Considerations for Developing Sound in Golf Putting Experiments

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Abstract. This chapter presents the core interests and challenges of using sound for learning motor skills and describes the development of sonification techniques for three separate golf-putting experiments. These studies are part of the ANR SoniMove project, which aims to develop new Human Machine Interfaces (HMI) that provide gestural control of sound in the areas of sports and music. After a brief introduction to sonification and sound-movement studies, the following addresses the ideas and sound synthesis techniques developed for each experiment.

Keywords: sonification, auditory feedback, biomechanics, kinematics, motor-coordination, golf

1 Introduction

This chapter describes the development of sonification techniques for three separate golf-putting experiments. These studies are part of the ANR SoniMove project, which aims to develop new Human Machine Interfaces (HMI) that provide gestural control of sound in the areas of sports and music. The SoniMove project poses how an intimate manipulation of sound, which is based on morphological invariants that bear meaning, is not only capable of informing, but also guiding or possibly modifying the motor behaviour of people in a given cognitive context. The SoniMove project is based on the collaboration between three partners: Institute of Movement Sciences (ISM) and Perception, Representation, Image, Sound, Music (PRISM) academic laboratories and Société Peugeot-Citroën Automobiles (PSA).

While the objectives of each golf-putting study differ, they all focus on studying the effects of sound on novice golfers. Each experiment involves the process of synthesising sound from data collected from participants or expert players performing the golf-putting gesture. This process of converting data into sound is commonly known as *sonification*. The following offers a brief overview of sonification and sound-movement studies.

1.1 Sonification definition

In general, sonification is the use of sound to represent data.[1] Sonification requires a fundamental understanding of the data being used. The context of its collection, scale, and properties are significant for development. Carla Scaletti defines sonification as "a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purpose of interpreting, understanding, or communicating relations in the domain under study."[48] One might view the goal of sonification as reflexive, where the data used for sound synthesis is capable of delivering, conveying, or relaying information about itself.[3]

Natural sonification of course happens all the time in our daily lives,[23] which is typically understood as acoustic feedback generated by the contact of two surfaces, for example, dropping a ball onto a surface. Research has shown healthy people can perceive and extract from environmental sound characteristics, such as an object's size[31] or material.[60]

But what makes people want to extract information from the sounds they hear? Is it because they are able to identify characteristics of the sound and associate them with a specific source? If a natural or artificial sonification is supposed to convey the data used for its synthesis, which characteristics of the data, if any, are significant? What sound criteria are necessary to make the data perceptible? These questions are at the center of developing artificial sonifications for studying its effect on subjects exposed to augmented realities.

Of course there are many ways to develop data-to-sound mapping schemes. Several papers discuss the data-to-sound development process, which can be categorised as one-to-one, one-to-many, many-to-one, and many-to-many mappings.[16][25] If someone wants to model a golf swing, for example, they could measure club head position, velocity, and acceleration, which - all or some - could then be mapped to different sound synthesis parameters, such as amplitude or brightness. This categorisation illustrates the numerous ways to map data-to-sound, so justifying the selection of mapping criteria and parameters are significant. However, when developing a mapping scheme for scientific study, not only is a mastery the data properties required, but also a clear direction as to the hypothetical subject responses one wants to elicit for examination, which, in this case, involve subject motor behaviour.

1.2 Sound and movement

A recent research focus has been on the relationships between sound and its affect on human motion. Several studies have found that people are able to utilise

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[1] In this context sound is defined as any non-verbal audio. Defining sonification is a bit of a controversial topic, especially in recent years, as some composers and sound artists make sound through the manipulation of values from data streams and large databases. What makes this process different from sonification is a matter of intention and interpretation: How *well* does the sound represent the data used for sonification? An overview of this problem is addressed by Hermann (2008).[27]

acoustic information for guiding their movement when reaching and grasping objects.[62][10] The study conducted by Castiello et al. (2010) suggests that, when trying to make contact with an object, the contact sound with a material is as significant as its perceived center of mass. These studies show that "auditory information affects grasping kinematics...when vision is present," which suggests the strong relationship between hearing and seeing when completing physical tasks.

Several studies propose that one possible reason sound has a capacity to influence or affect one's perception of motion or moving forms and multisensory nature of motor representations is due to the close-proximity between the auditory and multi-sensory motor areas in the brain.[5][30][46] A sonification of movement study found that when subjects viewed congruent audiovisual movement as opposed to incongruent movement, there was an increase in the brain activity in the human action observation system.[49] A summary of psychophysical studies also suggest sound has a capacity to prompt dynamic cues that are beyond the field of vision, which are the result of handicapping visual cues or strengthening auditory ones.[22][40] Research on the impact of sound in non-visual learning situations is particularly convincing when tests focus on learning different motor skills. A major study by Danna et al. (2014) showed "sonifying handwriting during the learning of unknown characters improved the fluency and speed of their production."[14] Thus, there is scientific precedence that the audio-motor coupling has benefits for learning a new skill.

Hebbian theory implies that experience gives rise to a pattern of coupling neural activity, which, through repetition, becomes entrained and more easily repeatable.[26] Of course an excellent example of this are skilled pianists, who create sound-patterns through the careful manipulation of their hands. They experience *auditory feedback* where their movement maps to sound, which, in turn, can help influence or guide their process of learning a particular task involving motion.[17] Numerous studies have traced this relationship, examining the activity of the motor cortex of professional pianists and non-musicians who listen to piano music.[33][38][6]

Like musicians, most athletes use their hands in a manner that requires high degree of fine motor control. Over the last decade, several research projects have been dedicated to developing audio-motor feedback schemes for the purposes of informing or aiding athletes about their physical actions. Effenberg et al. (2016) found an increase in the mean boat velocity for the elite rowing subjects who experienced acoustic feedback, where four movement parameters were mapped to modulations in frequency and amplitude.[18] A study by Brown et al. (2008) showed an inverse relationship between a sprinter's reaction time and the intensity of a starter signal.[9] A similar study was conducted in sports involving hurdling or hammer throwing.[2] There is growing scientific evidence that athletes use the sound of ball impact as acoustic feedback in ball sports to adjust their behaviour accordingly.[54] Specific to golf, Roberts et al. looked at the relationships between the subjective responses of elite golfers and the objective (acoustic) measurements of ball impact sounds.[45] In particular, the study found a strong and positive correlation between the ‘pleasant’ feel of a shot and the impact having a ‘loud, crisp, sharp sound.’

1.3 Why sonify golf-putting?

The physical fitness required to play and succeed in golf is unlike most other sports. The physical stature of expert and professional golfers is quite vast. However, successful golfers require, among other things, expert concentration, precision, and force management in order to swing a golf-club. In addition, golf requires players to keep their eyes on the ball before making contact, which stresses the importance of other sensory cues for guiding the gesture. These prerequisites make golf an ideal candidate for studying whether sound can be used as an affective tool for novice golfers.

The decision to use the putter, as opposed to other golf clubs (driver, iron, sand wedge), concerns the force and aim of its use. The general goal for using other clubs is to maximise the distance the ball travels, which requires a careful management of different forces. However, the aim of using the putter is to get the ball to a specified target by controlling club head motion at impact.[12] Moreover, there are many ways to swing the putter, for example, increasing movement in the wrist or elbow, each of which can effectively get the ball to the target. This variability is particularly interesting when considering how the sound could be used in real-time situations to give subject immediate auditory-feedback. This chapter describes the development of different sonification strategies based on the golf putting gesture.

2 Sonifying the expert

The first experiment proposed whether sound could be an affective tool for guidance in a golf putting setting. Over the course of an eight-week training period, participants were divided into control, audio, and visual groups. During each session, all subjects putted balls over three distances (3m, 6m, 9m), where their movement was recorded using the CodaMotion data acquisition system.[2] The subjects in the experimental groups were guided by auditory or visual stimuli, respectfully, which was based on professional golfer data. Prior to testing, a professional golfer’s movement was recorded while successfully completing putts over the three distances. The data collected and used for the experiment was based on kinematic smoothness and personal feedback from the professional. The following describes the development of sound for the experiment.

2.1 Parameter selection

Before developing strategies for sound synthesis, a movement parameter needs to be determined. Given certain ecological observations based on aerodynamics and

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[2] Two markers were placed near the putter hand grip and the top of the club head. The data acquisition sampling rate was 200 Hz.

mechanical noise, velocity was an intuitive choice for sonification.[42][23]. After classifying the general trajectory of the club head as quasi-circular, the club head angular velocity was selected. In order to calculate the angular velocity of the club head, a center of rotation, which can be imagined to be at the shoulder, was estimated from club head and handgrip expert position data. Following this estimation, the club head angular velocity of the expert was calculated offline.

The other candidate variable was 'time-to-arrival' (τ)[34], which was selected because of its use in a study involving golf and the rate of 'gap closures.'[12] The study found a strong relationship between the perceived distance between the golf club and the ball and the rate in which golfers arrive at impact with the ball. In addition, as of the date of the pretest, studies had yet to use the τ-variable for sonification, all of which made it worthy of further examination.

A 15-person survey was conducted to determine whether participants could discriminate sounds based on the two candidate variables. Subjects listened[3] to a series of sound pairs and were told to imagine that the sound corresponded with the golf putting movement. They were asked whether the sounds were the same, and, if different, which (imagined) ball went further. To make the sounds used for testing, the professional putting data at all three distances was mapped to sound synthesis parameters of a custom synthesiser written in Matlab. In general, the synthesiser maps and scales data to a user-specified frequency range. In this manner, data drives the center frequency of a band-pass filter (BPF) with white noise input. Nicknamed the 'whoosh' synthesiser, it was designed to create a sound that resembles the aural consequence of metal passing through the air. For this pretest, a Bark scale[4] (range 5) was used with center frequencies ranging from 150 to 700 Hz.

For each distance the candidate data was linearly mapped in two ways: to frequency (Hz) and to mels, where the Bark scale is first transformed into a Mel scale.[41] This second mapping is known as *psychometric*, which was selected because it has been proven to be more indicative of how humans perceive pitch.[55]

The results of the survey (**Figure 1**) showed participants were unable to distinguish sounds based on the τ-variable. In addition, participants were better at discriminating sounds that were psychometrically (Mel scale) mapped as opposed to those that were frequency mapped. Thus velocity was selected for sonification with psychometric mapping.

2.2 Mapping velocity to sound synthesis parameters

As stated in the introduction and alluded above, there are many ways to map and scale velocity. It was important to create a sound that might evoke for the

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[3] For this pretest and all experiments described throughout the chapter, subjects wore Sennheiser headphones.

[4] A Bark scale is a psychoacoustic scale developed by Edward Zwicker in 1961.[64] It can be defined as a scale in which equal distances between frequencies correspond with equal distances in perception. The scale ranges from 1 to 24, which corresponds with the first 24 critical bands of hearing.

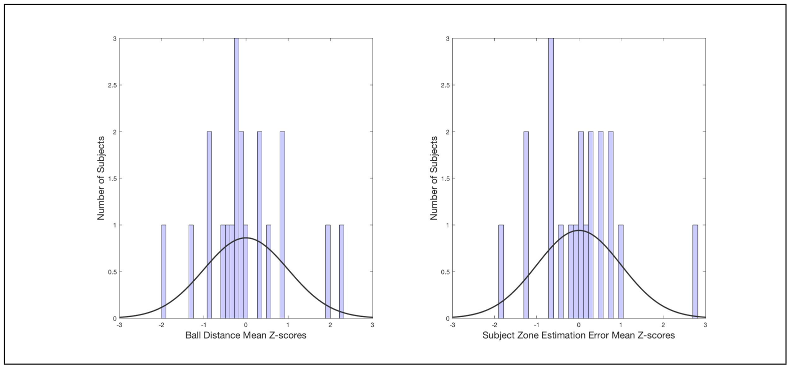

Fig. 1. Summary of discrimination rates in pretest, which tested the different combinations of parameters (velocity, τ) and mappings (Hz, mels) used for sonification

subjects the sound associated with the golf putting gesture and the parameter being sonified (club head angular velocity) and not just some metal object passing through the air at any velocity. Thus, as a way of learning about its spectral content, the sound of the experimental putter passing through the air was recorded with a semi-circular microphone consisting of 32 captors in the anechoic laboratory at PRISM. After reviewing the spectrogram of the recording, a maximum frequency of 450 Hz was determined.

Next a 20-person pretest was designed to examine the behavioural effects of subjects performing the golf putting task while listening to sound. Subjects were asked to perform a putting-like motion without actually making impact with the ball, and their only instruction was to return to their starting position whenever they heard ball impact through their headphones. Three different synthesis conditions were developed: center frequency range (I), mapping function (II), and display (III). As a way of observing whether the frequency content of the sounds had any effect on subjects, Condition I shifted the range of the center frequency used for the BPF with white noise input. Condition II was developed to similarly examine the effects, if any, of using different functions (linear, logarithmic) to map velocity to sound. Finally Condition III was developed to see whether display (monophonic, stereophonic[5]) had any significant effect on subjects. In all cases, a Bark scale was selected and transformed into a Mel scale, which velocity was then mapped onto. The specifics of each condition are outlined in **Table 1**. Each sound was preceded by three metronome beeps (60 bpm), as a way of preparing the subject, and concluded with a recording of ball impact. Each condition was presented five times (70 trials per participant) in random order.

Pretest Root-Square-Mean Error (RSME) analysis showed that, for Condition I, the best match for sound had a center frequency range of 250-450 Hz. A similar assessment was determined for Conditions II and III with center fre-

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[5] Club head position was used to map sound to stereo.

Table 1. Each of the Pretest #2 Conditions I (6 sounds), II (4 sounds), and III (4 sounds) were presented to subjects five times.

Condition	Distance	Bark scale	Center Freq. (Hz)	Mel scale (mels)	Mapping	Display
I	9m	1-5	50-450	78-560	linear	Mono
					logarithmic	
		3-5	250-450	344-560	linear	
					logarithmic	
		4-5	350-450	457-560	linear	
					logarithmic	
II	3m	1-3	50-250	78-344	linear	Mono
					logarithmic	
		2-4	150-350	219-457	linear	
					logarithmic	
III	9m	1-5	50-450	78-560	linear	Mono
					logarithmic	
					linear	Stereo
					logarithmic	

Note: All logarithmic mappings are base 10.

quency ranges of 0-253 Hz and 0-450 Hz, respectfully. With regards to Condition III analysis showed that a stereophonic display diminished the RSME.

2.3 Experiment #1 Sounds

Following the analyses of the pretests, it was decided to linearly map velocity to mels with a stereo display. However, given the three distances being tested, different sounds should be developed, such that the center frequency range of each reflects these differences in distance. In general, to transfer energy from the putter to the ball over a greater distance, there needs to be an increase in velocity. Thus, given our analysis of Condition I, which showed that mapping the velocity of 9m putts to sounds with a center frequency range of 250-450 Hz (Barks 3-5) worked best, it was decided to scale the velocity of the 3m and 6m putts in proportion to Barks 1-3 and 2-4, respectfully. **Table 2** outlines the sounds used in the experiment.

Table 2. The following outlines the relationship between target distance and sounds developed for the auditory group in Experiment #1.

Distance	Barks	Center Freq. (Hz)	Mel scale (mels)	Mapping	Display
3m	1-3	50-250	78-344	linear	Stereo
6m	2-4	150-350	219-457	linear	Stereo
9m	3-5	250-450	344-560	linear	Stereo

In general, the study showed that, in comparison with the control group, subjects in the auditory and visual groups benefited from the augmented sensory information. Our analysis of the retention tests, however, suggested sensory dependence, which is inline with the 'guidance hypothesis.'[1][47] One possible way of enhancing learning while diminishing the guiding effect of concurrent augmented sensory feedback is to introduce online feedback, which is an approach that has been shown to be successful.[18]

3 The effects of different real-time sonifications

Unlike the previous study, the second experiment sonified subject movement in real-time. It was believed that if subjects could perceive their near-immediate[6] movement as affecting the synthesis of the sounds they heard, then their motor behaviour might change or become exaggerated.[57] To make this movement-sound connection obvious for subjects, velocity was mapped to the amplitude of the synthesiser, such that when there was no movement, there was no sound.

But because of the physiological differences between listeners, sound affects and is perceived differently, and thus any one strategy for sound synthesis does not guarantee subject engagement or interest. Thus, a first step was to develop different ways of mapping velocity[7] to sound. Instead of using Matlab, all sounds were developed using the audio programming language Max/MSP. The following briefly describes this initial research and outlines the sounds used in the experiment and their construction from different combinations of synthesisers, modulations, scaling sizes, and mappings.

3.1 Synthesiser development

Three categories of synthesisers were developed to explore different ways velocity could be mapped to synthesis parameters. The first two concerned the *timbre* of the synthesised sound. Although a complex and much discussed topic,[37][19] timbre is what makes one sound different from another despite having the same pitch and loudness. This distinction is a combination of a sound's spectrum, the energy of vibrations at each frequency, and its amplitude envelope over time.

As a way of getting subjects to engage with the sounds they heard, the last category sought to create sounds that (possibly) carried images or associations with the golf-putting gesture. This category follows closely to the *action-object* paradigm, which describes sound as a auditory consequence of some action on an object.[23] In this way, listeners can perceive or imagine the properties of the object or the morphologies that carry information about the action. The goal was to make the relationship between movement and sound perceptible for

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[6] During pretesting, a 25-27 millisecond (ms) latency was measured.

[7] To calculate angular velocity in real-time, additional markers would be required and placed near the subject's shoulder. Moreover, variance in the amount of wrist rotation can greatly affect the club head's angular velocity. Thus linear velocity across the x-z plane was selected for sonification.

subjects so as to entice them to play, experiment, and reflect on the sound they affected through their movement.

Frequency & brightness Research on timbre spaces[59][24][44] illustrates a strong correlation between a sound's *onset transients*[8] and its *brightness*, the weighted-mean of frequencies present in a signal, which can be calculated by taking its *spectral centroid*. As a first step, two simple synthesisers were developed that scale and map velocity to the frequency parameter of sine and sawtooth wave oscillators. Because the waveforms of the oscillators differ,[9] despite having the same frequency, each synthesiser generates a distinctly different sound. As expected the synthesiser with the sine wave oscillator has a smoother sound, whereas the one with the sawtooth wave oscillator has a rougher sound.

Following this initial work, a subtractive-synthesis synthesiser was developed that maps and scales velocity to the center frequency of a second-order IIR digital resonator filter[10] with white noise input. Because decay rate, or *damping*, is proportional to the width of the filter, increasing it also increases the presence of previous input values, yielding a richer output signal with a more robust frequency spectrum. Fixing the decay rate to 30 ms creates, like the synthesiser used in the first experiment, a 'whoosh' sound, which (to some) evokes the sound of an object passing through the air.

Developing the previous synthesis model a bit further, another synthesiser first maps and scales velocity to a (low) frequency between 20 and 160 Hz that serves as the fundamental frequency of a collection of 50 harmonics. Each harmonic is set to the center frequency of a BPF with white noise input. In addition, velocity is also mapped and scaled to the BPF gain and bandwidth. The filtered white noise then serves as the input for a second-order IIR digital resonator filter with a center frequency set to the harmonic frequency. These 50 synthesisers then sum together to create a rich, but sharp sound.

Rhythmicity Rather than modulate the (spectral) content of synthesised sound, this category seeks to modulate its form by employing different enveloping techniques. Studies show that altering a sound's natural amplitude envelope, which can be described in terms of attack, sustain, decay, and release (ASDR) times, makes identifying it more difficult.[13][35] Moreover, given a continuous sound, envelopes with different durations can be applied to create impulses and, subsequently, a sense of rhythm.

This interest in rhythmicity follows studies that propose a strong correlation between body movement and auditory rhythm.[56][43][61] In order to examine

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[8] A *transient* is a sound at the beginning of a waveform that has a very short duration and high amplitude. It typically has non-periodic components.

[9] A sine wave is continuous and periodic and has as smooth form due to its fundamental relationship to the circle. This differs from the sawtooth wave, which is also continuous, but has the conventional form of ramping up and then dropping sharply.

[10] For the second-order IIR filter, the s2m.resFS1∼ Max/MSP object was used and is available at https://metason.prism.cnrs.fr//Resultats/MaxMSP/

these timbral changes as a result of impulse density and rhythmicity, it was important to develop synthesisers whose frequency parameters were not dramatically altered by changes in velocity. Thus, a method was developed that maps velocity to envelope duration, such that as velocity increases, the envelope duration decreases, which effectively maps velocity in proportion to the rate of impulses.

Two simple synthesisers were developed to test this mapping. Adopting a basic tubular bell model the first synthesiser uses a two-pole resonant filter with a fixed collection of frequency, gain, and decay rate values. For the second synthesiser, a simple frequency modulation synthesis instrument was developed. During preliminary pretests, several team researchers mentioned that they noticed their 'natural' swing changed or was 'disrupted,' which they attributed to variations in the sound's rhythm.

Sounds & their associations Finally a more creative category of synthesisers was developed, where velocity was mapped to parameters that modulated particular settings of physical-model synthesisers. These models were selected and developed so that might inspire imagery of things relating to the task of golf putting.

Wristwatch : Several golf studies have examined the effects of pre- and post-training with metronomes and timing devices.[32][53] Coupling this research with the comments regarding the mapping of velocity to sound rhythmicity, a synthesiser was developed that employs a wristwatch synthesis model. In this case, velocity maps and scales to an impulse rate of between 50 and 125 ms. Because of the inverse relationship between them, as velocity increases, so too does the duration between impulses, which increases a sense of regularity. Alternatively, as velocity decreases, there is an increase in impulse rate and, subsequently, sound density.

Vowel synthesis : Like most sporting events, crowds of supporters often congregate and voice their support for athletes. With this observation, a synthesiser was developed that simulates a virtual crowd. Following a similar development by Kleiman-Weiner and Berger,[29] a vowel synthesis synthesiser was developed that, depending on the velocity along the x-axis, selects the center frequencies, gains, and bandwidths of four *formants*[11] for BPFs with a shared sawtooth oscillator input. Using the sign function, when the velocity is negative (backswing), a method selects, synthesises, and sums together the first four formant values for the *Ʊ* ("oh") vowel. Alternatively, when velocity is positive (downswing), the method does the same process for the a ("ah") vowel. To simulate a crowd, ten different voices were created, where, for each one, a random frequency, between 60 and 300 Hz, is selected and set to the frequency parameter of the sawtooth oscillator. This range was selected because the fundamental frequency of an adult male is between 85 and 180 Hz and, for an adult female,

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[11] *Formants* are amplitude peaks in the frequency spectrum of a sound.

the range is 165 to 255 Hz. Depending on the selected vowel, the velocity scales the sawtooth oscillator frequencies up and down an octave, respectfully.[12]

Jet engine : Another way to develop sounds that might bring attention to the putting gesture is to design a synthesiser that exaggerates the speed of swinging the putter. Studies have shown that acoustic feedback has an effect on a person's ability to perceive speed,[15] and, more specifically, the relationship between vehicle speed and engine rotations-per-minute.[58] Bringoux et al. (2017) examined the role of auditory feedback in scenarios involving continuous speed, and found significance with regards to acoustic content and its dynamics for car speed control.[8] All of these points are inline with a study on the effect of sound on elite rowing subjects, where acceleration data was mapped to the "brightness of the sound of a car engine when pressing the gas pedal for accelerating."[16]

With these points in mind, a synthesiser was developed that adapts a jet engine model developed by Andy Farnell.[20] Unlike the previous synthesisers, this one introduces the concept of *inertia*. Farnell writes, "Mechanical systems can speed up and slow down at a limited rate, and can sound wrong if you change speed too quickly" (Farnell 2010: 511-512). First velocity maps and scales to a range of 0.0 ('engine off') and 1.0 ('engine maximum speed'), where it is then converted into a signal that is filtered by a single-pole low-pass filter (LPF) with a 0.2 Hz center frequency. With a sampling rate of 44.1 kHz, this center frequency creates a 5 second roll-off, which creates the effect of a mechanical system "speed[ing] up" or "slow[ing] down" at a "limited rate." Thus, velocity maps to the *speed scalar* of the synthesiser, which affects the overall brightness of the synthesised sound in two ways.

This change in brightness mainly happens in the synthesis model of the engine's "turbine," which is composed of five fixed-frequency sine wave oscillators,[13] whose sounding *partials*[14] change depending on the value of speed scalar signal. This is summed together with filtered noise, whose amplitude is also modulated by the speed scalar, and filtered with a cutoff frequency of 11 kHz. During pretests, multiple researchers made comments that the synthesised sound "pumped [them] up" and that they "felt the inertia" while swinging the putter.

3.2 Experiment #2 Sounds

Following a demonstration of the synthesisers developed, a study was proposed by SoniMove researchers to examine whether sounds synthesised from particular combinations of synthesisers, timbral modulations, scaling ranges, or mapping functions have any effect on the behaviour of novice golf putting subjects. Unlike

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[12] This scaling choice was purely intuitive. One might imagine a crowd's "excitement" and frequency as proportional.

[13] To better explain how the speed scalar affects brightness, consider when the value of the speed scalar is 0.5, a 1000 Hz fixed-frequency, for example, sine wave oscillator is halved (500 Hz). Thus, velocity, as mapped to the speed scalar, affects the frequencies of the five sine wave oscillators. The following are the frequencies (in Hz) of the five oscillators: 3097, 4495, 5588, 7471, and 11100.

[14] A *partial* is any tone composed in a complex sound.

the previous experiment, subjects would only have one target distance (3.5m). The following describes the development of sounds used in the experiment by selecting these synthesis factors.

Synthesiser selection Based on comments regarding the noticeable perceptual differences between their sounds, the 'whoosh' and 'jet' synthesisers were selected. In general, the former creates a softer, gentler sound and the latter creates a more acute and sharp sound. In general, the 'whoosh' synthesiser follows a subtractive synthesis model, whereas the 'jet' adopts a (mostly) additive synthesis model.

Timbral modulations Given these two synthesisers, a first point of study was to examine the effects of mapping velocity to parameters that modulate sound brightness or rhythmicity. Of course to study one parameter, the other must remain fixed. Thus, to study the effects of modulating brightness, the parameter controlling rhythmicity needs to be set to zero - in other words, continuous. Alternatively, to examine the effects of modulating rhythmicity, the brightness parameter needs to be fixed.

Scaling ranges Similar to pretesting in the first experiment, two scaling ranges were developed for each synthesiser and modulation. But, when considering brightness, because of the differences in synthesiser design, the range of acceptable minimum and maximum values for which to scale velocity differ. Thus, it was necessary to develop a robust method, such that a change in range reflects a proportional change in brightness for both synthesisers.

As previously discussed the 'jet' synthesiser maps velocity to the speed scalar with a fixed-range of 0.0 to 1.0. Considering this limited range, one might imagine the two states of the jet engine as starting off (0.0) or resting at a certain speed (0.5) and then shifting to maximum speed (1.0). Thus, the two ranges selected were 0.5-1.0 (1:1) and 0.0-1.0 (1:2).

Considering the 'whoosh' synthesiser, because subjects would be wearing headphones during the experiment, it was necessary to select a frequency range that minimised discomfort and not require amplitude adjustments for each subject. Equal-contour loudness curves show that the lower limit of human hearing is around 20 Hz, and that there is a relative flatness - a continuous number of phons - between 300 and 1000 Hz. Following the work conducted in the previous experiment, where there was a decision to select frequencies in the low-mid range, a minimum frequency of 80 Hz and a maximum of 1000 Hz were selected. Thus the two ranges selected were 540-1000 Hz (1:1) and 80-1000 Hz (1:2).

Fortunately, the parameters affecting rhythmicity are the same for both synthesisers. To create a sense of rhythmicity, a simple method was developed that continuously sends an attack-decay-release (ADR) amplitude envelope to the signal generated by a synthesiser. The attack duration was fixed with a duration of 5 ms, whereas the decay duration was variable and controlled by the scaled velocity. Once the envelope is released, the method retrieves a decay duration value from the scaled velocity and repeats the process. A minimum of 20 ms and maximum of 200 ms were selected - between a fifth and a fiftieth of a second. Unlike the relationship with brightness, velocity and decay length are inversely proportional, so that velocity and impulse rate are proportional. Thus, the two ranges, for both synthesisers, are 110-20 ms (1:1) and 200-20 ms (1:2).

Mapping functions Three different types of mapping functions were used: linear, exponential (coefficient 2), and logarithmic (base 2). Because the human ear can detect pressure changes from micro- to kilo-pascals, sound pressure levels are typically measured in dB, a logarithmic unit. This justifies studying any effects of logarithmic mapping, which might yield, for subjects, a better relationship between their movement and the sound they hear. It was also decided that its inverse, exponential mapping, might yield interesting comparative results. Finally, linear mapping provides a baseline.

Calibration & Experimental trials To test the effects of sound, during the experiment, at the moment of impact with the ball, subject vision would be eliminated. This being based on the assumption that if subjects could see how far the ball travelled and its distance from a target 3.5m away, they might make adjustments to their swing. However, it was also important that subjects had an opportunity to assess their progress. Thus, during this calibration period subjects would hear pink noise through their headphones. Reasons for this decision are twofold. First, it is common in psychometric experiments to use noise as a way of attenuating feedback sound to enhance proprioception. In this case, pink noise is used to minimise or mask the effects of the impact sound with the ball. Second, the use of pink noise is to match exposure to sound sources in other auditory conditions in the experiment - the experimental trials.

The experimental trials test 25 different sounds, which are outlined in **Figure 2**. The 25 sounds include static pink noise and 24 sounds synthesised by mapping velocity to unique combinations of synthesisers (‘whoosh’, ‘jet’), modulations (brightness, rhythmicity), scale sizes (1:1, 1:2), and mappings (linear, exponential, logarithmic).

After several pretests, where subjects began with 10 calibrations followed by 40 experimental trials, we found a noticeable drift, as subjects increasingly overshot the target. To adjust for this drift, following a sequence of 25 experimental trials, subjects would have 5 calibration trials. These calibrations provide subjects with a period to reassess their swing and re-familiarise themselves with their distance from the target. Additionally, in order to see if the experimental trials have any overall affect on performance, a final round of calibrations concludes experiment.

Because each experimental trial consists of 25 different sounds, it is important to develop a method that does not bias any one sound over another. Thus, the sequence of sounds in each experimental trial is pseudo-randomised. Each sequence is composed of five bins that contain five different sounds. For each

Fig. 2. shows the different synthesis parameters, combinations, and sounds developed for the second experiment

Synthesis parameters :
Synthesiser : {Jet, Whoosh}
Modulation : {Brightness, Rhythmicity}
Scale : {1:1, 1:2}
Mapping : {Linear, Exponential, Logarithmic}

Combinations : Synthesiser * Modulation * Scale * Mapping = 24 combinations
Sounds : 24 combinations + 1 pink noise = 25 sounds

repetition, each sound is randomly distributed into a different bin. In total, the experiment consists of 185 trials, divided into several sections. It begins and ends with calibration trials, 20 and 15, respectfully. The remaining 150 trials are organised into five repetitions of 30, which divide into 25 experimental and 5 calibration trials.

3.3 Preliminary results

While analysis is ongoing, we found great variability between subjects. After normalising subject ball distance by each round, a Repeated Measures (RM) ANOVA analysis was conducted, which found significance ($p < 0.05$) with sounds synthesised from combinations of modulation and mapping. Given a target distance of 350 cm, **Table 3** compares the mean ball distance for sonified putts as grouped by the different combinations of modulation (brightness, rhythmicity) and mapping (linear, exponential, logarithmic). While there is little difference between the exponentially mapped sounds, there are differences of around 10 cm for linearly and logarithmically mapped sounds.

Table 3. shows the mean ball distance for the different combinations of modulation (brightness, rhythmicity) and mapping (linear, exponential, logarithmic).

	Brightness	Rhythmicity
Linear	344.47cm	353.51cm
Exponential	350.15cm	352.26cm
Logarithmic	354.84cm	344.57cm

Looking closer at the effects of mapping, we calculated each subjects skill level by taking their average distance away from the target during the calibration trials (60). Given their skill level, the mean standard deviation distance from the target was calculated for each mapping (linear, exponential, logarithmic) and fitted regression lines were added (**Figure 3**). While the type of mapping seemed to have little effect on the more skilled subjects, logarithmically mapped sounds seemed to exacerbate the effects of the poorly-skilled subjects ($R^2 = 0.6756$).

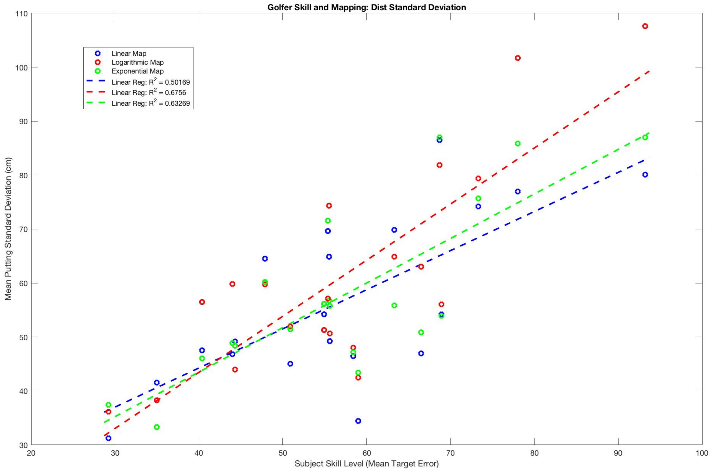

Fig. 3. shows the relationship between subject skill level and mean standard deviation distance from target for sonified putts. For each subject, sonified putts were grouped by the mapping functions used. Fitted regression lines were then added: linear ($R^2 = 0.50169$), exponential ($R^2 = 0.63269$), and logarithmic ($R^2 = 0.6756$).

In addition to ball distance, we also wanted to see whether certain sounds would produce variations in velocity. Each subject's Mean-Velocity Profile (MVP) was calculated by lining up all sonified putts at the time of impact and then averaging them. A RM ANOVA analysis was then conducted with subject MVP as the response variable, which showed significance ($p = 0.008$, effect size 0.3) between both synthesisers and pink noise. A pairwise post-hoc comparison was then applied which found the pink noise case to be most significant ($p <= 0.05$). It was while developing this form of analysis that we began thinking about our third experiment and the possibility of developing sound that reflects each subject's average velocity while completing the golf-putting task.

4 Sonification for consistency

Following observations from the previous study, the third experiment was designed to study whether sound could be used as a tool for creating swing consistency.[46][50] After a period of measuring movement during 20 putts at 2m and

4m, each subject's MVP was calculated for successful[15] trials at both distances. After dividing subjects into different groups (5), they completed a number trials at both distances where club head speed was mapped to parameters controlling the sonification of their unique MVP data. In some groups, the sounds subjects heard were modulated by real-time deviations from their MVP. In other words, changes to the sound were because they were too 'fast' or 'slow' in comparison to their MVP.[16] The following describes the sounds developed for the experiment.

4.1 MVP Sound

The purpose of sonifying the MVP is to transform the average speed of movement necessary for a successful putt (at the same distance) into sound, so that it might be more palpable, accessible, and, through repetition, familiar for subjects. Following discussions with golf professionals, who, to describe the golf-putting swing, often whistled in an upwards-downwards direction, a simple sinusoidal oscillator was selected to sonify the MVP. For each distance, the absolute value of the MVP is first taken, linearly mapped, and scaled to a frequency range of 80 to 2000 Hz, which is further transformed to a Mel scale (122 to 1521 mels). For each distance, the glissando profile is the same. For subjects in this group, the MVP sound was consistent and complete. Any deviation between a subject's real-time speed and MVP was not sonified.

4.2 Modulations

Two different synthesis strategies were developed to provide subjects with immediate auditory feedback based on real-time deviations from their MVPs. Both take the MVP sound signal and modulate it in different ways. Because of this, it was important to develop synthesis strategies that did not ask too much more of the subjects, who are already given the arduous task of simultaneously completing a putt and listening to sound through their headphones. Before the experimental trials, subjects in each group were instructed on how to interpret the modulations relative to their speed.

Modulation 1: Directivity In an effort to extend previous research involving golf training and sound directivity,[32] the first synthesis technique modulates the MVP sound signal by panning it in real-time. The percentage of this stereo panning is based on error intensity. For example, if a subject begins slow and then speeds up, she hears the MVP sound shift from right to left. It was important to let subjects know that the stereo panning corresponded to differences in speed and not club head position.

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[15] Trials were considered successful if they measured within a distance of 25cm from the target.

[16] A method was developed that takes a subject's real-time club head speed and position and, using her MVP and mean-acceleration profile (MAP), calculates a real-time error. The error corresponds to the difference between the current estimation time of impact and that of the MVP.

Modulation 2: Roughness To develop a second method for conveying the error between real-time and MVP speeds, an amplitude modulation model was developed. The error is mapped and scaled to the frequency of a sinusoidal oscillator (modulator signal), which modulates the MVP sound (carrier signal). Like before, error intensity affects the modulation frequency. Many sonification studies have used amplitude modulation to test our ability to perceive changes, such as *tremolo* or *roughness*, to a carrier sound signal.[21][4] Tremolo is a variation in amplitude, which is caused by a modulator signal with a low frequency, which is typically between 0 and 16 Hz. Roughness is a multimodal descriptor of texture, which can be applied in visual, haptic, and auditory modalities. In the auditory domain, it can be simulating when the modulator has a frequency between 15 and 70 Hz.[63]

For this experiment, if subjects are too slow, sound is modulated in a way that creates a tremolo effect, where error is mapped to a frequency range of 0 to 4 Hz. However, if the subject is too fast, a sense of roughness is synthesised, where error is mapped to a frequency range of 16 to 70 Hz.

4.3 Musical sonification

Some sonification studies note subjects have difficulty interpreting synthesised sound and have found success when musical material is used.[17][51] These studies suggest subjects find musical sonifications to be more intuitive. With these observations in mind, a sound was developed that maps the error between real-time and MVP speeds to the playback of a popular music excerpt. Michael Jackson's *Billie Jean* (1983) was selected, as it is popular and has tempo of 117 beats-per-minute (bpm). The tempo is close to 120 bpm, which some movement and music studies have shown is the 'spontaneous tempo of locomotion' for humans.[36][39] The real-time error is scaled in a way that limits speed playback to half and twice speed.

4.4 Experiment #3 Groups

As previously discussed, the third experiment tested five groups, including a control group. Subjects in the control group heard static pink noise for the duration of their swing for both distances. **Table 4** outlines the sounds used in each group. Testing began February 2018 and analysis has yet to be conducted.

Table 4. Experiment #3 Groups. 'X' constitutes auditory condition and text, if any, specifies modulation type.

Groups	Pink noise	MVP	Music	Error
1. Control	X			
2. MVP		X		
3. Mod. 1		X		Directivity
4. Mod. 2		X		Roughness
3. Playback			X	Speed

5 Discussion

This chapters outlined different strategies for developing sound to study its affect on novice golf-putting subjects. The first experiment proposed to sonify professional golf data and used it to study the effectiveness of sound as a guidance tool. The second experiment looked at the effects of different real-time sound synthesis strategies on subjects. Combining many of the themes in the previous two experiments, the third experiment involved the development of sound based on averaging subject speed during golf-putting swings in an effort to create more consistent motor behaviour.

There are still many pending questions on how sonification could yield optimal effects on golf putting improvement. Among them, future research may consider the availability of auditory feedback during execution. Indeed, several studies emphasised the powerful influence of a concurrent sensory feedback that was displayed on demand by observers or actors during motor execution, as compared to sustained feedback.[28][52] Such active or transient use of sensory-available cues may decrease the well-known dependence upon artificial feedback during learning,[1][47] hence avoiding learning transfer to ecological conditions of practice.

In closing, the way sound can be used to complement or invite engagement with other sensory information, such as haptic or visual feedback, is of great interest for the upcoming challenges to be tackled around multi-sensory-based learning. Of course the manner of its use invites many questions. For example, does congruent multimodal information always lead to an improvement of gesture control and learning, especially in terms of precision and accuracy?[7] Or does one sensory channel mask or override the others, yielding no benefits from multi-sensory feedback enhancement? These are some of the question to consider moving forward in developing sound for future golf-related studies.

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