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Benjamin O'Brien, Brett Juhas, Marta Bieńkiewicz, Frank Buloup, Lionel Bringoux, et al.. Online sonification for golf putting gesture: reduced variability of motor behaviour and perceptual judgement. *Experimental Brain Research*, 2020, 238, pp.883 - 895. 10.1007/s00221-020-05757-3 . hal-02506149

HAL Id: hal-02506149

<https://amu.hal.science/hal-02506149>

Submitted on 19 Apr 2021

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

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Received: date / Accepted: date

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 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

1 Introduction

A recent research trend has focused on studying the effects of online auditory feedback on human movement. [44] 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 [10]. [12] 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 [22,31]. In comparison, auditory information seems less demanding of attention and more portable [41]. A summary of psychophysical research also suggests sound can prompt

dynamic cues that are beyond the field of vision [16,32]. This point is underscored by a significant sonification of movement study by [39], which found 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 [38,21], which, through entrainment, can make these actions more easily repeatable. [9] 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 [43,28,29], which showed participants used rhythmic auditory cues as 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 [2,30,40].

Like musicians, athletes also require a high-level of fine motor control that is easily repeatable. [7] showed that elite swimmers enhanced their motor control by using real-time sonification based on pressure exerted by their hands. [1] 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 [14] 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 [50]. Although the physical fitness required to play and succeed in golf is vast, it requires expert concentration, precision, and force management in order to swing a golf club [5]. 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 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 [8]. The putting motion requires considerable fine motor control processes in order 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 [5]. 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 [20,26].

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. [42] reviewed numerous studies that found success in developing artificial auditory feedback based on velocity. In addition [17] posited that listeners can make ecological observations

62 based on aerodynamics and mechanical noise and use them as auditory indices. For example,
63 listeners might identify changes in speed by identifying sounds associated with the wind or
64 a car engine. More recently, [3] found that the movement of novice golfers was influenced
65 by the presence of auditory guidance based on club head speed. Based on this research, we
66 believed that if participants could perceive that their movement had a direct and immediate
67 effect on the sounds they heard, then we might observe changes to their motor behaviour.

68 As there are innumerable ways to map data-to-sound [19], it was important to develop
69 sound that participants could easily perceive and interpret as metaphor for club head speed.
70 Although research has shown that healthy people can extract information from character-
71 istics in sound [6], such as an object's size [27] or material [49], they do not perceive
72 sound similarly due to their physiological and psychological differences. Based on [25],
73 who found that patterns of individual differences identified in healthy adults similarly af-
74 fected their auditory performance, we expected participants would most likely perceive,
75 interpret, and possibly use artificial sounds based on their movement on an individual-basis,
76 if at all. Therefore, as a way of maximising the potential for participants to engage with and
77 become influenced by sound, our goal was to develop and combine methods for mapping
78 club head speed to parameters controlling sound synthesis and study their effects on perfor-
79 mance. By doing so, we might develop a method for enhancing performance by sonifying
80 the golf putting gesturing.

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

90 The primary goal of our study was to examine whether real-time auditory feedback can
91 play a significant role in behavioural performance and its perceptual correlates. Specifically
92 we wanted to study whether online sonification had an immediate effect on performance, as
93 opposed to studying its effects on novices learning a complex motor skill. A corollary then
94 was to examine whether sonification affected aspects required to execute the complex motor
95 task and, if so, were there any correspondences with performance.

96 2 Methods

97 2.1 Participants

98 Twenty right-handed participants (12 male; ages 24.2 ± 6.7) affiliated with Aix-Marseille
99 University participated in the experiment. All participants had good or corrected vision and
100 hearing and self-reported having no motor control problems and being right-handed. All
101 participants consented to voluntary participation in the study and were informed of their
102 right to withdraw at any time. This study was performed in accordance with the ethical
103 standards of the Declaration of Helsinki [37]. The protocol was approved by the Ethics
104 Committee of Aix-Marseille University.

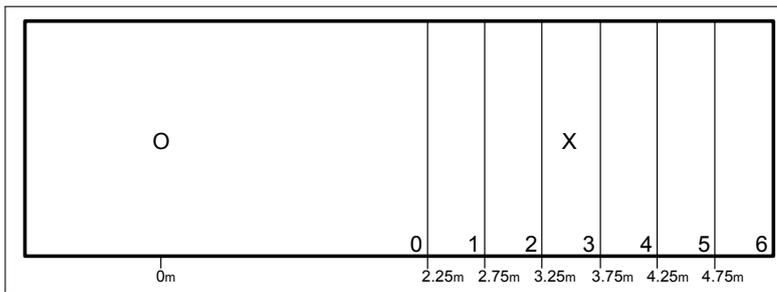


Fig. 1 Overhead diagram of putting terrain, where **O** is the starting position (0 m) and **X** is the target (3.5 m). Zones 0-6 are 0.5 m apart.

105 2.2 Experimental setup

106 2.2.1 Materials

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

116 2.2.2 Sound Design

117 Participants were presented 24 different sonifications, which were created by combining dif-
 118 ferent synthesisers, timbral modulations, scales, and mappings. Unlike some sounds, such
 119 as piano notes, which might carry additional, nested information to some participants in
 120 ways that might affect their performance, our method allowed us to parameterise and de-
 121 velop different sounds that might be more contextually relevant to the performance of the
 122 golf putting gesture. Although their development is described in greater detail in [33], the
 123 following offers a brief description.

124 Following closely to the *action-object* paradigm [17], we designed two synthesisers with
 125 the goal of getting participants to perceive or imagine the properties of the object (the putter)
 126 or the morphologies that carry information about the action (the golf putting gesture). The
 127 *whoosh* synthesiser produced a sound similar to that of a metal object passing through the
 128 air by mapping club head speed to the center frequency of a second-order IIR digital res-
 129 onator filter (decay rate: 30 ms) with white noise input. In order to bring attention to swing
 130 speed we wanted to create an exaggerated sound based on the sound of metal-air contact via
 131 mechanical processes. Adapting a model developed by [15], our *jet* synthesiser mapped club
 132 head speed to a *speed scalar* with a range of 0.0 (“engine off”) and 1.0 (“engine maximum
 133 speed”). This signal was then filtered by a single-pole low-pass filter with a 0.2 Hz center
 134 frequency, creating the auditory effect of a mechanical system speeding up or slowing down,
 135 which then scaled the frequencies of five sine wave oscillators.

136 Given the two synthesisers, we wanted to examine whether there were any effects on
137 performance if club head speed was mapped to parameters that modulated either sound
138 *brightness* [48, 34] or *rhythmicity*¹. To study the effects of one parameter, of course the
139 other must remain fixed. Therefore, when velocity was mapped to parameters that modulated
140 brightness, it was not mapped to rhythmicity parameters, and vice-versa.

141 The scale in which to map club head speed to brightness was different for each syn-
142 thesiser. Based on similar selections made in a sonification of golf putting study by [3], we
143 selected a frequency range of 80-1000 Hz for the *whoosh*, as it is just below the 2-5 kHz
144 sensitivity of the human ear. The *jet* was composed of five sinusoidal oscillators with dif-
145 ferent amplitudes and maximum frequencies (3-11 kHz), which were scaled between 0.0 to
146 1.0 relative club head speed (“speed scalar”). As the human auditory system is sensitive to
147 frequencies from 20 Hz to 20 kHz, both synthesisers produced sounds in the lower half of
148 this frequency sensitivity spectrum. It is commonplace that sensitivity to upper-range fre-
149 quencies degrades with age, although this was most likely not a factor for our participants.
150 Thus, we selected frequency ranges of 540-1000 Hz (1:1) and 80-1000 Hz (1:2) for the
151 *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
152 rhythmicity was similar for both synthesisers, so a single method was developed that con-
153 tinually repeated the process of sending attack-decay-release envelopes (attack: 5 ms). For
154 decay times we selected a range between a fifth and a fiftieth of a second, which yielded 20-
155 110 ms (1:1) and 20-200 ms (1:2). Unlike the relationship with brightness, speed and decay
156 length are inversely proportional, so that club head speed and impulse rate are proportional.

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

162 All sonifications are listed in **Table 1. Appendix 1** illustrates club head speeds per-
163 formed by a participant when presented different auditory conditions. The **Supplementary**
164 **Materials** demonstrate some of the sound synthesis combinations and their effects on sound
165 produced from club head speed.

166 In addition to the 24 different sonifications described above, a static pink noise case was
167 added to serve as a reference, such that its synthesis and display were independent of move-
168 ment. The static pink noise was to control for the effect of headphones, but not to isolate
169 the participants from the environmental sounds, including ball impact. To demonstrate that
170 the sound of impact was available to participants across the different auditory conditions,
171 **Appendix 2** illustrates a participant performing the golf putting task with and without static
172 pink noise.

173 2.2.3 Task

174 Participants were tasked with hitting a golf ball towards a 3.5 m target. While completing
175 the putting gesture, participants were exposed to different sonifications (**2.2.2**). Once partici-
176 pants made contact with the ball, their shutters closed. Their second task was then to estimate
177 the final distance of the ball. Participants verbally offered a number that corresponded to a
178 provided diagram that outlined zones on the putting terrain (**Figure 1**). An experimenter
179 then measured the distance between the ball and the target, which was used as a reference

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.

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

180 to compare against the webcam recordings (2.2.4), removed the ball, and then reopened the
 181 participant's shutters.

182 After completing a sequence of 25 experimental trials, whose order was pseudo-randomised,
 183 participants had five calibration trials to avoid a drift of overshooting the target due to the
 184 lack of visual assessment during the experimental trials. During these trials, shutters re-
 185 mained opened and participants were presented static pink noise. 25 experimental trials
 186 followed by 5 calibrations were repeated five times for a total of 145 putts, where the last 5
 187 calibrations were removed from testing.

188 2.2.4 Data recordings and statistics

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

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

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

198 Because our goal was to examine the effects of online sonification, it was important to
 199 minimise latency between club head speed and the sound synthesised from it. While we

200 were unable to calculate temporal differences in auditory processing between participants,
201 it was important to determine a latency reference that was not so large that it might inad-
202 vertently affect performance. A pretest was developed, where sound would be generated by
203 a sinusoidal oscillator (frequency: 200 Hz) if the CodaMotion marker located near the club
204 head crossed a pre-determined point under a ball. A microphone was placed near the ball to
205 record the sound of impact, while the sound generated by Max/MSP was stored directly on a
206 computer. Three novice participants were instructed to perform 20 3.5 m putts. Empirically
207 comparing the start times of the sound of impact and the sound generated in Max/MSP, we
208 determined a 25-28 ms delay. For the three participants, the average putting duration was
209 1.05 ± 0.32 seconds, and we decided a latency of around 2.3-2.6% was not meaningful.

210 To examine the effects of real-time auditory feedback on behavioural performance and
211 perceptual correlates, two variables were used. To assess the success of a putt, we measured
212 the distance between the target and the final position of the ball, or the *target distance error*
213 (*TDE*). Using a similar method described in [3], we selected the image with the final po-
214 sition of the ball and calculated the distance between target and the ball by using a custom
215 MATLAB program. This calculation was then compared to our manual distance calculation,
216 where any discrepancies were averaged but did not exceed 1 cm. To quantify perceptual ac-
217 curacy and precision, we calculated the difference between the estimation and the observed
218 final ball position, or the *zone estimation error* (*ZEE*). Because we were interested in both
219 participant average and variability, for both *TDE* and *ZEE* we calculated both the mean (μ)
220 and standard deviation (σ).

221 To better understand the relationship between putting performance and swing mechan-
222 ics and the potential influence of sound on them, we analysed impact velocity (*IV*). [8]
223 reported a strong direct correlation between putting distance and velocity at impact, ranging
224 from 0.98 to 0.99. These findings support observations made by [5], which underscore the
225 importance of club head speed in order to have successful putts. Thus, we wanted to exam-
226 ine whether real-time auditory feedback might affect impact velocity in manner similar to
227 performance. Both impact velocity average IV_{μ} and standard deviation IV_{σ} were calculated.

228 In our preliminary analysis, we wanted to first confirm group normality and analysed
229 all participant TDE_{μ} and ZEE_{μ} during experimental trials by calculating their respective z-
230 scores. All participants were included in our study, $|z| < 3\sigma$. Next, we wanted to confirm our
231 method of sound randomisation did not bias any one sound and, by applying Repeated Mea-
232 sures ANOVAs, found no main effect of sound position in sequence on TDE_{μ} nor TDE_{σ} ,
233 $p > 0.05$. Thus, all sounds were treated as equal and independent of their position in the
234 experimental trial sequence.

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

3 Results

3.1 Target Distance Error

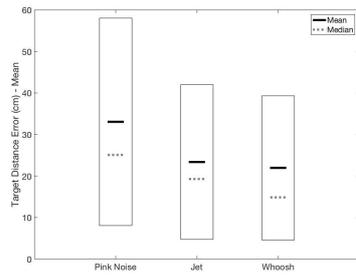
To examine whether real-time auditory feedback influenced putting performance, we analysed both TDE_μ and TDE_σ . For the TDE_μ , we found main effects for types of synthesiser $F_{2,38} = 27.24, p < 0.001, \eta_p^2 = 0.59$ and modulation $F_{2,38} = 27.63, p < 0.001, \eta_p^2 = 0.59$, and an interaction 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), $p < 0.001$. **Figures 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.

3.2 Zone Estimation Error

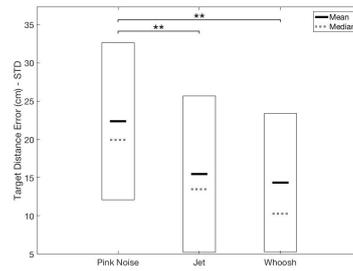
To examine whether real-time auditory feedback had an effect on ball distance estimation, we analysed both ZEE_μ and ZEE_σ . For ZEE_μ , we found main effects for types of synthesiser $F_{2,38} = 11.59, p < 0.001, \eta_p^2 = 0.38$, modulation $F_{2,38} = 12.84, p < 0.001, \eta_p^2 = 0.4$, and an interaction 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, $p < 0.05$. **Figures 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.

3.3 Impact Velocity

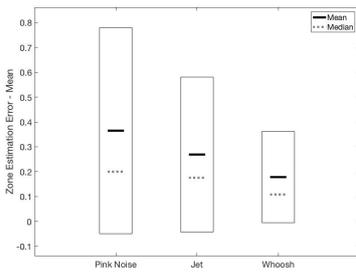
To examine whether real-time auditory feedback played a similar role in both performance and swing mechanics, we analysed impact velocity (IV_μ and IV_σ). For IV_μ there were main



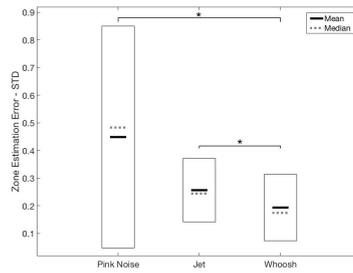
(a) TDE_{μ} - synthesisers & static pink noise trials



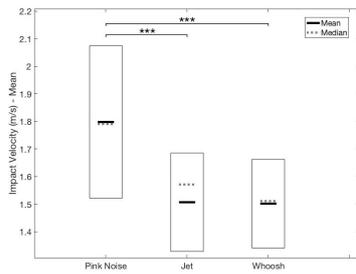
(b) TDE_{σ} - synthesisers & static pink noise trials



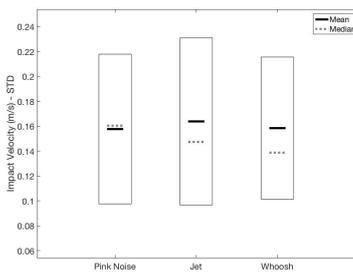
(c) ZEE_{μ} - synthesisers & static pink noise trials



(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. {*, **, ***} mark significance for $p < \{0.05, 0.01, 0.001\}$. Boxes represent the standard deviation from mean.

282 effects for types of synthesiser $F_{2,38} = 1468.77, p < 0.001, \eta_p^2 = 0.99$, modulation $F_{2,38} =$
 283 $1471.25, p < 0.001, \eta_p^2 = 0.99$, and an interaction between synthesiser * scale * mapping
 284 $F_{2,38} = 1450.28, p < 0.001, \eta_p^2 = 0.99$. Post-hoc tests revealed both types of synthesisers
 285 and modulations had significantly lower impact velocity means when compared to those as-
 286 sociated with the static pink noise trials: *whoosh* (0.3 ± 0.05), *jet* (0.29 ± 0.04), *brightness*
 287 (0.29 ± 0.04), and *rhythmicity* (0.29 ± 0.05), $p < 0.001$. Similarly, we found all interac-
 288 tions ($n=12$) between synthesiser * scale * mapping had significantly lower impact velocity

289 means when compared to those associated with the static pink noise trials, where the average
 290 difference between them was $\mu_n = 0.29 \pm 0.03$ and the average standard error was $\mu_n = 0.05$
 291 ± 0.01 , $p < 0.001$. For IV_σ there were main effects for types of synthesiser $F_{2,38} = 121.01$,
 292 $p < 0.001$, $\eta_p^2 = 0.86$, modulation $F_{2,38} = 118.8$, $p < 0.001$, $\eta_p^2 = 0.86$, and an interaction
 293 between synthesiser * scale * mapping $F_{4,76} = 113.46$, $p < 0.001$, $\eta_p^2 = 0.88$. But post-
 294 hoc tests revealed no significant differences when comparing trials associated with different
 295 sound synthesis parameters to those with static pink noise, $p > 0.05$ **Figures 2e-f** illustrate
 296 the differences between IV_μ and IV_σ when comparing different synthesiser and static pink
 297 noise trials. These results reveal sound played a significant role in affecting average impact
 298 velocity, but not its variability.

299 4 Discussion

300 Our goal was to examine whether real-time auditory feedback played a role in the be-
 301 havioural or perceptual performance of novice golfers when vision was limited and study
 302 any similarities. With regards to the effect of sonification on average target distance error,
 303 we reported significant main effects and interactions, but our post-hoc results revealed no
 304 significance. However, both synthesisers and modulations had lower average target distance
 305 error when compared to trials with static pink noise: *whoosh* (11.1 ± 4.88), $p = 0.08$; *jet*
 306 (9.68 ± 4.67), $p = 0.13$; *brightness* (10.26 ± 4.65), $p = 0.09$; and *rhythmicity* ($10.51 \pm$
 307 4.89), $p = 0.1$. Despite trials associated with each synthesiser and modulation having lower
 308 target distance error averages of approximately 10 cm when compared to those with static
 309 pink noise, neither was found to be significant.

310 In comparison to trials associated with static pink noise, we observed that participants
 311 were able to significantly reduce their target distance error standard deviation when pre-
 312 sented either type of synthesiser or modulation. This suggests they were able to interpret
 313 information regarding their speed and make adjustments to their motor control in ways that
 314 stabilised their ball distance from the target performance. This important result supports evi-
 315 dence that the auditory channel is well-suited to act as a conduit for which motor-related
 316 information can be transmitted [42, 10, 4, 1]. Our results build upon those reported in [47],
 317 where concurrent sound was shown to improve performance by reducing temporal irregu-
 318 larities, as we found novices completing a more complex motor task were able to use sound
 319 to reduce performance variability.

320 While the important take away is that participants improved their target distance error
 321 standard deviation when presented sonification, no synthesiser or modulation class distin-
 322 guished itself from another. Interestingly, we found that when participants were presented
 323 sonification based on the combination of the *whoosh* * 1:1 scale plus any mapping type,
 324 they were able to significantly reduce their target distance error standard deviation when
 325 compared to static pink noise. It is possible participants found it easier to use sounds gen-
 326 erated by the *whoosh* synthesiser when club head speed was mapped onto a more limited
 327 scale. Based on the findings made in [25], we anticipated that participants would perceive
 328 and interpret the 24 different types of sonification differently, which, in turn, might affect
 329 performance. As demonstrated in the **Supplementary Materials** the timbral differences
 330 between synthesisers and modulations are considerable, while the scales and mapping func-
 331 tions are purposefully more abstract and, depending on their combination, possibly less ob-
 332 vious to listeners. Despite our care and interest in developing distinguishable sounds based
 333 on a complex motor task, there are still many questions regarding the effects of sound on
 334 human movement.

335 Our zone estimation error standard deviation results showed that only the *whoosh* syn-
336 thesiser proved to be significantly different from both static pink noise and *jet*, whereas
337 no other synthesis parameter affected performance. Interestingly, this synthesiser produced
338 sounds with a more limited frequency spectrum, and it is possible that participants found
339 them easier to interpret and read their movements as embedded in the sound [25][23]. [3] de-
340 veloped a similar synthesiser for their golf putting study, which reported novice participants
341 exposed to sound improved motor learning. These studies together provide further evidence
342 that, when studying the relationship between human audition and motor control, an ecolog-
343 ical, as opposed to timbrally rich or complex, sound might be more affective [17]. Reports
344 and findings from [42, 11, 13] similarly advocate the use of more ecological sounds as a way
345 of maximising sonification efficiency while executing motor tasks. By coupling these find-
346 ings with our target distance error standard deviation results, sonification can clearly be used
347 by novices to improve performance variability, however, its significance appears to depend
348 on sound type and the goal of its use.

349 Interestingly, participants did not improve their average zone estimation error when pre-
350 sented real-time auditory feedback. Although we observed a trend towards an effect on target
351 distance error average, our post-hoc tests offered little evidence of this when considering av-
352 erage zone estimation error. This result differs from those reported in a pilot study by [33],
353 where participants were able to identify swing speed as represented by auditory signals,
354 and [31], which found expert golfers were able to recognise their own idiosyncratic swings
355 via sonification. Unrelated to golf, [45] similarly found participants were able to associate
356 profiles with particular shapes. However, it is possible that our task was much too difficult
357 and complex for the participants to adequately complete, as they were asked to estimate the
358 distance of an object (ball) that was displaced by another (putter) as a consequence of their
359 speed. This of course requires participants to make predictions based on their interpretation
360 of 24 different sounds acting as metaphors for their speed.

361 In general, it appears sonification affected both target distance error and zone estimation
362 similarly. While sonification did not appear to significantly influence average performance,
363 it did similarly affect the variability of motor and, when presented the *whoosh* synthesiser,
364 perceptive aspects of the task. Using a linear regression model, we computed the correlation
365 between the two variables for each participant during the trials with the *whoosh* synthesiser
366 ($R^2 = 0.51$, $p < 0.001$) and static pink noise ($R^2 = 0.28$, $p < 0.05$). **Figures 3a-b** illustrate
367 and compare the models. The significant relationship between target distance error and zone
368 estimation error standard deviation when the *whoosh* synthesiser was present strongly sug-
369 gests participants were capable of reading their movement in sound in a way that allowed
370 them to stabilise their putting performance and estimations based on them. Based on these
371 results, we might hypothesise that by presenting novices with online sonification, their re-
372 duced performance variability would make them more consistent, which would then allow
373 professional trainers to better instruct on making swing modifications to improve overall
374 performance [46, 18].

375 We observed that participants were able to significantly lower their average impact ve-
376 locity when online sonification was present, but not their variability. Golf research suggests
377 swing timing is a significant factor that contributes to the success of a putt [5, 26], which [8]
378 found to be strongly correlated to impact velocity. More specifically, our findings suggest
379 online sonification played a role in modifying swing timing or acceleration profiles, which
380 in turn caused participants to affectively lower their impact velocity. Although their impact
381 velocities appeared to be affected by sonification, because no sound synthesis parameter
382 emerged as significantly different suggests participants were unaffected by the timbral dif-
383 ferences between the sounds. This is an interesting observation with regards to distinctions

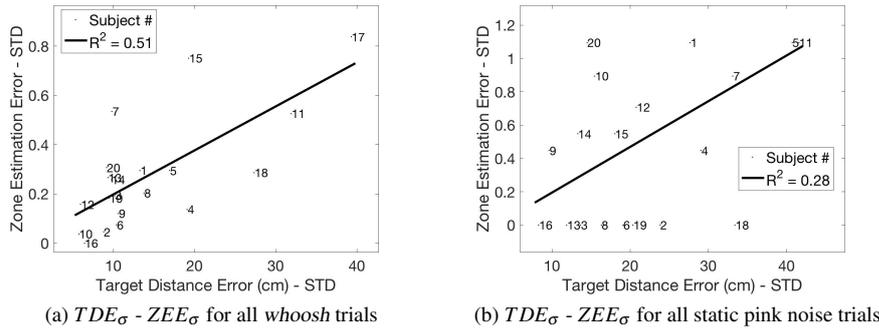


Fig. 3 R^2 correlations between Target Distance Error standard deviation (TDE_{σ}) and Zone Estimation Error standard deviation (ZEE_{σ}) for trials with the *whoosh* synthesiser, $R^2 = 0.51$, $p < 0.001$ (a) and static pink noise, $R^2 = 0.28$, $p < 0.05$ (b).

384 made in the auditory system, which demands further study. Although we did not test all possible
 385 sound configurations, it is possible that participants might have found some sounds to
 386 be more efficient. That said, this was not the goal of our study but rather whether participants
 387 were able to extract information (club head speed) from the presented sounds.

388 Using linear regression models, we found average impact velocity correlated poorly to
 389 target distance error standard deviation ($R^2 = 0.02$, $p > 0.05$) and zone estimation error
 390 standard deviations ($R^2 < 0.01$, $p > 0.05$) during *whoosh* synthesiser trials. Similarly we
 391 found that during static pink noise trials, average impact velocity correlated poorly to target
 392 distance error standard deviation ($R^2 = 0.12$, $p > 0.05$) and zone estimation error standard
 393 deviation ($R^2 = 0.02$, $p > 0.05$). These results suggest that the sound of impact did not play
 394 an important role when participants made performance-based estimations. Of course one
 395 way to verify this would be to sonify the moment of impact with the ball. If we masked
 396 the sound of contact with the ball by exaggerating or minimising the presence of natural
 397 acoustic feedback [36], we might examine the effects on performance.

398 However, [35] reported strong correlations between performance and subjective percep-
 399 tions based on impact sound for elite golfers. One might then hypothesise that a “good”
 400 impact sound would motivate players to maintain or continue executing the complex motor
 401 task, whereas a “bad” sound would encourage them to make adjustments to their swings. Of
 402 course an impact sound is a short impulse that follows the execution of a complex move-
 403 ment (**Appendix 2**), whereas the sonifications provided to our participants are based on this
 404 gesture and display each unique history. Because participants offered their estimations after
 405 making impact, our significant findings for target distance error and zone estimation error
 406 standard deviations reinforce the influence of sonification on behavioural performance and
 407 perceptual correlates.

408 Reflecting on our testing and analysis, we acknowledge that studying the effects of 24
 409 different sonifications developed from combinations of types of synthesisers, modulations,
 410 scales, and mappings was ambitious. In some part this was due to our implementation of
 411 sonification parameters that were dependent on our synthesiser design. However, studying
 412 and reporting on them are important contributions to help researchers identify which sound
 413 synthesis parameters and combinations can affect performance and perceptual correlates.
 414 Moreover, our findings revealed that some parameters could be varied in ways that affected
 415 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). Taken together these findings suggest participants found sounds generated by the *whoosh* synthesiser easier to use to enhance behavioural and perceptual performance. Nevertheless these different combinations permitted us to observe different effects.

4.1 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 [13].

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, [24] found they were able to lower variability in professional woman golf players by 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 [33]. 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 [47], 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

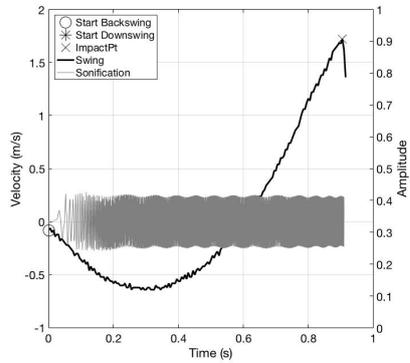
This work was funded by the French National Research Agency (ANR) under the SoniMove: Inform, Guide and Learn Actions by Sounds project (ANR-14-CE24-0018- 01).

References

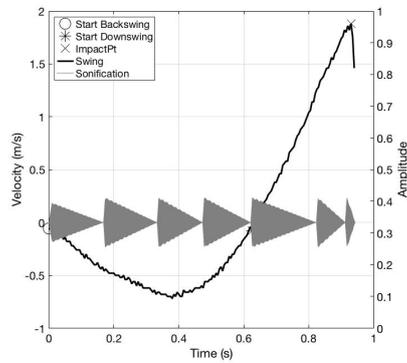
- 458 1. Baudry, L., Leroy, D., Thouvaireq, R., & Choller, D. (2006) Auditory concurrent feedback
459 benefits on the circle performed in gymnastics, *Journal of Sports Sciences* 24(2), 149–156.
460 doi:10.1080/02640410500130979
- 461 2. Baumann, S., Koeneke, S., Schmidt, C., Meyer, M., Lutz, K., & Jancke, L. (2007) A network
462 for audio-motor coordination in skilled pianists and non-musicians, *Brain Research*, 1161, 65–78.
463 doi:10.1016/j.brainres.2007.05.045
- 464 3. Biełkiewicz, M., Bourdin, C., Bringoux, C., Buloup, F., Craig, C., Prouvost, L., Rodger, M. (2019) The
465 Limitations of Being a Copycat: Learning Golf Putting Through Auditory and Visual Guidance, *Frontiers*
466 10, 92. doi:10.3389/fpsyg.2019.00092
- 467 4. Boyer, E., Bevilacqua F., Susini, P., & Hanneton S. (2016). Investigating three types of continuous auditory
468 feedback in visuo-manual tracking. *Experimental Brain Research* 235, 691–701. doi:10.1007/s00221-016-
469 4827-x
- 470 5. Burchfield, R. & S. Venkatesan (2010) A Framework for Golf Training Using Low-Cost Inertial Sensors,
471 *Proceedings of the 2010 International Conference on Body Sensor Networks*. doi:10.1109/BSN.2010.46
- 472 6. Castiello, U., Giordano, B., Begliomini, C., Ansuini, C., & Grassi, M. (2010) When Ears Drive Hands:
473 The Influence of Contact Sound on Reaching to Grasp. *PLOS ONE* 5(8). doi:10.1371/journal.pone.0012240
- 474 7. Chollet, D., Micallef, J. P., and Rabischong, P. (1988). Biomechanical signals for external biofeedback to
475 improve swimming techniques, in *Swimming Science V. International Series of Sport Sciences*, 18, eds B.
476 Ungerechts, K. Wilke, and K. Reischle (Champaign, IL: Human Kinetics Books), 389–396.
- 477 8. Craig, C. M., Delay, D., Greal, M. A., & Lee, D. N. (2000) Guiding the swing in golf putting, *Nature*,
478 295–6. doi:10.1038/35012690
- 479 9. Crasta, J., Thaut, M., Anderson, C., Davies, P., & Gavin, W. J. (2018). Auditory priming
480 improves neural synchronization in auditory-motor entrainment. *Neuropsychologia* 117, 102–112.
481 doi:10.1016/j.neuropsychologia.2018.05.017
- 482 10. Danna, J., Fontaine, M., Paz-Villagrán, V., Gondre, C., Thoret, E., Aramaki, M., Kronland-Martinet,
483 R., Ystad, S., & Velay, J. (2014) The effect of real-time auditory feedback on learning new characters,
484 *Human Movement Science*, 43, 216–228. doi:10.1016/j.humov.2014.12.002
- 485 11. Dubus, G. & R. Bresin. (2014) Exploration and evaluation of a system for interactive sonification of elite
486 rowing, *Sports Engineering*, 18. doi:10.1007/s12283-014-0164-0
- 487 12. Dyer, J., Rodger, M., & Stapleton, P. (2016) Transposing Musical Skill: Sonification of movement
488 as concurrent augmented feedback enhances learning in a bimanual task, *Psychological Research*, 81.
489 doi:10.1007/s00426-016-0775-0
- 490 13. Dyer, J. F., Stapleton, P., & Rodger, M. (2017). Mapping sonification for perception and action in motor
491 skill learning. *Frontiers in Neuroscience* 11: 463. doi: 10.3389/fnins.2017.00463
- 492 14. Effenberg, A., Ursula, F., Schmitz, G., Krueger, B., & Mechling, H. (2016) Movement Soni-
493 fication: Effects on Motor Learning beyond Rhythmic Adjustments, *Frontiers in Neuroscience*.
494 doi:10.3389/fnins.2016.00219
- 495 15. Farnell, A. (2010) *Designing Sound*. London: The MIT Press: 491–497.
- 496 16. Fitch, W.T. & G. Kramer. (1994) Sonifying the body electric: Superiority of an auditory over a visual
497 display in a complex, multivariate system, G. Kramer (ed.), *Auditory display: Sonification, audification and*
498 *auditory interfaces*, 307–325. Reading MA: Addison-Wesley. doi:10.2307/3680606
- 499 17. Gaver, W. (1993) What in the World Do We Hear?: An Ecological Approach to Auditory Event Perception,
500 *Ecological Psychology*, 5, 1–29. doi:10.1207/s15326969eco0501
- 501 18. Glazier, P. (2011) Movement Variability in the Golf Swing, *Research quarterly for exercise and sport*
502 82: 157–161. doi:10.5641/027013611X13119541883429
- 503 19. Grond, F. & Berger, J. (2011) Parameter mapping sonification. In Hermann, T., Hunt, A.,
504 Neuhoff, J. G., editors, *The Sonification Handbook*: 363–397. Logos Publishing House: Berlin.
505 doi:10.1080/13658816.2017.1420192
- 506 20. Grober, R. (2009) Resonance in putting, *arXiv*, doi:0903.1762.
- 507 21. Hebb, D. (1949) *The Organization of Behavior*. New York: Wiley & Sons. doi:10.1037/h0088061
- 508 22. Hirsh, I. & C. Watson. (1996) Auditory psychophysics and perception, *Annual Review of Psychology*,
509 47, 461–84. doi:10.1146/annurev.psych.47.1.461
- 510 23. Kidd, G. R., Watson, C. S., and Gygi, B. (2007). Individual differences in auditory abilities. *The Journal*
511 *of the Acoustical Society of America*, 122(1): 418–435. doi:10.1121/1.2743154
- 512 24. Kim, J., Han, J., and Han, D. (2018) Training effects of Interactive Metronome on golf perfor-
513 mance and brain activity in professional woman golf players, *Human Movement Science*, 61, 63–71.
514 doi:10.1016/j.humov.2018.07.005
- 515 25. Johnson, D., Watson, C., and Jensen, J. K. (1987). Individual differences in auditory capabilities. *The*
516 *Journal of the Acoustical Society of America*, 81(2), 427–438. doi:10.1037/10119-004

- 517 26. Kooyman, D., James, D., & Rowlands, D. (2013) A Feedback System for the Motor Learning of Skills
518 in Golf, *Procedia Engineering*, 60, 226–231. doi:10.1016/j.proeng.2013.07.014
- 519 27. Lakatos, S., McAdams, S., & Causse, R. (1997) The representation of auditory source characteristics:
520 Simple geometric form. *Perception & psychophysics*, Vol. 59, 180–90. doi:10.3758/BF03214206
- 521 28. Merchant, H., Grahn, J., Trainor, L., Rohrmeier, M., & Fitch, W. T. (2015). Finding the beat: a neural
522 perspective across humans and non-human primates. *Philos. Trans. R. Soc. B Biol. Sci* 370: 20140093.
523 doi:10.1098/rstb.2014.0093
- 524 29. Morillon, B., & Baillet, S. (2017). Motor origin of temporal predictions in auditory attention. *Proc. Natl.*
525 *Acad. Sci. U.S.A.* 114, E8913–E8921. doi: 10.1073/pnas.1705373114
- 526 30. Munte, T., Altenmüller, E., and Jancke, L. (2002) The musician's brain as a model of neuroplasticity,
527 *National Review of Neuroscience* 3, 473–478. doi:10.1038/nrn843
- 528 31. Murgia, M., Prpic, V., O. J., McCullagh, P., Santoro, I., Galmonte, A., & Agostini, T. (2017). Modality
529 and Perceptual-Motor Experience Influence the Detection of Temporal Deviations in Tap Dance Sequences,
530 *Frontiers in Psychology*, 8: 1340. doi:10.3389/fpsyg.2017.01340
- 531 32. Newton, P. (2015) The Learning Styles Myth is Thriving in Higher Education, *Frontiers in Psychology*,
532 6. doi:10.3389/fpsyg.2015.01908
- 533 33. O'Brien, B., Juhás, B., Bienkiewicz, M., Pruvost, L., Buloup, F., Bringnoux, L., and Bourdin, C.
534 (2018) Considerations for Developing Sound in Golf Putting Experiments. *Post-proceedings of CMMR*
535 *2017 - Music Technology with Swing*, Lecture Notes in Computer Science, Springer-Verlag Heidelberg.
536 doi:10.1007/978-3-030-01692-0
- 537 34. Risset, J. & Mathews, M. (1969) Analysis of Musical Instrument Tones, *Physics Today*, 22, 23–30.
538 doi:10.1063/1.3035399
- 539 35. Roberts, J., Jones, R., Mansfield, N., Rothberg, S. (2005) Evaluation of impact sound on the 'feel' of a
540 golf shot, *Journal of Sound and Vibration* 287: 651–666. doi:10.1016/j.jsv.2004.11.026
- 541 36. Rocchesso, D., Bresin, R. & Fernström, M. (2003) Sounding objects, *IEEE Multimedia*, 10 (2), 42–52.
542 doi: 10.1109/MMUL.2003.1195160
- 543 37. Salako, S. E. (2006). The Declaration of Helsinki 2000: ethical principles and the dignity of difference.
544 *Medicine and Law* 2, 341–354. doi:10.1515/9783110208856.233
- 545 38. Schaffert, N., Janzen, T., Mattes, K., & Thaut, M. (2019) A Review on the Relationship Between Sound
546 and Movement in Sports and Rehabilitation, *Front Psycho* 10: 244. doi:10.3389/fpsyg.2019.00244
- 547 39. Schmitz, G., Mohammadi, B., Hammer, A., Heldmann, M., Samii, A., Münte, T. F., et al. (2013). Obser-
548 vation of sonified movements engages a basal ganglia frontocortical network. *BMC Neuroscience*, 14-32.
549 doi:10.1186/1471-2202-14-32
- 550 40. Schlaug, G. (2001) The brain of musicians: a model for functional and structural adaptation, *Annals of*
551 *the New York Academy of Sciences* 930, 281–99. doi:0.1111/j.1749-6632.2001.tb05739.x
- 552 41. Secoli, R., Milot, M.-H., Rosati, G., & Reinkensmeyer, D. J. (2011). Effect of visual distraction and
553 auditory feedback on patient effort during robot-assisted movement training after stroke, *Journal of neuro-*
554 *engineering and rehabilitation*, 8(1): 21. doi:10.1186/1743-0003-8-21
- 555 42. Sigrist, R., Rauter, G., Riener, R., Wolf, P. (2013) Augmented visual, auditory, haptic, and multimodal
556 feedback in motor learning: A review, *Psychonomic Bulletin & Review*, 20(1), 21–53. doi:10.3758/s13423-
557 012-0333-8
- 558 43. Thaut, M., McIntosh, G., & Hoemberg, V. (2015). Neurobiological foundations of neurologic music ther-
559 apy: rhythmic entrainment and the motor system. *Front. Psychol.* 6: 1185. doi:10.3389/fpsyg.2015.01185
- 560 44. Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J-L., Ystad, S. (2014) From sound to shape:
561 auditory perception of drawing movements, *Journal of experimental Psychology: Human Perception and*
562 *Performance*, American Psychological Association, 40(3), 983–994. doi:0.1037/a0035441
- 563 45. Thoret, E., Aramaki, M., Bringoux, L., Ystad, S., Kronland-Martinet, R. (2016) Seeing Circles
564 and Drawing Ellipses: When Sound Biases Reproduction of Visual Motion, *PLoS ONE*, 11(4).
565 doi:10.1371/journal.pone.0154475
- 566 46. Tucker, C, Anderson R, & Kenny, I. (2013) Is outcome related to movement variability in golf? *Sport*
567 *Biomechanics*, 12: 343–354. doi:10.1080/14763141.2013.784350
- 568 47. van Vugt, F. & Tillmann, B. (2015) Auditory feedback in error-based learning of motor regularity, *Brain*
569 *Research* 1606, 54–67. doi: 10.1016/j.brainres.2015.02.026
- 570 48. Wessel, D. (1979) Timbre Space as a Musical Control Structure, *Computer Music Journal* 3(2), 45–52.
571 doi:10.2307/3680283
- 572 49. Wildes, R. P., & Richards, W. (1988) Recovering Material Properties from Sound, *Natural Computation*.
573 Cambridge, Massachusetts: MIT Press, 356–363. doi:10.1037//0096-1523.10.5.704
- 574 50. Wulf, G. & Shea, C. (2002) Principles derived from the study of simple skills do not generalize to
575 complex skill learning, *Psychonomic Bulletin and Review*, 9(2), 185–211. doi:10.3758/BF03196276

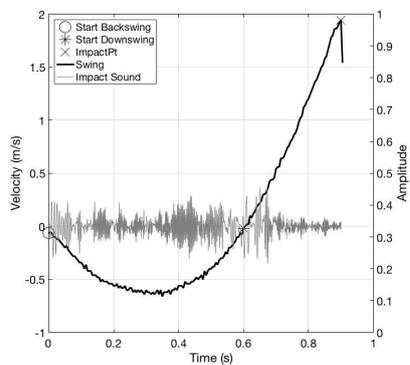
576 Appendix 1. Club head speed and sonification comparisons



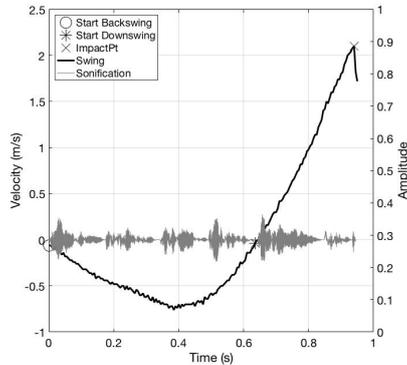
(a) *jet* * brightness * scale 1:2 * linear mapping



(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).

577 **Appendix 2. Impact sound and static pink noise**

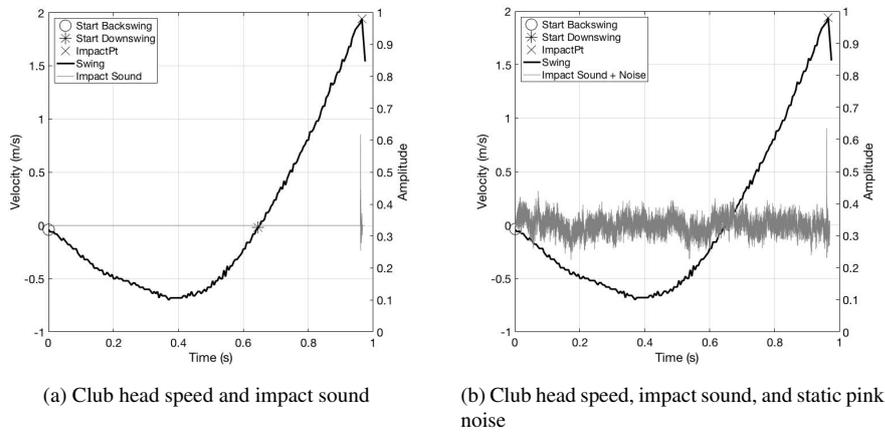


Fig. 5 Participant performing putting task without (a) and with (b) static pink noise.