This paper contributes a new perspective on sonification as a feedback-channel for the user's action on different levels, ranging from the action level to the effect level. While the end points of this continuum have been explored in other work, we suggest the sonification of an *intermediate level* as something that we believe to be very relevant for scaffolding the learning, training and optimization of actions. For mastering or optimizing complex movements, all information levels on the continuum may be important at different stages. Thus, *multi-level sonifications* that convey information from all the levels (kinetics, intermediate effects and end effect) may be the most versatile approach, and even more so if the user or trainer can adjust the sound levels to let the most useful information stream stand out in the display as needed.

We have selected pressure data from crawl-swimming as they are an intermediate structure where we know from domain research that they matter greatly for optimizing self-propulsion. The sonifications in this paper were computed from pre-recorded data, yet the systematic variation of speed, and the availability of various executions of crawl-strokes at each swimming speed allows the listener to get an impression of what information the sonification is capable to offer. Finally, with this paper we have also documented an exploratory phase and gained some insight and gave an example how to organize research at the interface.

The next steps will be to optimize selected methods at hand of feedback from swimmers and other potential users (trainers, swimming researchers), to create sonified videos that will allow swimming researchers to better interrelate actions, data and sound, and to work towards a first real-time pressure sonification that allows us to experience the sonification while swimming. On the way we hope for discoveries and surprises.

7. ACKNOWLEDGMENT

We thank the German Research Foundation (DFG) and the Center of Excellence 277 Cognitive Interaction Technology (CITEC) that enabled this work within the German Excellence Initiative.

8. REFERENCES

[1] Schaffert, N., Mattes, K. & Effenberg A. O. (2010). Listen to the boat motion: acoustic information for elite rowers. In R. Bresin, T. Hermann, and A. Hunt, editors, Proceedings of the 3rd Interactive Sonification Workshop (ISon 2010), Stockholm, Sweden, 31–37.

[2] Effenberg, A.O. & Mechling, H. (2003). Multimodal Convergent Information Enhances Reproduction Accuracy of Sport Movements, Proc. 8th Ann. Congress of the European College of Sport Science (ECSS), ECSS, 196–197.

[3] Godbout, A., & Boyd, J. E. (2010). Corrective sonic feedback for speed skating: A case study. Proceedings of the 16th International Conference on Auditory Display (ICAD2010) Washington, DC. 23–30.

[4] Hummel J., Hermann T., Frauenberger C. & Stockman T. (2010). Interactive sonification of german wheel sports movements. Proc.ISon 2010, 3rd Interactive Sonification Workshop, KTH, Stockholm, Sweden, April 7, 2010. 17–22.

[5] Grosshauser T., Spieth, C., Bläsing, B., and Hermann, T. (2012). Wearable sensor-based real-time Sonification of motion and gesture in dance teaching and training. J. Audio Eng. Soc., (accepted for publication, to appear 2012).

[6] Grond, F., Hermann, T., Verfaille, V., and Wanderley, M. M. (2009). Methods for effective sonification of clarinetists' ancillary gestures. In Kopp, S. and Wachsmuth, I., (eds.), Gesture in Embodied Communication and Human Computer Interfaces: Proc. 8th Int. Gesture Workshop, LNCS, Berlin, Heidelberg. Springer Verlag.

[7] Höner, O., Hunt, A., Pauletto, S., Röber, N., Hermann, T., and Effenberg, A. O. (2011). Aiding movement with sonification in 'exercise, play and sport'. In Hermann, T., Hunt, A., and Neuhoff, J. G., editors, The Sonification Handbook, chapter 21, p. 525–553. Logos Publishing House, Berlin, Germany. Höner, O. (chapter ed.).

[8] Schack, T. & Mechsner, F. (2006). Representation of motor skills in human long-term memory. Neuroscience Letters, 2006, 391, 77–81.

[9] Toussaint H. M., v. d. Berg, C. & Beek, W. J. (2002). Pumped-up propulsion during front crawl swimming. Med Sci Sports Exerc. 34, 314–319.

[10] Loetz C., Reischle K. & Schmitt, G. (1988). The evaluation of highly skilled swimmers vai quanitative and qualitative Analysis. In: Swimming Science V, (Ed. by B. E. Ungerechts, K. Reischle & K. Wilke), Human Kinetics, Champaign, IL. 361–367.

[11] Takagi, H. & Wilson, B. (1999). Calculating hydrodynamic force by using pressure differences in swimming. In: K. L. Keskinen, P. V. Komi, & A. P. Hollander (Eds.), Biomechanics and Medicine in Swimming VIII. Finland: University of Jyvaskyla. 101–106.

[12] Loetz C., Reischle K. & Albrecht C. (1984). The dynamics of patterns in swimming. Leistungssport 6, 39–43.

[13] Van Manen, J. & Rijken, H. (1975). Dynamic measurement technique on swimming bodies at the Netherlands ship model basin. In: Swimming II, (Ed. by L. Lewillie & J. P. Clarys), University Park press, Baltimore. 70–79.

[14] Videler, J. J., Müller, U. K., & Stamhuis, E. J., (1999). Aquatic vertebrate locomotion: wakes from body waves. J. Exp. Biol. 202(Pt 23):3423–30.