Experimental Brain Research
https://doi.org/10.1007/s00221-020-05757-3

RESEARCH ARTICLE

Online sonification for golf putting gesture: reduced variability of motor behaviour and perceptual judgement

Benjamin O'Brien[1] · Brett Juhas[1] · Marta Bieńkiewicz[1] · Frank Buloup[1] · Lionel Bringoux[1] · Christophe Bourdin[1]

Received: 20 July 2019 / Accepted: 19 February 2020

Abstract
This study investigates whether real-time auditory feedback has a direct behavioural or perceptual effect on novices performing a golf putting task with limited visual feedback. Due to its significant role in the success of a putt, club head speed was selected as the parameter for sonification. Different combinations of synthesisers, timbral modulations, scales, and mappings were developed to examine whether particular sound classes influenced performance. When compared to trials with static pink noise, we found that, despite their vision being limited at impact, participants were able to use different types of sonification to significantly reduce variability in their distance from the target and ball location estimation. These results suggest that concurrent sound can play an important role in reducing variability in behavioural performance and related perceptual estimations. In addition, we found that, when compared to trials with static pink noise, participants were able to use sonification to significantly lower their average impact velocity. In the discussion, we offer some trends and observations relative to the different sound synthesis parameters and their effects on behavioural and perceptual performance.

Keywords Sonification · Auditory feedback · Kinematics · Motor coordination · Golf

Introduction

A recent research trend has focused on studying the effects of online auditory feedback on human movement. Thoret et al. (2014) found that participants were able to perceive and associate movement profiles when acoustic information was concurrent with their movement. Speed and fluency were improved in novel handwriting tasks when kinematic movement was mapped to sound (Danna et al. 2014). Dyer et al. (2016) demonstrated that online auditory feedback can enhance complex motor learning and make tracing bimanual shapes more easily repeatable. There is increasing evidence that online *sonification*, the real-time use of sound to represent data, is an effective medium for conveying motor-related information.

Its effectiveness may be because auditory cues are more temporally accurate than visual ones (Hirsh and Watson 1996; Murgia et al. 2017). In comparison, auditory information seems less demanding of attention and more portable (Secoli et al. 2011). A summary of psychophysical research also suggests that sound can prompt dynamic cues that are beyond the field of vision (Fitch and Kramer 1994; Newton 2015). This point is underscored by a significant sonification of movement study by Schmitz et al. (2013), which found that brain activity increased in the human action observation system when participants viewed congruent audiovisual movement as opposed to incongruent movement. These studies suggest why augmenting auditory, as opposed to visual, information might be more suitable for channelling supplemental information.

Research suggests that the repetition of auditory–motor activities promotes neural coupling (Schaffert et al. 2019; Hebb 1949), which, through entrainment, can make these actions more easily repeatable. Crasta et al. (2018) showed that listening to auditory rhythmic stimuli primed participants while they completed tasks tapping to auditory stimuli. Similar evidence of interactions between the auditory and motor systems was shown in studies by Thaut et al. (2015), Merchant et al. (2015) and Morillon and Baillet (2017), which showed participants used rhythmic auditory cues as

Communicated by Francesco Lacquaniti.

Electronic supplementary material The online version of this article (doi:https://doi.org/10.1007/s00221-020-05757-3) contains supplementary material, which is available to authorized users.

✉ Benjamin O'Brien
benjamin.o-brien@univ-amu.fr

[1] Aix Marseille Univ, CNRS, ISM, Marseille, France

Published online: 11 March 2020

references to predict, prepare, and anticipate movements. There are numerous studies that have examined the differences in motor cortex activity between skilled musicians, who carefully manipulate their hands with instruments, and non-musicians (Baumann et al. 2007; Munte et al. 2002; Schlaug 2001).

Like musicians, athletes also require a high level of fine motor control that is easily repeatable. Chollet et al. (1988) showed that elite swimmers enhanced their motor control using real-time sonification based on pressure exerted by their hands. Baudry et al. (2006) found gymnasts were able to use concurrent auditory feedback to correct complex movements. These works demonstrate how highly skilled athletes are capable of improving mechanics when training with online sonification. However, there appears to be only a few studies that focus on the effects of real-time auditory feedback on novices. A major study by Effenberg et al. (2016) found that novice rowers, who experienced online sonification of four movement parameters, were able to increase their average boat velocity. Similarly, we were interested in studying the effects of sound on novices and whether it enhanced their natural execution of a complex motor task.

For our study, we selected golf, as it fits the definition of a sport involving a complex motor task (Wulf and Shea 2002). Although the physical fitness required to play and succeed in golf is vast, it requires expert concentration, precision, and force management to swing a golf club (Burchfield and Venkatesan 2010). 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 pre-requisites make it an ideal candidate for studying whether sound can be used as an effective tool for novices.

We decided to focus on golf putting, as the sole purpose of using the putter is to get the ball to a specified target by controlling club head motion at impact (Craig et al. 2000). The putting motion requires considerable fine motor control processes to move the putter at a speed in which impact is adequate enough for the ball to follow the intended path and distance to the target (Burchfield and Venkatesan 2010). In general, the gesture can be partitioned into two sub-movements: the backswing and the downswing. While there are many ways to swing the putter, for example, increasing movement in the wrist or elbow, these two phases remain and are required to be effective at getting the ball to the target. Although research has been conducted on identifying an 'ideal ratio' of backswing to downswing, golfers may apply different forces during these phases, but nonetheless have comparable velocity profiles (Grober 2009; Kooyman et al. 2013).

With a population of novice golfers, we anticipated that our participants would have diverse putting swing mechanics and, therefore, require a robust sonification parameter that could accommodate these differences. Because some participants might choose to putt by fixing their wrists, creating parallel as opposed to angular movement between the hands and the club head, we selected club head linear velocity as the candidate for sonification. Sigrist et al. (2013) reviewed numerous studies that found success in developing artificial auditory feedback based on velocity. In addition, Gaver (1993) posited that listeners can make ecological observations based on aerodynamics and mechanical noise and use them as auditory indices. For example, listeners might identify changes in speed by identifying sounds associated with the wind or a car engine. More recently, Bieńkiewicz et al. (2019) found that the movement of novice golfers was influenced by the presence of auditory guidance based on club head speed. Based on this research, we believed that if participants could perceive that their movement had a direct and immediate effect on the sounds they heard, then we might observe changes to their motor behaviour.

As there are innumerable ways to map data-to-sound (Grond and Berger 2011), it was important to develop sound that participants could easily perceive and interpret as metaphor for club head speed. Although research has shown that healthy people can extract information from characteristics in sound (Castiello et al. 2010), such as an object's size (Lakatos et al. 1997) or material (Wildes and Richards 1988), they do not perceive sound similarly due to their physiological and psychological differences. Based on Johnson et al. (1987), who found that patterns of individual differences identified in healthy adults similarly affected their auditory performance, we expected participants would most likely perceive, interpret, and possibly use artificial sounds based on their movement on an individual basis, if at all. Therefore, as a way of maximising the potential for participants to engage with and become influenced by sound, our goal was to develop and combine methods for mapping club head speed to parameters controlling sound synthesis and study their effects on performance. By doing so, we might develop a method for enhancing performance by sonifying the golf putting gesturing.

Although the effect of sound on golf putting can be easily measured by calculating the distance between the target and the final position of the ball, a more elaborate method was required to evaluate whether artificial sound affected their perception. If participants could visually assess the distance between the ball and the target, they would most likely make adjustments to their swings, which would make it impossible to measure whether visual or auditory factors played significant roles on performance. However, if their vision was masked after impact with the ball, participants would be forced to rely on audition to estimate ball distance and assess their performance. In turn, this extra-sensory information could be used to influence the performance of future putting attempts.

The primary goal of our study was to examine whether real-time auditory feedback can play a significant role in behavioural performance and its perceptual correlates. Specifically, we wanted to study whether online sonification had an immediate effect on performance, as opposed to studying

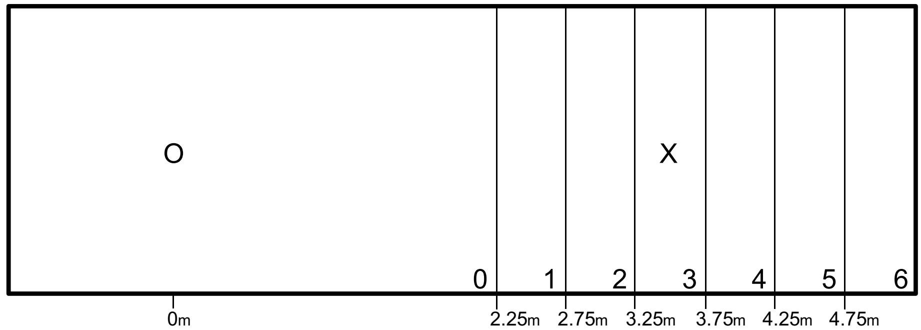


Fig. 1 Overhead diagram of putting terrain, where *O* is the starting position (0 m) and *X* is the target (3.5 m). Zones 0–6 are 0.5 m apart

its effects on novices learning a complex motor skill. A corollary then was to examine whether sonification affected aspects required to execute the complex motor task and, if so, were there any correspondences with performance.

Methods

Participants

Twenty right-handed participants (12 men; age 24.2 ± 6.7) affiliated with Aix-Marseille University participated in the experiment. All participants had good or corrected vision and hearing and self-reported having no motor control problems and being right-handed. All participants consented to voluntary participation in the study and were informed of their right to withdraw at any time. This study was performed in accordance with the ethical standards of the Declaration of Helsinki Salako (2006). The protocol was approved by the Ethics Committee of Aix-Marseille University.

Experimental setup

Materials

Participants used an Odyssey White Ice putter (length 0.97 m; weight 0.59 kg) to hit Titleist PRO V1X balls. A synthetic grass terrain was used (length 5 m; width 1.8 m). The target was a painted white circle with a 0.11-m diameter, which is the same size as a conventional golf course hole. Beginning 2.25 m away from the starting position, six different coloured lines were painted 0.5 m apart. These lines denoted zones 0–6, where the target was located in zone 3 (Fig. 1). A HD Video Camera-Pro Webcam C930e was mounted on the ceiling above the putting terrain and overlooked the putting hole (2.5 m), which was used to measure the accuracy of each putt. All participants wore Sennheiser headphones and shutter glasses throughout the course of the experiment.

Sound design

Participants were presented 24 different sonifications, which were created by combining different synthesisers, timbral modulations, scales, and mappings. Unlike some sounds, such as piano notes, which might carry additional, nested information to some participants in ways that might affect their performance, our method allowed us to parameterise and develop different sounds that might be more contextually relevant to the performance of the golf putting gesture. Although their development is described in greater detail in O'Brien et al. (2018), the following offers a brief description.

Following closely to the *action-object* paradigm proposed by Gaver (1993), we designed two synthesisers with the goal of getting participants to perceive or imagine the properties of the object (the putter) or the morphologies that carry information about the action (the golf putting gesture). The *whoosh* synthesiser produced a sound similar to that of a metal object passing through the air by mapping club head speed to the centre frequency of a second-order IIR digital resonator filter (decay rate 30 ms) with white noise input. To bring attention to swing speed, we wanted to create an exaggerated sound based on the sound of metal–air contact via mechanical processes. Adapting a model developed by Farnell (2010), our *jet* synthesiser mapped club head speed to a *speed scalar* with a range of 0.0 ("engine off") and 1.0 ("engine maximum speed"). This signal was then filtered by a single-pole low-pass filter with a 0.2-Hz centre frequency, creating the auditory effect of a mechanical system speeding up or slowing down, which then scaled the frequencies of five sine wave oscillators.

Given the two synthesisers, we wanted to examine whether there were any effects on performance if club head speed was mapped to parameters that modulated either sound *brightness* (Wessel 1979; Risset and Mathews 1969) or *rhythmicity*.[1] To study the effects of one parameter, of

[1] Rhythmicity can be described as creating a sense of accelerating or decelerating rhythms by changing the decay times of envelopes applied to a continuous sound.

course the other must remain fixed. Therefore, when velocity was mapped to parameters that modulated brightness, it was not mapped to rhythmicity parameters, and vice versa.

The scale in which to map club head speed to brightness was different for each synthesiser. Based on similar selections made in a sonification of golf putting study by Bieńkiewicz et al. (2019), we selected a frequency range of 80–1000 Hz for the *whoosh*, as it is just below the 2–5 kHz sensitivity of the human ear. The *jet* was composed of five sinusoidal oscillators with different amplitudes and maximum frequencies (3–11 kHz), which were scaled between 0.0 and 1.0 relative club head speed ("speed scalar"). As the human auditory system is sensitive to frequencies from 20 Hz to 20 kHz, both synthesisers produced sounds in the lower half of this frequency sensitivity spectrum. It is commonplace that sensitivity to upper-range frequencies degrades with age, although this was most likely not a factor for our participants. Thus, we selected frequency ranges of 540–1000 Hz (1:1) and 80–1000 Hz (1:2) for the *whoosh* and 0.5–1.0 (1:1) and 0.0–1.0 (1:2) for the *jet*. The scale in which to map speed to rhythmicity was similar for both synthesisers, so a single method was developed that continually repeated the process of sending attack–decay–release envelopes (attack: 5 ms). For decay times, we selected a range between a fifth and a fiftieth of a second, which yielded 20–110 ms (1:1) and 20–200 ms (1:2). Unlike the relationship with brightness, speed and decay length are inversely proportional, so that club head speed and impulse rate are proportional.

To map club head speed onto sound, we required a function. Because sound pressure levels are typically measured logarithmically in dB, we wanted to examine whether any effects on performance if club head speed was mapped logarithmically (base 2). We then wanted to observe if there were any differences in comparison to its inverse—exponential (coefficient 2)—and linear mappings.

All sonifications are listed in Table 1. Figure 4 in "Appendix 1" illustrates club head speeds performed by a participant when presented different auditory conditions. The Supplementary Materials demonstrate some of the sound synthesis combinations and their effects on sound produced from club head speed.

In addition to the 24 different sonifications described above, a static pink noise case was added to serve as a reference, such that its synthesis and display were independent of movement. The static pink noise was to control for the effect of headphones, but not to isolate the participants from the environmental sounds, including ball impact. To demonstrate that the sound of impact was available to participants across the different auditory conditions, Fig. 5 in "Appendix 2" illustrates a participant performing the golf putting task with and without static pink noise.

Table 1 Sonification types

Synthesiser	Modulation	Scale	Mapping	Number
Whoosh	Brightness	1:1	Linear	1
			Exponential	2
			Logarithmic	3
		1:2	Linear	4
			Exponential	5
			Logarithmic	6
	Rhythmicity	1:1	Linear	7
			Exponential	8
			Logarithmic	9
		1:2	Linear	10
			Exponential	11
			Logarithmic	12
Jet	Brightness	1:1	Linear	13
			Exponential	14
			Logarithmic	15
		1:2	Linear	16
			Exponential	17
			Logarithmic	18
	Rhythmicity	1:1	Linear	19
			Exponential	20
			Logarithmic	21
		1:2	Linear	22
			Exponential	23
			Logarithmic	24

Task

Participants were tasked with hitting a golf ball towards a 3.5-m target. While completing the putting gesture, participants were exposed to different sonifications (2.2.2). Once participants made contact with the ball, their shutters closed. Their second task was then to estimate the final distance of the ball. Participants verbally offered a number that corresponded to a provided diagram that outlined zones on the putting terrain (Fig. 1). An experimenter then measured the distance between the ball and the target, which was used as a reference to compare against the webcam recordings (2.2.4), removed the ball, and then reopened the participant's shutters.

After completing a sequence of 25 experimental trials, whose order was pseudo-randomised, participants had five calibration trials to avoid a drift of overshooting the target due to the lack of visual assessment during the experimental trials. During these trials, shutters remained opened and participants were presented static pink noise. 25 experimental trials followed by five calibrations were repeated five times for a total of 145 putts, where the last five calibrations were removed from testing.

Data recordings and statistics

Codamotion CX1 Scanner was used to measure club head and hand grip position data (distance: 2 m; elevation: 1 m; sampling rate: 200 Hz). Two infra-red active markers were placed near the club head at the bottom of the club shaft and below the hand grip. Each marker position was encoded into an 8-byte message that was sent locally to a separate computer running Max/MSP for sound synthesis.

A custom Max/MSP program was used to decode each 2-byte club head position vector value, which was used to calculate club head linear velocity v_t at time t and marker values x_t and z_t (1). In addition, Max/MSP was used to capture images with the webcam (sampling rate: 0.2 Hz).

$$v_t = \sqrt{\left(\frac{x_t - x_{t-1}}{t_t - t_{t-1}}\right)^2 + \left(\frac{z_t - z_{t-1}}{t_t - t_{t-1}}\right)^2}. \quad (1)$$

Because our goal was to examine the effects of online sonification, it was important to minimise latency between club head speed and the sound synthesised from it. While we were unable to calculate temporal differences in auditory processing between participants, it was important to determine a latency reference that was not so large that it might inadvertently affect performance. A pretest was developed, where sound would be generated by a sinusoidal oscillator (frequency 200 Hz) if the CodaMotion marker located near the club head crossed a pre-determined point under a ball. A microphone was placed near the ball to record the sound of impact, while the sound generated by Max/MSP was stored directly on a computer. Three novice participants were instructed to perform 20 3.5-m putts. Empirically comparing the start times of the sound of impact and the sound generated in Max/MSP, we determined a 25–28 ms delay. For the three participants, the average putting duration was 1.05 ± 0.32 seconds, and we decided a latency of around 2.3–2.6% was not meaningful.

To examine the effects of real-time auditory feedback on behavioural performance and perceptual correlates, two variables were used. To assess the success of a putt, we measured the distance between the target and the final position of the ball, or the *target distance error* (TDE). Using a similar method described in Bieńkiewicz et al. (2019), we selected the image with the final position of the ball and calculated the distance between target and the ball by using a custom MATLAB program. This calculation was then compared to our manual distance calculation, where any discrepancies were averaged but did not exceed 1 cm. To quantify perceptual accuracy and precision, we calculated the difference between the estimation and the observed final ball position, or the zone estimation error (ZEE). Because we were interested in both participant average and variability, for both TDE and ZEE we calculated both the mean (μ) and standard deviation (σ).

To better understand the relationship between putting performance and swing mechanics and the potential influence of sound on them, we analysed impact velocity (IV). Craig et al. (2000) reported a strong direct correlation between putting distance and velocity at impact, ranging from 0.98 to 0.99. These findings support observations made by Burchfield and Venkatesan (2010), which underscore the importance of club head speed to have successful putts. Thus, we wanted to examine whether real-time auditory feedback might affect impact velocity in manner similar to performance. Both impact velocity average IV_μ and standard deviation IV_σ were calculated.

In our preliminary analysis, we wanted to first confirm group normality and analysed all participant TDE_μ and ZEE_μ during experimental trials by calculating their respective z-scores. All participants were included in our study, $|z| < 3\sigma$. Next, we wanted to confirm our method of sound randomisation did not bias any one sound and, by applying Repeated Measures ANOVAs, found no main effect of sound position in sequence on TDE_μ nor TDE_σ, $p > 0.05$. Thus, all sounds were treated as equal and independent of their position in the experimental trial sequence.

For all outcome variables, Repeated-Measures ANOVAs were carried out with Greenhouse-Geisser adjustments. We reported main effects on synthesiser (*whoosh*, *jet*) and modulation (brightness, rhythmicity). Because club head speed was mapped to a selected mapping function (linear, exponential, logarithmic) onto a scale (1:1, 1:2), which was different depending on the type of synthesiser selected, we decided to also report interactions between synthesiser * scale * mapping. Where main effects and interactions were detected, post hoc Bonferroni-adjusted *t* tests were carried out with the alpha level set to 0.01.

Results

Target distance error

To examine whether real-time auditory feedback influenced putting performance, we analysed both TDE_μ and TDE_σ. For the TDE_μ, we found main effects for types of synthesiser $F_{2,38} = 27.24$, $p < 0.001$, $\eta_p^2 = 0.59$ and modulation $F_{2,38} = 27.63$, $p < 0.001$, $\eta_p^2 = 0.59$, and an interaction between synthesiser * scale * mapping $F_{4,76} = 35.44$, $p < 0.001$, $\eta_p^2 = 0.65$. But post hoc tests revealed no significant differences when comparing trials associated with different sound synthesis parameters to those with static pink noise, $p > 0.05$. For TDE_σ, we found main effects for types of synthesiser $F_{2,38} = 41.2$, $p < 0.001$, $\eta_p^2 = 0.68$, modulation $F_{2,38} = 41.35$, $p < 0.001$, $\eta_p^2 = 0.69$, and an interaction between synthesiser

* scale * mapping $F_{4,76} = 51.75$, $p < 0.001$, $\eta_p^2 = 0.73$. Post hoc tests revealed the following had lower target distance error standard deviation averages when compared to those associated with the static pink noise trials: synthesisers *whoosh* (7.98 ± 1.69), $p < 0.001$, and *jet* (6.87 ± 1.72), $p < 0.01$; modulations *brightness* (7.43 ± 1.76), $p < 0.01$, and *rhythmicity* (7.43 ± 1.64), $p < 0.001$; an interaction between the *jet* and 1:1 * exponential mapping (10.34 ± 1.84) and 1:2 * linear mapping (7.35 ± 1.42), $p < 0.01$; and an interaction between the *whoosh* * 1:1 and linear mapping (10.55 ± 2.31), exponential mapping(8.18 ± 2.11), logarithmic mapping (8.1 ± 1.77), $p < 0.001$. Figure 2a, b illustrate the differences between TDE_μ and TDE_σ when comparing different synthesisers and static pink noise trials. These results suggest that when real-time auditory feedback was present, participants did not significantly reduce their average ball distance to the target, but were able to reduce their variability.

Zone estimation error

To examine whether real-time auditory feedback had an effect on ball distance estimation, we analysed both ZEE_μ and ZEE_σ. For ZEE_μ, we found main effects for types of synthesiser $F_{2,38} = 11.59$, $p < 0.001$, $\eta_p^2 = 0.38$, modulation $F_{2,38} = 12.84$, $p < 0.001$, $\eta_p^2 = 0.4$, and an interaction between synthesiser * scale * mapping $F_{4,76} = 15.28$, $p < 0.001$, $\eta_p^2 = 0.45$. But post hoc tests revealed no significant differences when comparing trials associated with different sound synthesis parameters to those with static pink noise, $p > 0.05$. For ZEE_σ, there were main effects for types of synthesiser $F_{2,38} = 31.89$, $p < 0.001$, $\eta_p^2 = 0.63$, modulation $F_{2,38} = 33.34$, $p < 0.001$, $\eta_p^2 = 0.64$, and an interaction between synthesiser * scale * mapping $F_{2,38} = 31.37$, $p < 0.001$, $\eta_p^2 = 0.62$. However, the post hoc tests revealed that only the *whoosh* synthesiser had a significantly lower average standard deviation when compared to both static pink noise (0.26 ± 0.1) and *jet* (0.13 ± 0.05) trials, $p < 0.05$. Figure 2c, d illustrate the differences between ZEE_μ and ZEE_σ when comparing different synthesiser and static pink noise trials. These results suggest that the presence of real-time auditory feedback did not have a significant effect on estimating ball distance; however, when some synthesis parameters were used, it did play a role in reducing estimation variability.

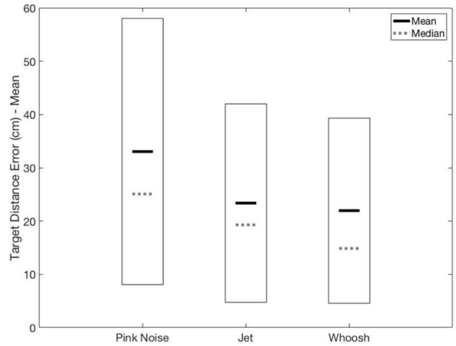
Impact velocity

To examine whether real-time auditory feedback played a similar role in both performance and swing mechanics, we analysed impact velocity (IV_μ and IV_σ). For IV_μ, there were main effects for types of synthesiser $F_{2,38} = 1468.77$, $p < 0.001$, $\eta_p^2 = 0.99$, modulation $F_{2,38} = 1471.25$, $p < 0.001$, $\eta_p^2 = 0.99$, and an interaction between synthesiser * scale * mapping $F_{2,38} = 1450.28$, $p < 0.001$, $\eta_p^2 = 0.99$. Post hoc tests revealed that both types of synthesisers and modulations had significantly lower impact velocity means when compared to those associated with the static pink noise trials: *whoosh* (0.3 ± 0.05), *jet* (0.29 ± 0.04), *brightness* (0.29 ± 0.04), and *rhythmicity* (0.29 ± 0.05), $p < 0.001$. Similarly, we found all interactions (n =12) between synthesiser * scale * mapping had significantly lower impact velocity means when compared to those associated with the static pink noise trials, where the average difference between them was $\mu_n = 0.29 \pm 0.03$ and the average standard error was $\mu_n = 0.05 \pm 0.01$, $p < 0.001$. For IV_σ there were main effects for types of synthesiser $F_{2,38} = 121.01$, $p < 0.001$, $\eta_p^2 = 0.86$, modulation $F_{2,38} = 118.8$, $p < 0.001$, $\eta_p^2 = 0.86$, and an interaction between synthesiser * scale * mapping $F_{4,76} = 113.46$, $p < 0.001$, $\eta_p^2 = 0.88$. But post hoc tests revealed no significant differences when comparing trials associated with different sound synthesis parameters to those with static pink noise, $p > 0.05$. Figure 2e, f illustrate the differences between IV_μ and IV_σ when comparing different synthesiser and static pink noise trials. These results reveal that sound played a significant role in affecting average impact velocity, but not its variability.

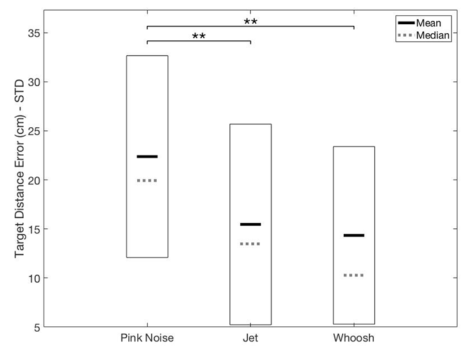
Discussion

Our goal was to examine whether real-time auditory feedback played a role in the behavioural or perceptual performance of novice golfers when vision was limited and study any similarities. With regards to the effect of sonification on average target distance error, we reported significant main effects and interactions, but our post hoc results revealed no significance. However, both synthesisers and modulations had lower average target distance error when compared to trials with static pink noise: *whoosh* (11.1 ± 4.88), $p = 0.08$; *jet* (9.68 ± 4.67), $p = 0.13$; *brightness* (10.26 ± 4.65), $p = 0.09$; and *rhythmicity* (10.51 ± 4.89), $p = 0.1$. Despite trials associated with each synthesiser and modulation having lower target distance error averages of approximately 10 cm when compared to those with static pink noise, neither was found to be significant.

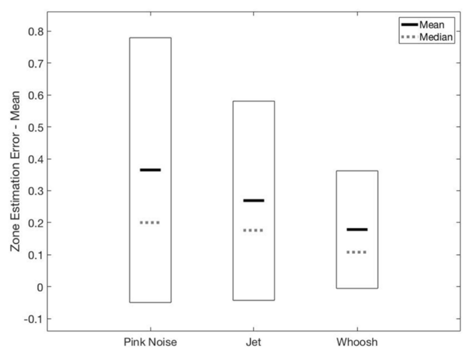
In comparison to trials associated with static pink noise, we observed that participants were able to significantly reduce their target distance error standard deviation when presented either type of synthesiser or modulation. This suggests they were able to interpret information regarding their speed and make adjustments to their motor control in ways that stabilised their ball distance from the target performance. This important result supports evidence that the auditory channel is well suited to act as a conduit



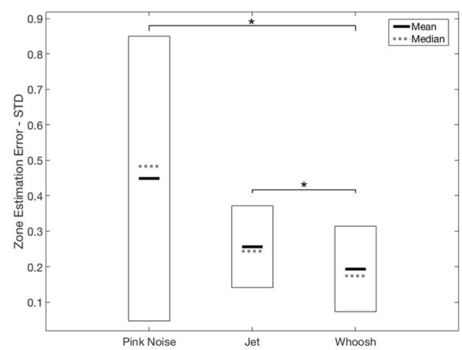
(a) TDE_{μ} - synthesisers & static pink noise trials



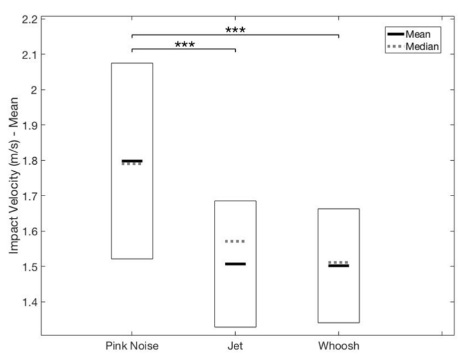
(b) TDE_{σ} - synthesisers & static pink noise trials



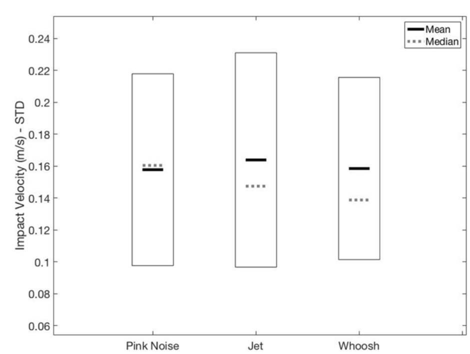
(c) ZEE_{μ} - synthesisers & static pink noise trials



(d) ZEE_{σ} - synthesisers & static pink noise trials



(e) IV_{μ} - synthesisers & static pink noise trials

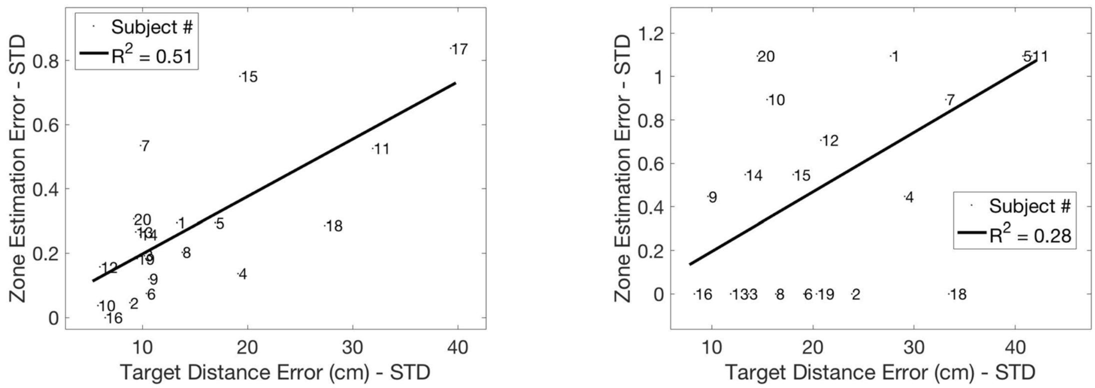


(f) IV_{σ} - synthesisers & static pink noise trials

Fig. 2 Comparisons between target distance error mean (TDE_{μ}) (**a**) and standard deviation (TDE_{σ}) (**b**), zone estimation error mean (ZEE_{μ}) (**c**) and standard deviation (ZEE_{σ}) (**d**), and Impact Velocity mean (IV_{μ}) (**e**) and standard deviation (IV_{σ}) (**f**) for synthesisers and static pink noise trials. *, **, *** Significance for $p < \{0.05, 0.01, 0.001\}$. Boxes represent the standard deviation from mean

for which motor-related information can be transmitted (Sigrist et al. 2013; Danna et al. 2014; Boyer et al. 2016; Baudry et al. 2006). Our results build upon those reported in van Vugt and Tillmann (2015), where concurrent sound was shown to improve performance by reducing temporal irregularities, as we found novices completing a more complex motor task were able to use sound to reduce performance variability.

While the important take-away is that participants improved their target distance error standard deviation when presented sonification, no synthesiser or modulation class distinguished itself from another. Interestingly, we found



(a) TDE_σ - ZEE_σ for all *whoosh* trials **(b)** TDE_σ - ZEE_σ for all static pink noise trials

Fig. 3 R^2 correlations between target distance error standard deviation (TDE_σ) and zone estimation error standard deviation (ZEE_σ) for trials with the *whoosh* synthesiser, $R^2 = 0.51$, $p < 0.001$ (**a**) and static pink noise, $R^2 = 0.28$, $p < 0.05$ (**b**)

that when participants were presented sonification based on the combination of the *whoosh* * 1:1 scale plus any mapping type, they were able to significantly reduce their target distance error standard deviation when compared to static pink noise. It is possible that participants found it easier to use sounds generated by the *whoosh* synthesiser when club head speed was mapped onto a more limited scale. Based on the findings made in Johnson et al. (1987), we anticipated that participants would perceive and interpret the 24 different types of sonification differently, which, in turn, might affect performance. As demonstrated in the Supplementary Materials, the timbral differences between synthesisers and modulations are considerable; while, the scales and mapping functions are purposefully more abstract and, depending on their combination, possibly less obvious to listeners. Despite our care and interest in developing distinguishable sounds based on a complex motor task, there are still many questions regarding the effects of sound on human movement.

Our zone estimation error standard deviation results showed that only the *whoosh* synthesiser proved to be significantly different from both static pink noise and *jet*; whereas, no other synthesis parameter affected performance. Interestingly, this synthesiser produced sounds with a more limited frequency spectrum, and it is possible that participants found them easier to interpret and read their movements as embedded in the sound Johnson et al. (1987) and Kidd et al. (2007). Bieńkiewicz et al. (2019) developed a similar synthesiser for their golf putting study, which reported novice participants exposed to sound improved motor learning. These studies together provide further evidence that, when studying the relationship between human audition and motor control, an ecological, as opposed to timbrally rich or complex, sound might be more affective Gaver (1993). Reports and findings from Sigrist et al. (2013), Dubus and Bresin (2014) and Dyer et al. (2017) similarly advocate the use of more ecological sounds as a way of maximising sonification efficiency while executing motor tasks. By coupling these findings with our target distance error standard deviation results, sonification can clearly be used by novices to improve performance variability; however, its significance appears to depend on sound type and the goal of its use.

Interestingly, participants did not improve their average zone estimation error when presented real-time auditory feedback. Although we observed a trend towards an effect on target distance error average, our post hoc tests offered little evidence of this when considering average zone estimation error. This result differs from those reported in a pilot study by O'Brien et al. (2018), where participants were able to identify swing speed as represented by auditory signals, and Murgia et al. (2017), which found expert golfers were able to recognise their own idiosyncratic swings via sonification. Unrelated to golf, Thoret et al. (2016) similarly found participants were able to associate profiles with particular shapes. However, it is possible that our task was much too difficult and complex for the participants to adequately complete, as they were asked to estimate the distance of an object (ball) that was displaced by another (putter) as a consequence of their speed. This of course requires participants to make predictions based on their interpretation of 24 different sounds acting as metaphors for their speed.

In general, it appears that sonification affected both target distance error and zone estimation similarly. While sonification did not appear to significantly influence average performance, it did similarly affect the variability of motor and, when presented the *whoosh* synthesiser, perceptive aspects of the task. Using a linear regression model, we computed the correlation between the two variables for each participant during the trials with the *whoosh* synthesiser ($R^2 = 0.51$, $p < 0.001$) and static pink noise ($R^2 = 0.28$, $p < 0.05$). Figure 3a, b illustrate and compare the models. The significant relationship between target distance error and zone estimation error standard deviation when the *whoosh* synthesiser was present strongly suggests that participants were capable of reading their movement in sound in a way that allowed them to stabilise their putting performance and estimations based on them. Based on these results, we might hypothesise that by presenting novices with online sonification, their reduced performance variability would make them more consistent, which would then allow professional trainers to better instruct on making swing modifications to improve overall performance (Tucker et al. 2013; Glazier 2011).

We observed that participants were able to significantly lower their average impact velocity when online sonification was present, but not their variability. Golf research suggests swing timing is a significant factor that contributes to the success of a putt (Burchfield and Venkatesan 2010; Kooyman et al. 2013), which Craig et al. (2000) found to be strongly correlated with impact velocity. More specifically, our findings suggest online sonification played a role in modifying swing timing or acceleration profiles, which in turn caused participants to affectively lower their impact velocity. Although their impact velocities appeared to be affected by sonification, because no sound synthesis parameter emerged as significantly different suggests participants were unaffected by the timbral differences between the sounds. This is an interesting observation with regards to distinctions made in the auditory system, which demands further study. Although we did not test all possible sound configurations, it is possible that participants might have found some sounds to be more efficient. That said, this was not the goal of our study but rather whether participants were able to extract information (club head speed) from the presented sounds.

Using linear regression models, we found average impact velocity correlated poorly with target distance error standard deviation ($R^2 = 0.02$, $p > 0.05$) and zone estimation error standard deviations ($R^2 < 0.01$, $p > 0.05$) during *whoosh* synthesiser trials. Similarly, we found that during static pink noise trials, average impact velocity correlated poorly with target distance error standard deviation ($R^2 = 0.12$, $p > 0.05$) and zone estimation error standard deviation ($R^2 = 0.02$, $p > 0.05$). These results suggest that the sound of impact did not play an important role when participants made performance-based estimations. Of course, one way to verify this would be to sonify the moment of impact with the ball. If we masked the sound of contact with the ball by exaggerating or minimising the presence of natural acoustic feedback Rocchesso et al. (2003), we might examine the effects on performance.

However, Roberts et al. (2005) reported strong correlations between performance and subjective perceptions based on impact sound for elite golfers. One might then hypothesise that a "good" impact sound would motivate players to maintain or continue executing the complex motor task, whereas a "bad" sound would encourage them to make adjustments to their swings. Of course an impact sound is a short impulse that follows the execution of a complex movement (Fig. 5 in "Appendix 2"); whereas, the sonifications provided to our participants are based on this gesture and display each unique history. Because participants offered their estimations after making impact, our significant findings for target distance error and zone estimation error standard deviations reinforce the influence of sonification on behavioural performance and perceptual correlates.

Reflecting on our testing and analysis, we acknowledge that studying the effects of 24 different sonifications developed from combinations of types of synthesisers, modulations, scales, and mappings was ambitious. In some part, this was due to our implementation of sonification parameters that were dependent on our synthesiser design. However, studying and reporting on them are important contributions to help researchers identify which sound synthesis parameters and combinations can affect performance and perceptual correlates. Moreover, our findings revealed that some parameters could be varied in ways that affected behavioural and perceptual performance differently. As previously discussed, a major take-away was that while participants reduced their target distance error standard deviation when either synthesiser was present, only the *whoosh* synthesiser led them to significantly reduce their zone estimation error variability when compared to trials associated with the *jet* synthesiser and static pink noise. That being the case, our findings also showed the *whoosh* synthesiser, when its scale was limited (1:1), interacted with all other mappings to produce significant differences in target distance error standard deviation when compared to static pink noise. Here, we observed that only the combination of *whoosh* * 1:1 scale yielded significant differences when compared to static pink noise, which suggests participants had greater difficulty using sounds where club head speed was mapped onto a greater range. Although no mapping type distinguished itself from another, we did observe a more pronounced effect with linear mapping (around 2 cm). When participants were presented sounds generated by the *whoosh* synthesiser, we observed behavioural and perceptual enhancements, which suggests they found these sounds were easier to use. Nevertheless, these different combinations permitted us to observe different effects.

Conclusion

The results of this study demonstrate that novices were able to use sound to reduce performance variability, while completing a complex motor task. A major highlight of these significant findings was that participants were not required to synchronise or conform their movements to the sound presented to them. Concurrent sound enhanced their natural execution of the swing gesture, a point advocated by Dyer et al. (2017).

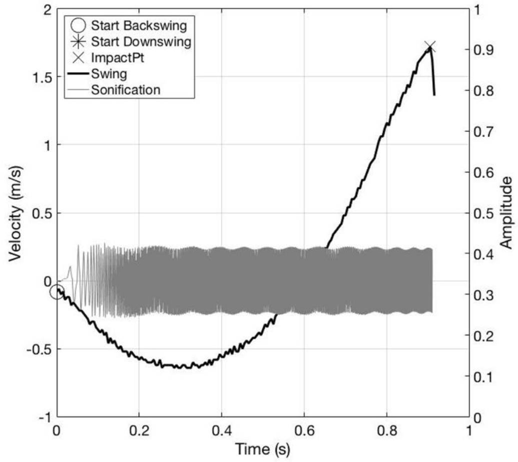
Based on our target distance error and zone estimation error standard deviation results, one could propose the use of auditory feedback to lower variability in executing complex motor skills. For example, Kim et al. (2018) found they were able to lower variability in professional woman golf players using neural networks to develop training exercises based on previous training trials. One might imagine auditory feedback could be developed in a way that considers the unique features of the novice participant, while minimising the factors that deviate from their average or optimal swing form.

Motivated by this proposition, we recently finished a new golf putting study where auditory feedback was developed and dedicated to giving information based on the real-time comparison between optimal and observed swings O'Brien et al. (2018). Following a number of successful trials, we identified unique characteristics in their swings and used this information to develop participant-dependent swing models that could be used to compare and calculate real-time differences for each swing. These differences were then sonified in different ways and presented to participants. Based on results from van Vugt and Tillmann (2015), we believed that this type of error-based personalised sonification might help novices reduce movement variability, which, in turn, might affect and effectively optimise their performance. Although a comprehensive report of our findings is forthcoming, the initial results suggest that participants who experienced a specific type of online auditory feedback significantly reduced movement variability.

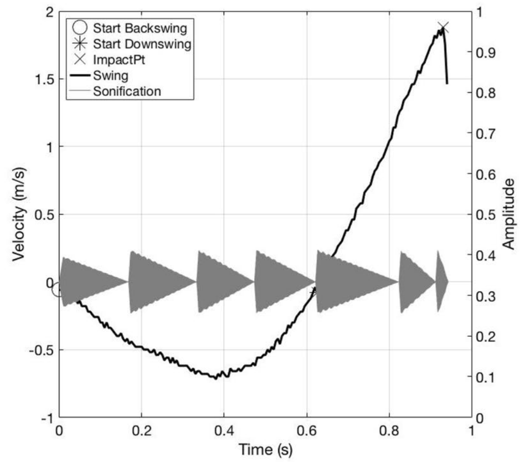
Funding This work was funded by the French National Research Agency (ANR) under the SoniMove: Inform, Guide and Learn Actions by Sounds project (ANR-14-CE24-0018- 01).

Appendix 1: Club head speed and sonification comparisons

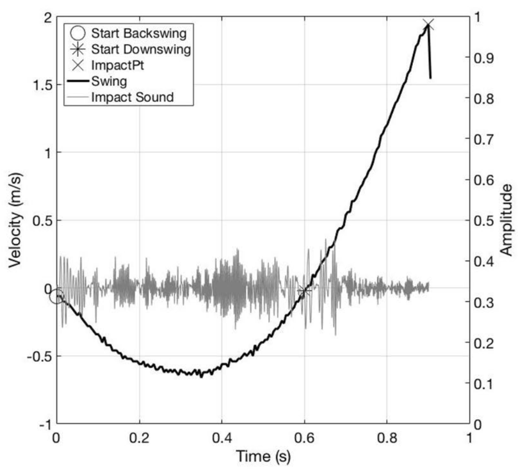
See Fig. 4.



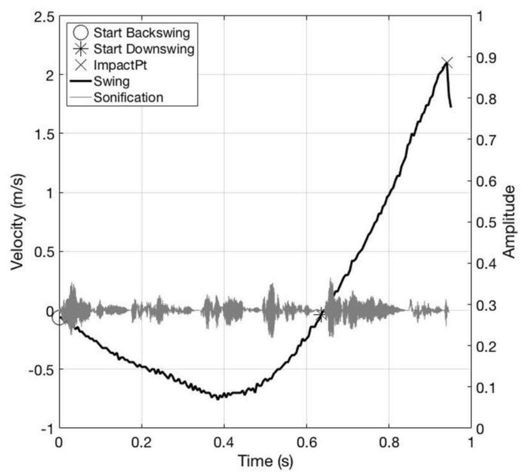
(a) *jet* * brightness * scale 1:2 * linear mapping



(b) *jet* * rhythmicity * scale 1:2 * linear mapping



(c) *whoosh* * brightness * scale 1:2 * linear mapping

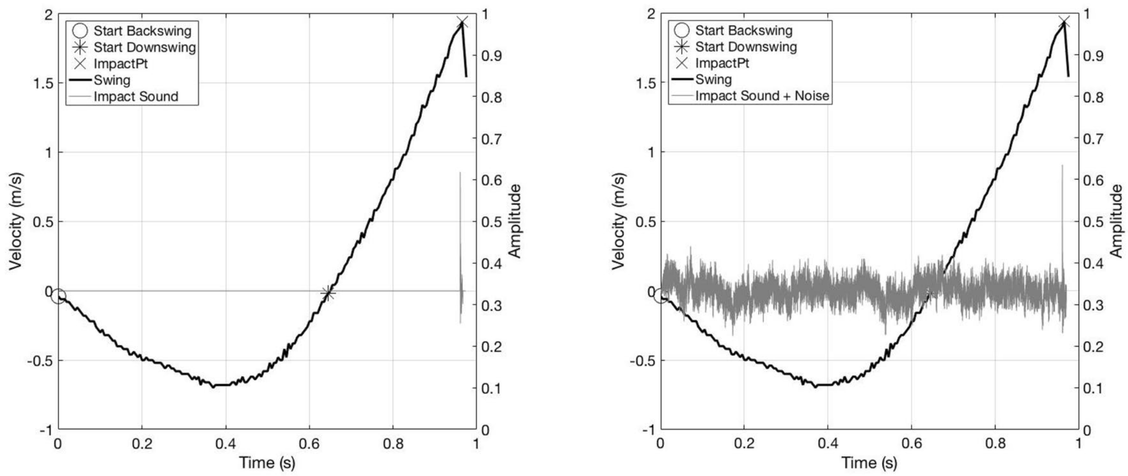


(d) *whoosh* * rhythmicity * scale 1:2 * linear mapping

Fig. 4 Comparison of participant performing golf putting task with different club head speeds and the auditory signals generated from them. The following sound synthesis combinations were used, where scale 1:2 and linear mapping were fixed: *jet* * brightness (**a**); *jet* * rhythmicity (**b**); *whoosh* * brightness (**c**); and *whoosh* * rhythmicity (**d**)

Appendix 2: Impact sound and static pink noise

See Fig. 5.



(a) Club head speed and impact sound

(b) Club head speed, impact sound, and static pink noise

Fig. 5 Participant performing putting task without (**a**) and with (**b**) static pink noise

References

Baudry L, Leroy D, Thouvareq R, Choller D (2006) Auditory concurrent feedback benefits on the circle performed in gymnastics. J Sports Sci 24(2):149–156. https://doi.org/10.1080/02640410500130979

Baumann S, Koeneke S, Schmidt C, Meyer M, Lutz K, Jancke L (2007) A network for audio-motor coordination in skilled pianists and non-musicians. Brain Res 1161:65–78. https://doi.org/10.1016/j.brainres.2007.05.045

Bieńkiewicz M, Bourdin C, Bringoux C, Buloup F, Craig C, Prouvost L, Rodger M (2019) The limitations of being a copycat: learning golf putting through auditory and visual guidance. Frontiers 10:92. https://doi.org/10.3389/fpsyg.2019.00092

Boyer E, Bevilacqua F, Susini P, Hanneton S (2016) Investigating three types of continuous auditory feedback in visuo-manual tracking. Exp Brain Res 235:691–701. https://doi.org/10.1007/s00221-016-4827-x

Burchfield R, Venkatesan S (2010) A Framework for Golf Training Using Low-Cost Inertial Sensors. In: Proceedings of the 2010 International Conference on Body Sensor Networks. https://doi.org/10.1109/BSN.2010.46

Castiello U, Giordano B, Begliomini C, Ansuini C, Grassi M (2010) When ears drive hands: the influence of contact sound on reaching to Grasp. PLoS One. https://doi.org/10.1371/journal.pone.0012240

Chollet D, Micallef JP, Rabischong P (1988) Biomechanical signals for external biofeedback to improve swimming techniques. In: Ungerechts B, Wilke K, Reischle K (eds) Swimming Science V. International Series of Sport Sciences, vol 18. Human Kinetics Books, Champaign, pp 389–396

Craig CM, Delay D, Grealy MA, Lee DN (2000) Guiding the swing in golf putting. Nature. https://doi.org/10.1038/35012690

Crasta J, Thaut M, Anderson C, Davies P, Gavin WJ (2018) Auditory priming improves neural synchronization in auditory-motor entrainment. Neuropsychologia 117:102–112. https://doi.org/10.1016/j.neuropsychologia.2018.05.017

Danna J, Fontaine M, Paz-Villagrán V, Gondre C, Thoret E, Aramaki M, Kronland-Martinet R, Ystad S, Velay J (2014) The effect of real-time auditory feedback on learning new characters. Hum Mov Sci 43:216–228. https://doi.org/10.1016/j.humov.2014.12.002

Dubus G, Bresin R (2014) Exploration and evaluation of a system for interactive sonification of elite rowing. Sports Eng. https://doi.org/10.1007/s12283-014-0164-0

Dyer J, Rodger M, Stapleton P (2016) Transposing Musical Skill: Sonification of movement as concurrent augmented feedback enhances learning in a bimanual task. Psychol Res. https://doi.org/10.1007/s00426-016-0775-0

Dyer JF, Stapleton P, Rodger M (2017) Mapping sonification for perception and action in motor skill learning. Front Neurosci 11:463. https://doi.org/10.3389/fnins.2017.00463

Effenberg A, Ursula F, Schmitz G, Krueger B, Mechling H (2016) Movement Sonification: effects on motor learning beyond rhythmic adjustments. Front Neurosci. https://doi.org/10.3389/fnins.2016.00219

Farnell A (2010) Designing sound. The MIT Press, London, pp 491–497

Fitch WT, Kramer G (1994) Sonifying the body electric: Superiority of an auditory over a visual display in a complex, multivariate system. In: Kramer G (ed) Auditory display: sonification, audification and auditory interfaces. Addison-Wesley, Reading, pp 307–325. https://doi.org/10.2307/3680606

Gaver W (1993) What in the world do we hear?: An ecological approach to auditory event perception. Ecol Psychol 5:1–29. https://doi.org/10.1207/s15326969eco0501

Glazier P (2011) Movement variability in the golf swing. Res Q Exerc Sport 82:157–161. https://doi.org/10.5641/027013611X13119541883429

Grond F, Berger J (2011) Parameter mapping sonification. In: Hermann T, Hunt A, Neuhoff JG (eds) The sonification handbook. Logos Publishing House, Berlin, pp 363–397. https://doi.org/10.1080/13658816.2017.1420192

Grober R (2009) Resonance in putting. arXiv:0903.1762

Hebb D (1949) The Organization of Behavior. Wiley, New York. https://doi.org/10.1037/h0088061

Hirsh I, Watson C (1996) Auditory psychophysics and perception. Annu Rev Psychol 47:461–84. https://doi.org/10.1146/annurev.psych.47.1.461

Kidd GR, Watson CS, Gygi B (2007) Individual differences in auditory abilities. J Acoust Soc Am 122(1):418–435. https://doi.org/10.1121/1.2743154
Kim J, Han J, Han D (2018) Training effects of Interactive Metronome on golf performance and brain activity in professional woman golf players. Hum Mov Sci 61:63–71. https://doi.org/10.1016/j.humov.2018.07.005
Johnson D, Watson C, Jensen JK (1987) Individual differences in auditory capabilities. J Acoust Soc Am 81(2):427–438. https://doi.org/10.1037/10119-004
Kooyman D, James D, Rowlands D (2013) A feedback system for the motor learning of skills in golf. Procedia Eng 60:226–231. https://doi.org/10.1016/j.proeng.2013.07.014
Lakatos S, McAdams S, Causse R (1997) The representation of auditory source characteristics: simple geometric form. Percept Psychophys 59:180–90. https://doi.org/10.3758/BF03214206
Merchant H, Grahn J, Trainor L, Rohrmeier M, Fitch WT (2015) Finding the beat: a neural perspective across humans and non-human primates. Philos Trans R Soc B Biol Sci 370:20140093. https://doi.org/10.1098/rstb.2014.0093
Morillon B, Baillet S (2017) Motor origin of temporal predictions in auditory attention. Proc Natl Acad Sci USA 114:E8913–E8921. https://doi.org/10.1073/pnas.1705373114
Munte T, Altenmuller E, Jancke L (2002) The musician's brain as a model of neuroplasticity. Natl Rev Neurosci 3:473–478. https://doi.org/10.1038/nrn843
Murgia M, Prpic V, O, J, McCullagh P, Santoro I, Galmonte A, Agostini T (2017) Modality and perceptual-motor experience influence the detection of temporal deviations in tap dance sequences. Front Psychol 8:1340. https://doi.org/10.3389/fpsyg.2017.01340
Newton P (2015) The learning styles myth is thriving in higher education. Front Psychol. https://doi.org/10.3389/fpsyg.2015.01908
O'Brien B, Juhas B, Bienkiewicz M, Pruvost L, Buloup F, Bringnoux L, Bourdin C (2018) Considerations for Developing Sound in Golf Putting Experiments. In: Post-proceedings of CMMR 2017 - Music Technology with Swing, Lecture Notes in Computer Science. Springer, Heidelberg. https://doi.org/10.1007/978-3-030-01692-0
Risset J, Mathews M (1969) Analysis of musical instrument tones. Phys Today 22:23–30. https://doi.org/10.1063/1.3035399
Roberts J, Jones R, Mansfield N, Rothberg S (2005) Evaluation of impact sound on the 'feel' of a golf shot. J Sound Vib 287:651–666. https://doi.org/10.1016/j.jsv.2004.11.026
Rocchesso D, Bresin R, Fernström M (2003) Sounding objects. IEEE Multimedia 10(2):42–52. https://doi.org/10.1109/MMUL.2003.1195160
Salako SE (2006) The declaration of Helsinki 2000: ethical principles and the dignity of difference. Med Law 2:341–354. https://doi.org/10.1515/9783110208856.233
Schaffert N, Janzen T, Mattes K, Thaut M (2019) A review on the relationship between sound and movement in sports and rehabilitation. Front Psychol 10:244. https://doi.org/10.3389/fpsyg.2019.00244
Schmitz G, Mohammadi B, Hammer A, Heldmann M, Samii A, Münte TF et al (2013) Observation of sonified movements engages a basal ganglia frontocortical network. BMC Neurosci. https://doi.org/10.1186/1471-2202-14-32
Schlaug G (2001) The brain of musicians: a model for functional and structural adaptation. Ann N Y Acad Sci 930:281–299. https://doi.org/10.1111/j.1749-6632.2001.tb05739.x
Secoli R, Milot M-H, Rosati G, Reinkensmeyer DJ (2011) Effect of visual distraction and auditory feedback on patient effort during robot-assisted movement training after stroke. J Eeuroeng Rehabil 8(1):21. https://doi.org/10.1186/1743-0003-8-21
Sigrist R, Rauter G, Riener R, Wolf P (2013) Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. Psychon Bull Rev 20(1):21–53. https://doi.org/10.3758/s13423-012-0333-8
Thaut M, McIntosh G, Hoemberg V (2015) Neurobiological foundations of neurologic music therapy: rhythmic entrainment and the motor system. Front Psychol 6:1185. https://doi.org/10.3389/fpsyg.2015.01185
Thoret E, Aramaki M, Kronland-Martinet R, Velay J-L, Ystad S (2014) From sound to shape: auditory perception of drawing movements. J Exp Psychol Human Percept Perform Am Psychol Assoc 40(3):983–994. https://doi.org/10.1037/a0035441
Thoret E, Aramaki M, Bringoux L, Ystad S, Kronland-Martinet R (2016) Seeing circles and drawing ellipses: when sound biases reproduction of visual motion. PLoS One. https://doi.org/10.1371/journal.pone.0154475
Tucker C, Anderson R, Kenny I (2013) Is outcome related to movement variability in golf? Sport Biomech 12:343–354. https://doi.org/10.1080/14763141.2013.784350
van Vugt F, Tillmann B (2015) Auditory feedback in error-based learning of motor regularity. Brain Res 1606:54–67. https://doi.org/10.1016/j.brainres.2015.02.026
Wessel D (1979) Timbre space as a musical control structure. Comput Music J 3(2):45–52. https://doi.org/10.2307/3680283
Wildes RP, Richards W (1988) Recovering material properties from sound, natural computation. MIT Press, Cambridge, pp 356–363. https://doi.org/10.1037//0096-1523.10.5.704
Wulf G, Shea C (2002) Principles derived from the study of simple skills do not generalize to complex skill learning. Psychon Bull Rev 9(2):185–211. https://doi.org/10.3758/BF03196276

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.