# INTERACTIVE SONIFICATION OF GERMAN WHEEL SPORTS MOVEMENT

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## ABSTRACT

This paper presents the design, implementation and evaluation of a sonification system, which gives real-time auditory feedback about the rolling motion of sports equipment called German wheel to a performer who is carrying out acrobatic moves on it. We explain the structure and functionality of the sonification system namely the modules for a) data acquisition, which uses a magnetometer to collect data about the wheel's motion, b) feature extraction, which derives more high level information, such as the location of the wheel, from the collected data and c) the sonification, which produces the acoustic representation. Several sonification approaches are introduced and finally an exemplary study that aims to examine whether such additional convergent audio feedback can lead to an improved performance of wheel moves is presented.[1]

## 1. AUTHOR KEYWORDS

movement sonifciation, interactive sonification, auditory interface,

## 2. ACM CLASSIFICATION KEYWORDS

H5.2. Information Systems: User Interfaces: Auditory (non-speech) feedback H5.5. Information Systems: Sound and Music Computing: Modeling

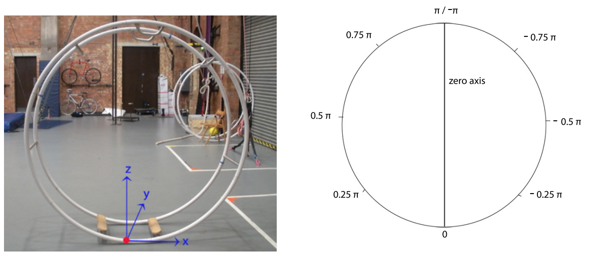
## 3. INTRODUCTION

Human perception is highly multimodal. Besides improving overall coherence, information on the acoustic channel reinforces the allocation of redundant information on the visual channel. In nature these properties of sonic feedback are used to the advantage of living organisms when retrieving information related to physical actions. A good example in which auditory information, as part of the multi-modal perception, contributes to motor control and task learning is the natural sound in sports.[2] The German wheel is a sports equipment on which many very dynamic moves are performed. These include very fast changes of perspective and can only be performed in a short time window, when the (rolling) wheel momentarily stands still or slows down. This means that they are highly time-critical and that the visual channel can barely be used for real-time feedback, because of the constant and quick changes of perspective the performer experiences. The suitability of sound to express time variant information and its complementary role in the natural perception of physical actions led to our hypothesis that additional auditory feedback, supplied by a real-time sonication system, can contribute significantly to an improved performance of wheel moves. The following sections describe the implementation and evaluation of the closed-loop audio feedback system, which we implemented for the purpose of substantiating our hypothesis.

## 4. RELATED WORK

Alongside other applications sonification allows to generate acoustic feedback for physical actions that do not naturally produce sound. Blindminton, a game similar to Badminton that can be played using auditory feedback only [4] and Digiwall, a hybrid between a climbing wall and a computer game [5] are examples from the field of sports games. Chen et al. describe their design of a real-time multimodal biofeedback system for stroke patient rehabilitation in [6]. Kapur et al. present a framework for sonification of Vicon motion capture data that aims to provide the infrastructure to map motion parameters of the human body to sound (see [7] ). Finally, and this is the most relevant category for this project, sonification of movement data has been used for *monitoring and skill learning* of several different categories of movement. In [8] Effenberg showed that the absolute accuracy of the reproduction of countermovement jumps was significantly better under convergent audio-visual conditions. In [9] Hermann, Höner and Grunow present their approach for the use of sound to assist the analysis of tactical training in sports games. Bovermann et al. designed 'juggling sounds', a system for real-time auditory monitoring of juggling patterns [10]. Kleinman-Weiner and Berger examine the sonification of a golf swing [11] and sonification of fine motor skills is presented by Fox and Carlile in [12]. Their system, called SoniMime, sonifies hand motion and works towards the goal of assisting a user to learn a particular motion or gesture with minimal deviation.

## 5. THE GERMAN WHEEL AND FEATURES TO REPRESENT ITS MOTION




(a) *The German wheel at* $\varphi = 0$ (b) *Angles, which the wheel can be in.*

[1]The work was done for the first author's Masters dissertation and the complete dissertation report can be found in [1] at http://www.techfak.uni-bielefeld.de/ags/ami/publications/Hummel2009-ISF/.

[2]This is discussed for tennis for instance in [2] and for rowing in [3])

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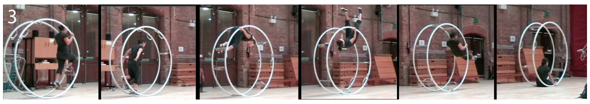
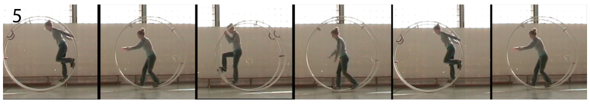
A German wheel is a sports apparatus, which consists of two rings that are connected by 6 bars (see Figure 1(a)). We identified a range of different German wheel move categories, and our research focuses on those, in which the wheel roles in a straight line. In centralised moves the centre of weight of the performer


(c) *Centralised straight line move*




(d) *Decentralised straight line move*




(e) *Basic rock*

Figure 1: *Different wheel move categories.*

is in the centre of weight of the wheel (see Figure 1(c)). Imagine someone doing a cart-wheel with a wheel around them, as depicted in Leonardo da Vinci's 'Vitruvian Man'. Decentralised moves are performed on one of the bars. If this bar is not directly above the centre of mass of the wheel, the performer's weight induces a or contributes to the rolling motion of the wheel, because it pushes the bar down towards the floor (see Figure 1(d)). A basic rock is a move which is used in both categories to generate momentum. The performer stands with one foot on each of the two foot-plates and straightens and bends the legs alternately, thereby causing the wheel to swing. The rock can be performed facing the rolling direction of the wheel or facing out (see Figure 1(e)).
For both categories of moves it is important for the performer to know which orientation the wheel is in and how fast it is rolling. The rotational angle of the wheel $\varphi$ which represents the orientation of the wheel in relation to an initial orientation and the angular velocity of the rolling wheel $\omega$ are therefore continuous features, which appear to be adequate to represent the motion. We define that $\varphi = 0$, when our reference point, which is located between the footplates, is on the floor as displayed in Figure 1(a). As many German wheel moves are highly time critical the execution of a move often has to take place within a very narrow time window. Based on our own knowledge and on statements of wheel performers we found the following discrete features, which indicate the right timing for the execution of a move: The moment when a specific bar reaches the highest point on top of the wheel or the lowest point where it passes the floor and the moment in which the wheel changes rolling direction.

## 6. THE REAL-TIME SONIFICATION SYSTEM

The following four modules of the real-time sonification system were implemented in the programming language SuperCollider.

### 6.1. Data acquisition

The first step in the generation of auditory feedback is the collection of data about the wheel's motion from which we then calculate the features. Due to its transportability, low cost and scalability for the use with several wheels we chose a MicroMag 3-axis

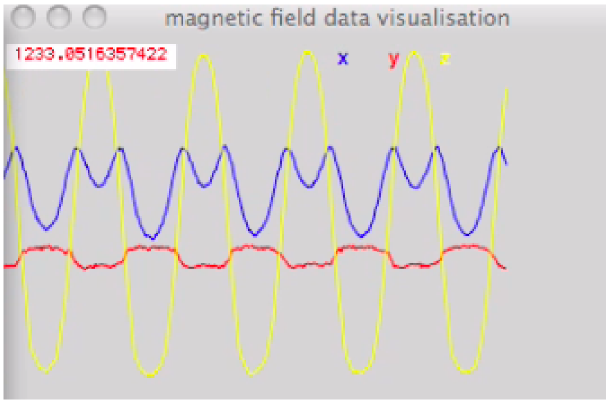



Figure 2: *3-D data measured by the magnetometer for a basic rock.*

magnetometer from SparkFun Electronics for our implementation (see Figure 3). For other applications more expensive combined sensors such as the MT9 from XSens technologies may be more suitable, as they are less prone to distortions.

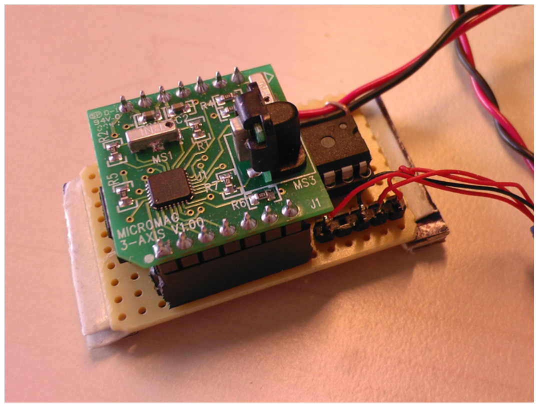


Figure 3: *MicroMag 3-axis magnetometer module assembled for the capture of German wheel rolling motion.*

### 6.2. Feature Extraction

In the following explanation we presume that the world coordinate system and the sensor coordinate system are congruent when the wheel is in its initial position ($\varphi$=0), and that their $y$-axes are orthogonal to the wheel's rolling direction (see Figure 1(a)). The MicroMag 3 axes magnetometer returns a 3D magnetic field vector $\vec{v}$. When $\vec{v}$ measures the magnetic field of the earth, it always points towards the magnetic north pole similar to a compass.
In a straight line move when the wheel rotates around the $y$-axis by $\varphi$, so do the $x$- and $z$-axis of the sensor that is attached to the wheel. To assign a value to $\varphi$ we compute the angle between this rotating $x$-axis and a constant reference vector in the x/z-plane of the world coordinate system. As $\vec{v}$ is constant, its projection $\vec{v}_{xz}$ onto the x/z-plane is constant as well and we can use it as a reference. The angle between $\vec{v}_{xz}$ and the $x$-axis of the sensor in world-coordinates provides the rotational angle of the wheel. We measure $\vec{v}$ in sensor coordinates however. The angle between $\vec{v}_{xz}$ and the sensor's $x$-axis in world-coordinates equals the angle between $\vec{v}_{xz}$ and the sensor's $x$-axis in sensor coordinates due to our definition of the coordinate systems. This angle again can easily be calculated by applying the arctan2, which returns the angle

between a vector (here $\vec{v}_{\mathrm{xz}} = (v_{\mathrm{x}}, v_{\mathrm{z}})^T$) and the $x$-axis of the coordinate system:

$$\varphi^* = -\text{arctan2}(v_{\mathrm{x}}, v_{\mathrm{z}}) \tag{1}$$

This calculation returns values between $-\pi$ and $\pi$ (see Figure 1(b)). To get the angle of a bar $\varphi_{\mathrm{bar}}$ the fixed angle between the bar and the reference point (see Figure 1(a)) can be added. To derive the angular velocity $\omega$, we differentiate this angle numerically:

$$\omega = \frac{\Delta\varphi}{\Delta t} = \frac{\varphi(t_{\mathrm{n}}) - \varphi(t_{\mathrm{n\text{-}k}})}{t_{\mathrm{n}} - t_{\mathrm{n\text{-}k}}} \tag{2}$$

The lowest points, highest points and changes of rolling direction, which indicate the correct timing for the execution of a move can be found by observing several successive values of $\varphi_{\mathrm{bar}}$. Every time the bar reaches a lowest point the value passes zero. At each highest point it jumps from $-\pi$ to $\pi$ or vice versa. In both cases it experiences a change of sign. Every time the wheel changes its rolling direction, $\varphi$ reaches either a minimum or a maximum, depending on the original rolling direction.

## 6.3. Sonification approaches

The system uses the described features to produce an acoustic representation of the wheel's motion. We implemented the following four different sonification approaches[3]. We chose these approaches, because they represent different levels of adaptation to the task which the sonification is to support. For each sonification Table 1 shows an overview of the used mappings of movement features to sound features.

### *6.3.1. Direct-data Sonification*

The Direct-data approach produces a sonification directly from the magnetic field input data, thus providing a sonification, which can be used for various types of three dimensional data and for arbitrary applications. As this approach does not use previous knowledge about the wheel, it leaves the interpretation of the resulting feedback up to the performer on the wheel.

The Direct-data sonification generates three sound streams. Each sound stream is a pulsing sound, whose pulse rate is controlled by one of the components of $\vec{v}$ (similar to a Geiger-counter). To distinguish the three streams, each data axis is assigned a fixed pitch. Intuitively there should be no acoustic feedback if no changes occur (when the wheel stands still.) For this reason the amplitude of each sound stream is set to be dependent on the changes in the respective axis.

### *6.3.2. Cartoonification*

In sonification the term Cartoonification is used for acoustic feedback that synthesises, amplifies and exaggerates real-life sounds. This allows the user to use real-life experience for the interpretation of the sound.

A natural rolling sound is produced by the friction between the floor and the rolling object. Bumps in the floor or on the object can cause additional sound events. To synthesise a rolling sound for the wheel we imitate these natural properties as follows. A continuous rolling sound, that mimics the friction between floor and wheel, is produced by playing a recorded friction sound. To cartoonify the rolling sound further and supply more audible information about the wheel's motion, we add the assumption that each of the six bars of the wheel produces a clicking sound when it reaches the floor. The volume and the velocity of the playback of the friction sound and the volume of the clicking sounds are controlled by the velocity of the wheel to avoid the production of sound when the wheel is standing still.

### *6.3.3. Vowel synthesis sonification*

The main idea of the Vowel synthesis sonification approach is to map the rotational angle of the wheel to a corresponding vowel sound or an interpolated sound between two vowels. The idea is motivated by the fact that the listener is already highly adapted to the task of distinguishing between vowels, as they form an essential part of speech. Besides others, vowel-based sonifications have been used for the sonification of hyperspectral colon tissue images, EEG data and hand motion due to these advantages (see [13], [14], [12], [15] and [11].)

Formants are peaks in the characteristic frequency spectrum of a sound. They can be synthesised with formant filters, which alter a frequency spectrum by amplifying the frequencies within a certain bandwidth around a given formant frequency. Vowel-like sounds can be generated by applying several formant filters (five in our case) according to the formant frequencies of the voice to a complex sound source. The resulting sounds are superimposed to form the vowel (also see: [16], [17] and [15]). The pitch of the vowel is determined by the fundamental frequency of the excitation sound source.

A natural vowel sound consists of a voiced and an unvoiced part. The voiced part is predominant for example when an opera singer is singing and the unvoiced part stands out when someone is whispering. For our Vowel synthesis sonification we use the vowel synthesiser described in [14], which allows to use a mix of the voiced and unvoiced parts. We only used the voiced part however as we found that this allows a more accurate perception of the data.

We use the vowel synthesiser to map the current angle of the wheel to a vowel sound in the spectrum 'a, e, i, o, u'. At a rotational angle of $\varphi = 0$ a clear 'a' is produced at $\varphi = \pm\frac{\pi}{4}$ an 'e' is audible etc. We chose the representation of each half circle by the spectrum 'a, e, i, o, u' because a mapping that preserves the symmetry observed in many wheel moves seemed perceptually coherent.

For all angles, that lie between the values assigned to two vowels, the frequencies, bandwidths and amplitudes of the formant filters adapt linearly interpolated values. The fundamental frequency, thus the pitch of the voice, is controlled by the angular velocity and ranges from 100 Hz to 166 Hz. When the full range of spoken language (100 - 350Hz) was used the acoustic results sounded overloaded. In order to avoid the wheel producing sound feedback when it is standing still, the angular velocity also controls the volume of the vowel sound. Additionally changes of rolling direction of the wheel are represented by a sound grain, which is reminiscent of the sound of a rebounding stick when a xylophone or gong is struck. The pitch of this sound is determined by the rotational angle of the wheel when the change of rolling direction occurs. To avoid many irrelevant changes of rolling direction being audible due to noise or small oscillations in the input data, the temporal distance ($t_{\mathrm{diff}}$) to the last change of rolling direction and the average angular velocity ($\omega_{\mathrm{av}}$) between them dictate the volume of these sound events. Additionally the highest points of the bars which most moves are performed on are sonified as clicking sounds.

### *6.3.4. Event-based sonification*

The Event-based sonification is motivated by the suitability of sound to represent time dependent patterns and the ability of human auditory perception to recognise the resulting rhythms. Event-based parameter mapping generates a sound event every time certain

[3]Example videos with sonification can be found on: `http://www.techfak.uni-bielefeld.de/ags/ami/publications/HHFS2010-ISO/`

Table 1: *Mappings of data features to sound features for the different sonification approaches*

| data feature | Direct-data | Cartoonification | Vowel | Event-based |
|---|---|---|---|---|
| data value | rate of pulsing sound | | | |
| change of data values | volume | | | |
| rotational angle $\varphi$ | | | 0 to $\pm\pi$ mapped to vowels 'a, e, i, o, u' | stream of sound events and its pitch (one event for each trespassed threshold ) |
| angular velocity $\omega$ | | volume/playback velocity of friction sound file | volume and pitch of vowels | density of sound events) |
| lowest points of bars | | clicking sounds | | same events but louder |
| changes of rolling direction | | | sound events reminiscent to xylophone | triangle sound |
| $\varphi$ at change of direction | | | pitch of xylophone sound | pitch of triangle sound |
| $t_{\text{diff}}$ and $\omega_{\text{av}}$ | | | volume of xylophone sound | volume of triangle sound |
| highest points of some bars | | | clicking sound | clicking sound |

conditions are fulfilled. The main input feature of the Event-based approach is $\varphi$. The values between 0 and $\pm\pi$ are divided into 30 equal steps (steps=30), which are numbered consecutively from 0 to 30 for each half circle. The values between 0 and $\frac{1}{30}\pi$ for instance are assigned to the step $s = 0$. Every time the rotational angle traverses a step a sound event is generated. The frequency of the sound events depends on the step that is being traversed and thereby on the rotational angle of the wheel:

$$f = 100\text{Hz} + f_{\text{step}} \cdot s \qquad (3)$$

Here $f_{\text{step}}$ is the difference in frequency between the auditory representation of two consecutive steps. The range of angles that are associated with one step has the size $'stepSize' = \frac{\pi}{steps}$. For each incoming angle $\varphi$ we find the step $s(\varphi)$, that the current angle is assigned to, by calculating how many steps of the size $stepSize$ fit into it and rounding the value down.

$$s^*(\varphi(t)) = \frac{\varphi(t)}{stepSize} = \frac{\varphi(t)}{\frac{\pi}{steps}} = \frac{\varphi(t) \cdot steps}{\pi} \qquad (4)$$

$$s(\varphi(t)) = \lfloor s^*(\varphi(t)) \rfloor$$

The resulting value is compared with the step of the previous angle $s(\varphi(t-1))$. If they are not equal a new step is reached and a sound event is generated.

We experimented with different amounts of steps and finally decided to use 30. For higher amounts of steps, the sound events are not clearly distinguishable and for lower amounts the resolution of the transmitted information is not as high.

The absolute value of the velocity is audible in form of the density of sound events and the frequency of each sound event gives information about the absolute position of the wheel.

The Event-based approach is based on the human ability to recognise and analyse rhythms. Additional characteristic rhythms can be produced by generating a sound event every time one of the bars reaches the floor. We therefore detect the timing of all lowest points of the bars and a sound event is generated for each of them. These sound events are generated by calculating $s^*$ when a lowest point is reached without rounding down. The fixed angles in which the bars touch the floor lie between two steps and likewise the frequency of the effected sounds lie between the two corresponding frequencies. The resulting sound also carry information about the rotational angle of the wheel and thus about which bar is on the floor. To ensure that the resulting rhythm is clearly audible and does not dissolve into a mere part of the 'continuous' rolling sound the amplitude of the sound events that are generated for each lowest point are significantly higher, which acoustically lifts the sound into a second sound layer.

A third layer of sound is formed by sound events which are generated for every change in the wheel's rolling direction. For their acoustic representation we chose the sound of a triangle instrument, the pitch of which adapts to $\varphi$, measured when the rolling direction changes. As in the Vowel synthesis sonification the volume of this third sound layer depends on $\omega_{\text{av}}$ and $t_{\text{diff}}$.

Due to the momentary stillness when the wheel changes its rolling direction, a short silence is audible before and after the stroke of the triangle. The resulting sounds is particularly pleasant if the absence of movement, and therefore the silence, is relatively long. This acoustic representation encourages the user to maintain the stillness for as long as possible. This effect is of special interest for the execution of a range of wheel moves, as for most of these moves a longer stillness means more time for the execution of the (usually time-critical) move.

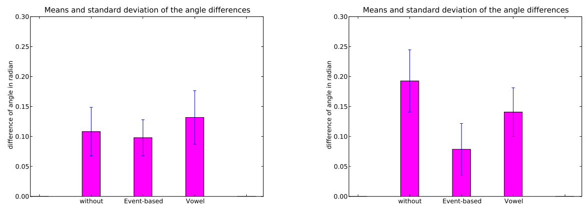
## 7. STUDIES AND EVALUATION

Due to their highest adaptation to the task of the performer, the Vowel synthesis sonification and Event-based sonification were chosen to conduct a comparison between a performance with and without sonification. The study gives an indication about the correctness of our hypothesis, which claims that a performance improvement can be achieved for a wheel performer through the use of sonification. The experiments were carried out with a group of seven novices, who had never used a German wheel and four experts, who had extensive experience using it. In both cases experiments were conducted under three different conditions: without sonification, with Vowel synthesis sonification and with Event-based sonification. The task of the participants was to perform a basic rock facing the rolling direction of the wheel (see Figure 1(e)). The aim was to let the swing come up to the same height in the front and the back. Novices were allowed a time span of ten minutes without sonification to practice the basic rock. Before each of the runs with or without sonification the participants were given two minutes to practice under the forthcoming condition. For each run the task was then carried out for a time span of approximately two minutes, during which data was recorded for later evaluation.

Due to our definition of $\varphi = 0$, bringing the swing up to equal heights in the front and the back is equivalent to rotating the wheel about the same absolute angle $|\varphi|$ away from the initial position. The difference $\Delta\varphi_{\text{value}}$ between the absolute angles measured at two consecutive changes of rolling direction was therefore used as our measure of performance. A smaller value of $\Delta\varphi_{\text{value}}$ indicates a better performance of the task. We refer to changes of the rolling direction as extrema as they are indicated by an extremum of $\varphi$.

$$\Delta\varphi_{\text{eval}} = |\,|\varphi(extremum(i))| - |\varphi(extremum(i-1))|\,| \qquad (5)$$

The means and medians of our measure of performance $\Delta\varphi_{\text{eval}}$ are compared in the bar charts in Figures 4(b) and 4(a). The charts do not show large differences under the three conditions for novices. For experts however a far larger difference is observable, in particular between the conditions 'without sonification' and 'with Event-based sonification' (see Figure 4(b)). To statistically support our




(a) *Novices* (b) *Experts*

Figure 4: *Means and standard deviations of the measure of performance $\Delta\varphi_{eval}$ without sonification, with Event-based sonification and with Vowel synthesis sonification for novices and experts*

hypothesis that the lower means of the measure of performance $\Delta\varphi_{\text{eval}}$ for experts was effectuated by the sonification, we conducted a Student's t-test (see [18]). When two distributions are thought to have the same variance, but a different mean, the t-test returns the test statistic $t$ from which a probability $p$ arises. This probability states how probable it is that the difference of the means is coincidental.
We used the t-test for dependent samples[4], because the same group of participants was tested twice. As input distributions we used the means that were observed for each expert without sonification and the means that were observed with Event-based sonification. The value we obtained was $p = 0.036$, which is below the level of significance $(0.05)$. Thus the null hypothesis of the t-test, which claims that the difference of the mean is coincidental, can be rejected. We can therefore assume that the coherence between the use of the Event-based sonification and the lower mean value of the measure of performance was not coincidental and that the Event-based sonification influenced the performance positively. For the Vowel synthesis we calculated $p = 0.448$ and can therefore not reject the null hypothesis that the lower mean is coincidental. All conclusions, including those that suggest less effectiveness of sonification for novices and for the Vowel synthesis approach have to be mediated by the fact that the study includes only small numbers of participants. Statements of the participants indicate that a longer adaptation time to the wheel would have been necessary for the novices to enable them to apply changes according to the multi modal feedback they perceived.

## 8. CONCLUSION AND OUTLOOK

The study conducted with the Vowel synthesis and Event-based sonification confirmed our hypothesis that sonification used as acoustic real-time feedback can significantly improve the performance of a German wheel move. In our study we observed different results for the Vowel synthesis sonification and the Event-based sonification even though they are based on a similar set of features. This shows that unequal sound settings can lead to very different results. A wider range of sonification approaches should therefore be designed and tested to elicit their advantages and disadvantages. This could include an implementation that is more adaptable to single moves or users or that uses predictive calculations. To further circumstantiate our findings more extensive psychophysical experiments are needed. A range of different tasks, that focus on different sub-tasks, which a wheel move includes, should be tested with different sonifications and a long term study should be undertaken to allow the judgement of the skill learning of more complex moves. Furthermore it should be tested if it can be statistically supported that the use of sonification can assist a trainer in the monitoring task and multiple wheel performers in the synchronisation of moves. The use of recorded sonifications to support skill learning could also be investigated. Our findings concerning the usefulness of real-time audio feedback for wheel performers also suggest that the results may be transferable to other sports disciplines which are also highly time critical and underlie similar restrictions in the use of vision (e.g. floor gymnastics or trampolining). The sonification system could also be used to make a simplified version of wheel gymnastics accessible for visually impaired people. Several participants also mentioned a relaxing effect as a result of the combination between the repetitive physical action and the resulting sonification, which suggests that the real-time sonification system could be used for therapeutic use.
In summary, the implementation and evaluation of our real-time sonification system for German wheel motion confirmed that real-time audio feedback can provide a means to significantly improve sports movement. Research in the young interdisciplinary field of movement sonification, that combines sports science with computer science, is only at its starting point. Our results are very promising and indicate that further investigation will prove to be very valuable.

[4]SciPy/Python ttest_rel

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