DEVELOPING MOVEMENT SONIFICATION FOR SPORTS PERFORMANCE: A SURVEY OF STUDIES DEVELOPED AT THE INSTITUTE OF MOVEMENT SCIENCE

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ABSTRACT

This paper offers a survey of movement sonification studies conducted over the last four years at the Institute of Movement Science. Our research focuses on studying the effects of online sonification on sporting performance and movement in golf and cycling. Given the different goals and motor control skills required to be successful, our experiences have provided us with significant insight when considering experimental design and analysis. Skill level and the complexity and ease of repeating motor tasks are major factors when developing sonification strategies and studying its effects. Decisions regarding which movement parameters and the presentation of sonification are equally important depending on study goals. The following outlines our perspectives and methodologies when developing and studying sonification and its effect on sports performance and movement.

1. INTRODUCTION

Improving sport performance is a major focus in the field of sciences. It traditionally involves multi-disciplinary knowledge, from sociology to psychology, biomechanics, and also neurosciences. A popular area of research over the last couple of decades is studying the effects of augmented reality and multi-sensory feedback on human movement and performance [18]. While vision is significant when performing motor control tasks, humans are multi-sensory, and thus the influence of other stimuli has to be more accurately studied. Our research interest focuses on studying the effects of online sonification on sporting performance and movement.

In general, *sonification* is the use of sound to represent data [13, 19]. Natural sonification happens all the time in our daily lives [10], which is typically understood as acoustic feedback generated by the contact of two surfaces, such as dropping a glass marble onto a marble table. However, more recently, artificial sonification is the process of synthesising sound from data abstracted from a source, such as human movement [18]. Artificial sonification of human movement can be presented as a history of performance (offline) or in real-time, concurrent with motor control tasks (online). An important focus then is to design (and present) sounds that relate to motor control tasks required to be successful.

Previous research has suggested that the repetition of auditory-motor activities promotes neural coupling [20], which can enhance motor learning, performance, and rehabilitation. An example of the influence of training these actions can be found in studies on professional pianists, such as [3], which showed auditory feedback enhances the learning of coordinated motor-related actions. Like musicians, athletes also require precise movements and timings, and studies by [9] and [2] have shown the effectiveness of training with sound.

Over the last four years, we have developed numerous sonification studies at the Institute of Movement Science based on golf and cycling. Although each sport appears quite different, they both require demands on vision - eyes on the ball and the road, respectfully. Because of this there is an opportunity to develop and use sound to augment and convey information regarding performance and movement.

Golf putting is a discrete complex motor skill sport, which requires considerable concentration and precision to move the club at a speed in which impact is sufficient enough for the ball to reach a target [7]. Although the putting gesture can be partitioned into backswing and downswing sub-movements or phases, there are numerous ways to swing the putter, such as increasing or decreasing wrist or elbow movement. Research has shown, however, that despite the innumerable ways of applying forces during the swing phases, most successful putts have comparable velocity profiles [11]. This observation supports findings by [8], which found *club head velocity* at impact strongly correlates to ball distance, which of course relates to performance.

Alternatively cycling requires continuous and coordinated movements to be performed across distances over time. A complex process, the pedal stroke consists of pushing and pulling phases and high and low transitions [17]. The most difficult is the pulling phase, as well as transitioning in to and out of it, and research has been dedicated to evaluate efficient pedalling techniques [4].

This paper details our studies on the effects of online sonification on sporting performance and movement in golf and cycling. The first part outlines early studies and pilot tests we developed to determine which movement parameters and sonification strategies affected performance with novices. Because of the obvious differences in skill levels with novices, the following section addresses research conducted with expert participants. As sound is perceived differently among humans, these sections seek to address some of the different ways sonification affects performance differently depending on sonification strategies and skill levels. The following section offers methodologies and results to golf putting and cycling sonification studies that focussed on learning and performance enhancement when vision was either limited or there was a greater demand on it. We conclude with a recent study for error-based sonification of golf putting and future work.

2. SELECTING SONIFICATION PARAMETERS

As there are many ways to map data to sound [12], our first goal was to select factors that play important roles when performing the motor control task. Moreover, it was equally important that those features map to sound in ways that participants are able to perceive and associate with their movements, which, in turn, they can use to enhance performance.

2.1. Golf putting parameters & sonification strategies

To study the effects of sonification on putting performance, we first devised several pretests to examine which swing parameters and sound characteristics best conveyed swing information to novices. Using the CodaMotion CX1 scanner, we placed infrared markers near the hand grip and club head of the putter and recorded the kinematic data of an expert golfer performing putts at 3 m, 6 m, and 9 m (sampling rate: 200 Hz). With this data, we synthesised sound in MATLAB (offline) by using different combinations of swing parameters (club head velocity, 'time to arrival' [8, 16]) and their sound mappings (frequency, psychometric) and asked 15 novices to identify which sonifications best conveyed swing information. Based on these results, we developed a second pretest to observe any behavioural effects of 20 participants performing the golf putting task while listening to sounds synthesised by different combinations of psychometric ranges (3), mapping functions (2), and displays (2). These sounds were based on the club head speed of an expert golfer performing putts at a similar distance. Based on the RMSE method, we averaged all participant trials and compared the means to the expert movement in four dimensions: maximum velocity during the (1) backswing and (2) downswing, and the standard deviation from velocity across the (3) backswing and (4) downswing. The results of both pretests are available in [16], all of which helped us develop the sonification methodology used for our golf putting learning study (see: **Section 4.1.1**). This first step was immeasurable, as it provided us with an opportunity to observe (some of) the limitations of novices and their ability to identify and associate golf putting swing features in sounds they heard.

2.2. Pedal stroke parameters & sonification strategies

Selecting which parameters to sonify and their methods was fundamental to our first sonification of the pedal stroke study. Our goal was to examine the effects of different sounds on right pedal performance. Both novice (12) and experienced (16) cyclists participated in our study, which consisted of five 2-minute sessions on a stationary bike. During all sessions, forces applied to the pedal, or *torque*, and pedal angle were measured with the Rotor crank and application (sampling rate: 50 Hz), which uses ANT+ transmission. Participants were presented no sound during sessions 1, 5, but were randomly represented three auditory conditions during sessions 2-4:

- *Squeak*: When the torque applied on the pedal was negative, a 'squeak' sound was produced from a custom Max/MSP synthesiser using wide-band noise ($f_c = 300$ Hz, $Q = 3$).
- *Dynamic*: The centre frequency of band-pass noise was correlated to pedal phase, such that frequency rose when the pedal ascended (and vice-versa).
- *Music*: Instead of sonification, the song "Gimme all your Lovin?" by ZZ Top was played, which emphasises the tempo (120 BPM) with strong attacks on snare and bass drums.

A major finding was that both novice and experienced cyclists were able to use sonification to improve average *torque effectiveness*[1] (TE). RM ANOVA revealed a main effect on mean TE of $F_{4,104}$ = 8.23, $p < 0.001$, and post-hoc Bonferroni-adjusted t-tests showed that, with the exception of Dynamic, the Squeak condition had a higher average TE than the Silence and Music conditions. Another takeaway of this study was that an error-based sonification work best. Our results suggest listening to sonification while cycling was not attention demanding, which was an important finding moving forward with future studies on the effects of sonification on the pedal stroke.

3. SKILL LEVEL

Participant skill level is also an important factor when considering the effects of sonification on sports performance. When studying novices, our goals are to examine whether they are able to use sonification to enhance performance or aid their learning of a new motor control task. When studying experts, we seek to examine whether they can use sound to sustain or improve upon their already high-level of performance.

3.1. Expert golfers

To date we have not yet conducted a study on the effects of sonification on expert golfers performing putts. A study by [14] found expert golfers were able to identify their own swings, associated with 65 m, targets by sound associated with them. This was an important reference for our development of a study on golf swing sonification, which is described in **Section 6**. As it too is a difficult aspect of the game, we might imagine developing a study that has expert participants performing putts at multiple distances, where personalised sonification is presented in ways that might help them associate putting club head speeds with distance.

3.2. Expert cyclists

Based on the results reported in **Section 2.2**, we developed a study for expert cyclists to examine the effects of bilateral sonification. As our previous study only presented sound relative to right pedal performance, we wanted to examine whether unilateral sonification might increase pedalling asymmetries, which, as reported in [6], would make sonification counter-productive by decreasing overall performance. Using the same sonification parameterisation and strategy, 24 expert cyclists performed five 4-minute pedalling sessions, each with different auditory conditions: sessions 1, 5 were silent, whereas sessions 2-4 were randomly selected from three sonification display conditions (left, right, stereo). RM ANOVA revealed a significant effect of auditory condition $F_{4,88}$ = 19.23, $p < 0.001$. Post-hoc Bonferroni-adjusted t-tests showed the left foot sonification was significantly higher for all conditions, except for the right foot sonification where performances were similar. The main takeaway from our findings show participants greatly improved their average torque effectiveness (TE) when presented bilateral sonification, as compared to unilateral sonification. Additionally, while unilateral sonification did improve the concerned foot, there was only a slight improvement for the opposite foot.

This work led to our current study examining the effects of sonification on torque effectiveness, kinematics, and muscular activity in experienced cyclists. While our previous research found

[1] Torque effectiveness $= \frac{\tau^{+} + \tau^{-}}{\tau^{+}}$, where τ^{+} and τ^{-} are the total positive and negative torque values over the cycle, respectfully.

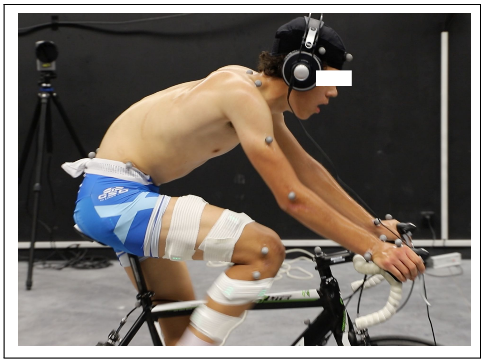

Figure 1: Experimental setup for current sonification of pedal stroke study. Qualysis (66) passive-markers were placed on the head, body, and limbs to measure kinematics. EMGs (10) were placed on the right leg to measure muscular activity. Headphones were used to deliver sonification.

that both novices and experienced cyclists were able to use sonification to become more efficient at pedalling, the goal of this study is to observe whether these changes are physiological or biomechanically costly. By focusing on only experts, we want to examine whether, given any significant effects of sonification, there are also any significant performance correlations or 'moments' when is sound used to enhance (already high-levels of) torque effectiveness and kinematic or muscular performance. Participants performed four 6-minute cycling sessions, where each session randomly presents sonification differently (silent, right, left, stereo). During each session, sonification was only presented for 20 seconds at the start of 1, 2, 3, 4 minutes, which allowed us to measure time it takes for participants to associate sound with their pedal performance. To measure the kinematic effects of sonification, 66 Qualysis markers (size: 19 mm, weight: 2.5 g) were placed on participants and bike, while 10 EMGs were placed on their right legs to measure muscular activity. **Figure 1** illustrates our setup. **Figure 2** illustrates one participant's average torque per angle for each auditory condition. In this instance, we observe that, in comparison to the silent condition, the participant reduced her negative torque for both feet when presented any sonification. Testing is on-going.

4. EFFECTS OF SONIFICATION

The previously discussed studies address some of the ways we look at studying the effects of sonification on sports performance. Each of them, in some way, position sonification as a tool to enhance performance in real-time. However, a different study goal is to examine whether sonification can be used by novices to learn complex motor skills or for experts to improve and sustain performance. Additionally, because of the visual demands of each sport, another perspective is to study how sonification can enhance motor skill performance when vision is either limited or there is a greater demand on it.

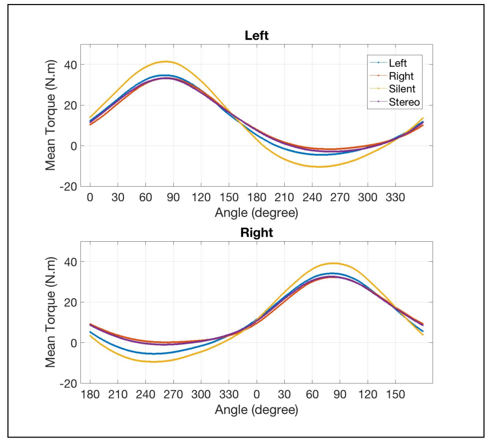

Figure 2: Participant's average torque per angle for each pedal when presented each auditory condition.

4.1. Learning studies

4.1.1. Golf putting learning study

The aim of our first comprehensive sonification of golf putting study was to examine whether novices can use sensory cues developed from expert swing performance to enhance motor learning of the golf putting gesture [5]. Thirty participants were divided into control, audio, and visual groups ($n = 10$) and participated in putting sessions over eight weeks. All participants putted balls across three distances (3 m, 6 m, 9 m) on an artificial terrain installed in our lab. During their putts, participants' swing movements and putting distances were measured with CodaMotion and analysed in MATLAB. Participants in the auditory and visual groups were presented offline sensory stimuli based on the previously collected expert kinematic data and were instructed to syncopate their movements. Following our pretesting (see: **Section 2.1**), we decided to linearly map the club head speed of an expert performing putts at similar distances to the centre frequency of a BPF with white noise input, and used different frequency ranges for each distance [16]. As reported in [5] all groups improved target distance over the course of the experiment, but the improvement in auditory and visual feedback groups was more pronounced. RM ANOVA found, among other things, a main effect on target distance $F_{1.18,30.7}$ = 38.18, $p < 0.01$, η_p^2 = 0.59. Although post-hoc Bonferroni-adjusted t-tests reported no group effects, both audio and visual feedback groups showed more pronounced improvements when compare to the control group. However, both types of sensory guidance led to display dependences, as performance dropped when participants were no longer exposed to sensory stimuli. Based on these results, we believed that developing sonification concurrent with putting movements might diminish any 'guiding effects' [1] and improve motor learning, which was reported in a study by [9]. This point served as the basis of our putting study discussed in **Section 4.2.1**.

4.1.2. Cycling learning study

We expanded our study described in **Section 3.2** by examining whether a small group of experts were able to use sonification to improve and stabilise their torque effectiveness over successful training sessions. Using the same experimental setup and protocol, participants (n =3) repeated one session per week over seven weeks, as well as a final session to examine retention one month later. Because of the small population of participants, statistical analysis was not conducted. However, we found participants improved their average torque effectiveness (TE) by the fourth session and then stabilised. The retention test also showed they were able to maintain this performance.

4.2. Limits of vision

4.2.1. Golf putting with limited vision

Despite swing idiosyncrasies and immeasurable strategies that separate successful golfers, they are all required to focus their vision on the ball in order to make precise contact with the ball. Because of these visual demands, we developed a study to examine whether online sonification had a direct behavioural or perceptual effect on golf putting with limited visual feedback. 20 novices performed a random sequence of 25 3.5 m putts. During each putt, they were exposed to a different online sonification of their club head velocity, which was synthesised from a combination of mapping (3), synthesisers (2), timbral modulations (2) and scale (2) types, whose constructions are described in [16]. Participants performed this 25-putt sequence five times (125 putts). At impact with the ball, shutters worn by participants were closed, whereupon they were asked to estimate the location of their ball.

For target distance error standard deviation, we found, among other things, a main effect for types of synthesiser $F_{2,38}$ = 41.2, $p < 0.001$, η_p^2 = 0.68, and our post-hoc Bonferroni-adjusted t-tests found both synthesisers had lower means when compared to the pink noise trials (8.02 $\pm$ 1.7; 6.91 $\pm$ 1.73), $p < 0.001$. For zone estimation error standard deviation there was, among other things, a main effect for types of synthesiser $F_{2,38}$ = 31.89, $p < 0.001$, η_p^2 = 0.63, and post-hoc Bonferroni-adjusted t-tests showed that one synthesiser had a significantly lower mean when compared to both pink noise (0.26 $\pm$ 0.1) and the other synthesiser (0.13 $\pm$ 0.05) trials, $p < 0.05$. Our analysis showed that, despite vision being limited at impact, participants significantly reduced variability in their distance from the target and ball location estimation when presented auditory feedback that was concurrent with their movements. We found the effect of online sonification with one type of synthesiser on these two performance features yielded a significant correlation ($R^2 = 0.51$, $p < 0.001$). Thus our findings illustrate that novices were able to use a particular (synthesiser) type of sonification to reduce variability in putting distance and estimations based on their performance despite vision limitations to their vision.

4.2.2. Cycling and visual demands

Because of the visual demands required to cycle in the real-world, we developed a study to examine the effects of auditory and visual stimuli on torque effectiveness and reaction times when identifying (virtual) obstacles while pedalling. 24 novices participated in six 2-minute sessions. The first three training sessions randomly presented subjects three conditions when the torque applied to the pedal was negative:

- Auditory feedback: the 'squeak' sound delivered by headphones
- Visual feedback: red circles generated in Jitter via a small digital screen positioned near the handle bars

Figure 3: Experimental setup for cycling study with visual and auditory feedback with real-time animation of road-cycling experience (screen), visual feedback (handlebars), and sonifciation (headphones).

- Control: no auditory or visual feedback

During all of these sessions, based on their pedal performance participants were presented a real-time animation depicting a typical road-cycling experience, which was developed in UNITY and presented on a monitor in front of them. For the remaining three sessions, participants were similarly presented the conditions, but were now asked to verbally identify when they noticed an obstacle ('a large white dome') displayed win the animation. **Figure 3** illustrates the experimental setup. In comparison to the Control condition, both visual and auditory feedbacks significantly enhanced participants' pedalling techniques $F_{2,46}$ = 8.265, $p < 0.001$. During the visual condition, the gaze behaviour was partially oriented towards the small screen on the handlebars, which was where the visual feedback presentation was located. Thus, participants were less attentive to the 'road' - the real-time animation of road-cycling experience. Our comprehensive results are reported in [21]. Moving forward, our findings suggest that participants benefit from artificial multi-sensory feedback, but what remains unclear is how do we determine which type - auditory, visual, haptic, or multi-modal - suits the individual best.

5. ERROR-BASED SONIFICATION FOR GOLF PUTTING

As evidenced we have studied the effects of both offline and online sonification on sports performance. As we found both novice and expert cyclists were able to use error-based sonification to improve torque effectiveness, we wanted to examine whether novices could use a similar strategy to improve putting performance. But given our previous experiences observing the immense swing variability between and within novices performing the golf putting gesture, we first required personalised swing models to calculate errors for which to develop sonification.

Described in [16], we developed a method that synchronised any number of putting trials at ball impact, shifted their swing velocities, and calculated the mean velocity profile (MVP). Our method then estimated the time to impact with the ball by using club head marker values to calculate its acceleration and distance from the ball. This estimated time to impact was then compared in real-time to the MVP, which, in turn, gave us a real-time difference, or *error*, between a participant's observed and MVP swings.

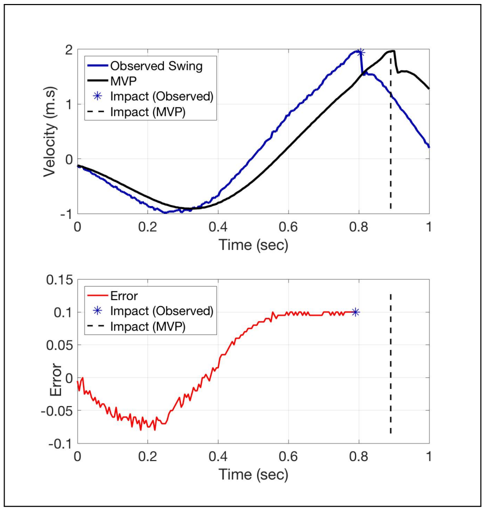

Figure 4: Top: Comparison between observed (blue) and MVP (black) swings. Bottom: Error (red) calculated from the difference between observed and MVP swings.

Figure 4 illustrates the real time difference (error) between a participants observed and MVP swings for a 2 m putt.

Forty participants first performed 20 2 m, 4 m putts, which were used to calculate their MVPs. Next participants were randomly assigned to a different group ($n = 10$), where they then performed 20 2 m, 4 m (total: 80 putts). During these trials, participants were presented different auditory conditions depending on their group: static pink noise ('Control'); MVP velocities mapped psychometrically to a sinusoidal oscillator ('MVP'); errors modulated the stereo display of the MVP auditory signal ('Directivity'); and errors modulated the 'roughness' of the MVP auditory signal ('Roughness').

Among other results, we found a main effect on group for percentage of improvement for average swing velocity deviation $F_{3,36}$ = 3.17, $p < 0.05$, η_p^2 = 0.21, and post-hoc Bonferroni-adjusted t-tests showed MVP participants significantly lowered improved in comparison to the Control group, $p < 0.05$. In addition, for temporal ratio standard deviation we found an interaction on trial type * group $F_{3,36}$ = 3.02, $p < 0.05$, η_p^2 = 0.2 and post-hoc tests showed Directivity participants significantly lowered their means when presented sonification, $p < 0.01$. These results provide further evidence of the benefits of sonification for novices learning new motor skills and suggest the use of personalised templates for sonification reduces variability in the execution and timing of complex movements. Our findings also suggest that sonification of real-time errors (auditory feedback) can be more influential on novice performance than personalised sonification (auditory guidance).

6. CONCLUSION

The studies presented in this paper demonstrate how sonification can be used as a tool to aid novices and experts alike in golf putting and pedalling tasks. Because of the complexity and speciality of motor skills required to improve performance, the scientific questions are numerous and quite challenging. Although learning, training, and improving this difficult motor task is de facto complex, it also presents an exciting opportunity for study, especially when considering the development of augmented reality tools for expert athletes, who wish to maintain or improve their performance and mechanics.

Our work has lead to recent research on the effects of online error-based sonification on a very rapid and complex motor control task: the golf swing. By adapting the Nesbit and McGinnis optimisation model of the golf swing [15], which identifies three swing parameters as possible for optimising swing velocity at impact, we developed a protocol that calculates and sonifies the real-time difference, or error, between observed and optimised swing paths for each swing parameter. The general idea of this study follows closely to our error-based sonification of golf putting study with novices (see: **Section 5**), which demonstrated how novices benefitted from error-based sonification. A major advantage of our model is that it adjusts to the kinematic capacities of the individual, which may prove useful in both healthy and rehabilitation research.

Due to the inter-individual performance differences between experts, the choice in media may relate to participant characteristics. Multi-sensory integration theories have shown that different modalities can be integrated and used differently among humans. Relative to sound, psychoacoustics tells us that sound is perceived differently among humans due to psychological and physiological differences, which may offer a general explanation as to why some participants used sounds developed from one sonification strategy, whereas others found another to be more easily useable. Nevertheless, audition appears to be important for performance improvement, but remains one - and very new - tool among others.

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