

Sonification of Golf Putting Gesture Reduces Swing Movement Variability in Novices

Benjamin O'Brien, Brett Juhas, Marta Bieńkiewicz, Frank Buloup, Lionel Bringoux, Christophe Bourdin

► **To cite this version:**

Benjamin O'Brien, Brett Juhas, Marta Bieńkiewicz, Frank Buloup, Lionel Bringoux, et al.. Sonification of Golf Putting Gesture Reduces Swing Movement Variability in Novices. *Research Quarterly for Exercise and Sport*, Taylor & Francis (Routledge), 2020, pp.1-10. 10.1080/02701367.2020.1726859 . hal-02495502

HAL Id: hal-02495502

<https://hal-amu.archives-ouvertes.fr/hal-02495502>

Submitted on 19 Apr 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Sonification of golf putting gesture reduces swing movement**

2 **variability in novices**

3 This study investigates whether novices can use sonification to enhance golf
4 putting performance and swing movements. Forty participants first performed a
5 series of 2 m and 4 m putts, where swing velocities associated with successful
6 trials were used to calculate their mean velocity profile (MVP). Participants were
7 then divided into four groups with different auditory conditions: static pink noise
8 unrelated to movement, auditory guidance based on personalized MVP, and two
9 sonification strategies that mapped the real-time error between observed and
10 MVP swings to modulate either the stereo display or roughness of the auditory
11 guidance signal. Participants then performed a series of 2 m and 4 m putts with
12 the auditory condition designated to their group. In general our results showed
13 significant correlations between swing movement variability and putting
14 performance for all sonification groups. More specifically, in comparison to the
15 group exposed to static pink noise, participants who were presented auditory
16 guidance significantly reduced the deviation from their average swing movement.
17 In addition, participants exposed to error-based sonification with stereo display
18 modulation significantly lowered their variability in timing swing movements.
19 These results provide further evidence of the benefits of sonification for novices
20 performing complex motor skill tasks. More importantly, our findings suggest
21 participants were able to better use online error-based sonification rather than
22 auditory guidance to reduce variability in the execution and timing of their
23 movements.

24 **Keywords:** auditory guidance; error-based sonification; motor control; golf

25 **Introduction**

26 Complex motor skill performance improvement can pertain to a myriad of things, from
27 goal attainment to movement efficiency and consistency. Humans of course are multi-
28 sensory, but vision is regarded as the primary sensory modality for provision of
29 feedback in the performance of complex motor tasks and goal attainment (Zhao &
30 Warren, 2014). However, findings from recent studies suggest other senses play
31 important roles in the guiding of motor actions (Arnott & Alain, 2011; Kohler et al.,

32 2002; Sigrist, Rauter, Riener, & Wolf, 2013). In this study we examined whether
33 novices can use *sonification*, the mapping of data onto sound, to enhance golf putting
34 performance and swing movement.

35 Real-time (“online”) sonification has been proven to enhance the performance of
36 motor control tasks (Schaffert et al., 2019; Sigrist et al., 2013). Thoret et al. (2014)
37 found participants enhanced their ability to perceive and associate movement profiles
38 when presented acoustic information concurrent with their movements. Dyer, Rodger,
39 & Stapleton (2016) found that, by repeating motor tasks with synchronous sound,
40 participants recreated these actions more easily. Similar benefits of online artificial
41 sonification have been shown in sports training studies, such as rowing (Effenberg,
42 Ursula, Schmitz, Krueger, & Mechling, 2016; Dubus & Bresin, 2014) and cycling
43 (Sigrist, Fox, Riener, & Wolf, 2016).

44 Online sonification can also be modelled to give information based on errors of
45 performance. In this way, sonification functions like an index that points to an error or
46 deviation from an ideal motor action. van Vugt & Tillmann (2015) found that
47 participants engaged with error-based sonification improved motor regularity when
48 performing tapping tasks. Dailly et al. (2012) similarly reported that participants who
49 were presented error-based sonification significantly reduced their spatial error
50 completing a simple figure-tracing task. Wolf et al. (2011) showed that novice
51 participants were able to immediately use auditory feedback to enhance their rowing
52 performance by reducing spatial and temporal errors during training. However, none of
53 the aforementioned studies focused on the effects of error-based sonification on
54 complex motor tasks.

55 An example of a complex motor skill is golf putting (Wulf & Shea, 2002; Frank
56 et al., 2013), a gesture with well defined sub-movements and, due to the design of the

57 putter club, requires a clear translation from the person's movement velocity to energy,
58 so the ball can travel the distance required. It also requires visual concentration on the
59 ball before making contact. Because of this, there is an opportunity to stress other
60 sensory cues for motor-skill guidance. Keogh & Hume (2012) demonstrated that a
61 primary focus in golf training is kinematics and posited that errorless learning might be
62 afforded by using different visual feedback strategies. A similar approach that replaces
63 visual with auditory feedback may prove to be particularly useful, as it would free
64 attentional resources required to visually monitor club and ball positions.

65 Interestingly, only a handful of comprehensive studies focus on the effects of
66 sonification in golf training. Kleiman-Weiner & Berger (2006) developed a method that
67 mapped, among other things, the club head velocity of an expert golfer performing the
68 golf swing to different sound parameters, such as pitch and vowel synthesis formants,
69 but no findings were reported. Bienkiewicz et al. (2019) investigated motor learning of
70 putting tasks in novices when presented either visual or auditory information developed
71 from the swing velocity of an expert golfer. In comparison to the control group, who
72 were not presented any additional sensory information, novices had lower variability of
73 their movements (measured as the standard deviation of impact velocity across trials)
74 and were putting closer to the target when presented either visual or auditory sensory
75 information. In addition a pilot study reported by O'Brien et al. (2018) found novices
76 were able to identify swing speed as represented by auditory signals. Similarly, Murgia
77 et al. (2017) found golfers were able to recognise their own idiosyncratic swings via
78 sonification, which demonstrates the relationship between performing golf swings and
79 perceiving sounds based on them. A distinguishing feature of this study was to focus on
80 the effects of error-based sonification on putting performance in novices.

81 A recent study with experienced golfers by Richardson, Mitchell, & Hughes
82 (2018) showed a significant correlation between left forearm segment variability and
83 horizontal launch angle and suggested that by reducing their variability, golfers might
84 enhance their performance. The authors also proposed that golfers employ different
85 putting styles, which vary between more stable and flexible motor outputs. As they
86 concluded, additional research into movement variability and putting is needed to
87 confirm this proposition, which asserts some practical implications, as golf instructors
88 might prioritize identifying whether a golf pupil utilizes movement variability or has a
89 more consistent swing profile. Thus, we wanted to look more deeply into the
90 relationship between performance variability and goal attainment. Expanding on this,
91 we wanted to examine whether sonification could help reduce complex motor
92 performance variability, which in turn might affect putting performance.

93 It was important to select an important feature in golf putting for which to
94 measure, model, and use to compare and calculate performance errors in real-time. A
95 fundamental factor in the success of a golf putt is swing speed (Burchfield &
96 Venkatesan, 2010), which was further evidenced by Craig, Delay, Grealy, & Lee (2000)
97 who reported club head velocity at impact strongly correlates to ball distance. However
98 the golf putting gesture is also uniquely personal, as there are many ways to swing the
99 putter club, such as increasing or decreasing wrist movement.

100 Our first objective then was to develop a method of sonification that was
101 participant-dependent, so as to accurately reflect swing idiosyncrasies and, moreover,
102 personalize the sounds presented to participants. We decided to present participants
103 auditory guidance based on their individual average swing performance, which was
104 calculated following a series of successful putts at different distances. A major

105 advantage of this method is that it adjusts to the kinematic capacities of the individual,
106 which may prove useful in both healthy and rehabilitation research.

107 In addition, we wanted to study whether novices were able to enhance
108 performance and swing movements by using online sonification based on errors of
109 performance. Our second goal was to develop an online sonification method that maps
110 performance errors in ways that modulated the auditory guidance signal. Although it is
111 known that healthy humans do not perceive sound similarly due to their physiological
112 and psychological differences, a study by Johnson, Watson, & Jensen (1987) found
113 patterns identified in healthy participants affected auditory performance similarly.
114 Based on these findings, we decided to develop different methods for modulating the
115 auditory guidance signal in real-time, so as to maximise the opportunity for participants
116 to perceive and use sonification based on errors of performance.

117 **Methods**

118 *Participants*

119 Forty right-handed participants (28 male; mean age: 22.4; standard deviation: 7.2)
120 affiliated with ----- participated in the experiment. All participants self-reported good or
121 corrected vision and normal hearing. All participants consented to voluntary
122 participation in the study and were informed of their right to withdraw at any time. This
123 study was performed in accordance with the ethical standards of the Declaration of
124 Helsinki (Salako, 2006). The Ethics Committee of ----- approved the protocol.

125 *Experimental setup*

126 Participants used an Odyssey White Ice putter (length: 0.97 m; weight: 0.59 kg) to hit
127 Titleist PRO V1X balls. A synthetic grass terrain was used (length: 5 m; width: 1.8 m).
128 White circles with 0.11 m diameters were painted at the starting position and the 2 m

129 and 4 m target distances. Participants wore Sennheiser headphones when presented
130 sound.

131 The Codamotion CX1 Scanner was used to collect club kinetic data (sampling
132 rate: 200 Hz). The CX1 Scanner was placed 2 m away from participants with 1 m
133 elevation. Two infra-red active markers were placed near the club head at the bottom of
134 the club shaft and just below the handgrip.

135 *Procedure*

136 Participants first completed 20 *Baseline* trials at 2 m and 4 m (total: 40 trials). Unless
137 20%¹ of their putts at both distances were within 0.25 m of the target, they were
138 excluded from the study. Participants were then randomly assigned to one of four
139 experimental groups ($n = 10$). Following a pause required to calculate their mean
140 velocity profile (MVP) (see: **Protocol**), participants completed two rounds of 20
141 *Experimental* trials at 2 m and 4 m (total: 80 trials, counterbalanced). Each participant
142 performed 120 putts in total over the course of the experiment. Participants were only
143 presented sound during Experimental trials.

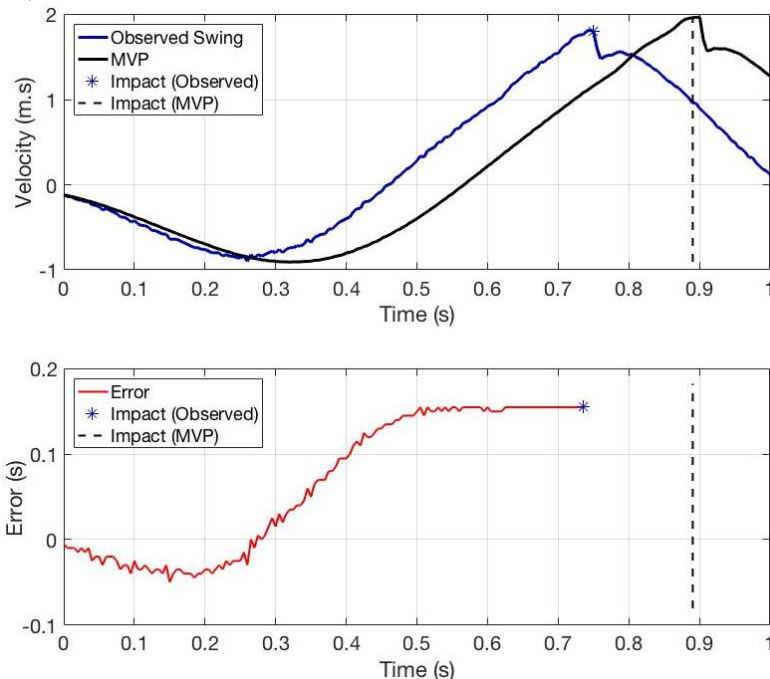
144 *Protocol*

145 A custom program developed in Python streamed and recorded all values monitored by
146 CodaMotion. To present personalized MVPs to participants, their successful Baseline
147 trials were selected and synchronised at impact point, where after their club head
148 velocities were shifted and averaged offline. During the Experimental trials we
149 estimated the time to impact with the ball by using club head marker values to calculate

¹ We decided that 20% was the minimum number of trials required to provide participants with auditory guidance or error-based sonification that faithfully represented their swing idiosyncrasies.

150 its velocity and distance from the ball. Once the backswing velocity reached a minimum
151 threshold of 0.1 m.s, we began the process of comparing the current position of the club
152 head with the starting position of the club (near the ball) and the current club head
153 velocity with the MVP. Error was then calculated by comparing the current estimated
154 time to impact with the MVP time of impact. This estimated time to impact was then
155 compared in real-time to the participant's MVP, which, in turn, gave us a real-time
156 difference, or *error*, between her observed and MVP swings. **Figure 1** illustrates the
157 real-time error between a participant's observed and MVP swings for a 2 m putt.

158 Figure 1 Top: comparison between observed (blue) and MVP (black) swings. Bottom:
159 error (red)



160
161 Before each trial, participants were asked to place the club head close to the ball and
162 remain motionless for approximately 1 s. This allowed us to accurately monitor a
163 significant change in velocity – the start of the backswing. Once identified, velocity and
164 error information was transmitted locally to a computer running Max/MSP, which was
165 used for sound synthesis. Sound was presented to participants at the start of their
166 backswing during the Experimental trials.

167 *Sound design*

168 Each group was presented a different auditory condition. ‘Control’ group participants
169 were presented static pink noise that was independent of observed movements and was
170 the same across all Experimental trials. The duration of the static pink noise was equal
171 to that of their MVP. ‘MVP’ group participants were presented auditory guidance based
172 on their personalized MVPs, where velocity values were sequenced and mapped to the
173 frequency of a sinusoidal oscillator. As described in O’Brien et al. (2018), this strategy
174 was based on discussions with golf instructors and trainers, who frequently whistled
175 upwards and then downwards to describe, in general, putting mechanics. The absolute
176 values of velocities were linearly mapped and scaled to a frequency range of 80 - 2000
177 Hz and transformed to a Mel scale (122 - 1521 mels). This sound was the same across
178 the Experimental trials (for each distance) and was independent of observed
179 movements. Because the sounds presented to both Control and MVP participants were
180 independent of observed movements, they were considered “offline.”

181 The remaining two groups were presented online sonification based on the
182 calculated errors between observed and MVP swings. Similar to the MVP group, both
183 groups were presented auditory signals generated by mapping and scaling velocity
184 values to the frequency of a sinusoidal oscillator, however they were modulated
185 differently depending on the group. In both cases, the magnitude of the error was
186 directly mapped to the magnitude of the modulation. The ‘Directivity’ group was
187 presented online sonification based on stereo display, where the auditory signal was
188 panned right if the error was negative (and vice-versa). This design was based on a
189 study by Libkum, Otani, & Steger (2002), which found participants who trained by
190 synchronising their hands and feet with a stereophonic metronome improved
191 performance. The ‘Roughness’ group was presented online sonification based on error

192 sign to modulate the *roughness*² of the auditory signal: if negative, it was processed by a
193 Coulomb friction sound synthesiser to become more “grating” if positive, it was
194 modulated by a von Kármán model (Diedrich & Drischler, 1957) to evoke wind speeds.
195 The **Supplementary Materials** demonstrate the differences between all auditory
196 conditions.

197 *Data processing and statistics*

198 To investigate whether sonification affected putting performance, we examined the
199 distance between the final location of the ball and the target – the target distance error.
200 Both target distance error mean (TDE_{μ}) and standard deviation (TDE_{σ}) were used in our
201 analysis of all Baseline and Experimental trials. In addition, we calculated the
202 *percentage of improvement* for both TDE_{μ} and TDE_{σ} by dividing the difference
203 between Baseline and Experimental trials by Baselines trials and multiplying it by 100.

204 To investigate the effects of sonification on movement and timing variability,
205 we examined participant deviation from average swing speed and temporal ratio,
206 respectively. To measure the former, we synchronised trials at impact, shifted their
207 velocities to the time of impact, and then calculated the Normalised Root Mean
208 Standard Deviation from their MVP (1), where \hat{x} represents participant MVP, x is the
209 collection of velocity values from the start of the backswing up to impact for trial n , and
210 N is the number of successful trials. These deviations were then averaged ($NRMSD_{\mu}$).

211 To measure temporal ratio variability (TR_{σ}), we calculated the standard deviation of the
212 temporal ratio, which is the ratio of the backswing duration to downswing duration.
213 Because sonification was developed from participant MVPs, which were based on the

² A multimodal descriptor of texture, *roughness* can be simulated in the auditory domain by using a number of methods, including amplitude modulation (Zwicker & Fastl, 1999) and physical modelling (Conan et al., 2014).

214 swing profiles associated with successful trials, we excluded all Baseline and
215 Experimental trials with putts that were greater than 0.25 m from the target from our
216 analysis of swing movement and timing. In addition, we calculated a percentage of
217 improvement for swing movement and timing variability based only on successful
218 trials.

$$219 \quad NRMSD = \frac{\sqrt{\frac{\sum_{n=1}^N (\bar{x} - x_n)^2}{N}}}{x_{max} - x_{min}} \quad (1)$$

220 For all outcome variables, mixed ANOVAs were carried out with group as a between-
221 subjects factor and both target distance and trial type (Baseline, Experimental) as
222 within-subject factors. Where main effects were detected, post-hoc Bonferroni-adjusted
223 t-tests were carried out. All significant post-hoc findings were reported ($X \pm Y$) with X
224 mean difference and Y standard error. Where the assumption of sphericity was violated,
225 Greenhouse-Geisser adjustments are reported.

226 *Preliminary analysis*

227 All participants were included in our analysis. At first glance it appeared participants
228 found the 2 m target (mean target distance error: 0.44 m; SD target distance error: 0.14
229 m) to be less difficult than the 4 m target (mean target distance error: 0.62 m; SD target
230 distance error: 0.16 m). Repeated measures ANOVA tests revealed main effects on
231 mean target distance error $F_{1,3} = 47.51, p < 0.001, \eta_p^2 = 0.94$ and SD target distance
232 error $F_{1,3} = 15.53, p < 0.001, \eta_p^2 = 0.67$. Our preliminary observations were
233 substantiated by post-hoc tests that revealed mean target distance error at 2 m was
234 significantly less than 4 m (0.18 ± 0.03), $p < 0.001$. Similarly participants showed
235 significantly lower SD target distance error at 2 m when compared to 4 m (0.12 ± 0.03),
236 $p < 0.001$.

237 **Results**

238 ***Target Distance Error***

239 We first examined the percentage of improvement for mean target distance error
240 (TDE_{μ}) at 2 m and 4 m and found a main effect on distance $F_{1,3} = 5.11, p < 0.05, \eta_p^2 =$
241 0.38 , but no group effects, $p > 0.05$. Post-hoc tests revealed participants significantly
242 improved their percentage of improvement for TDE_{μ} at 2 m when compared to 4 m
243 (9.38 ± 4.15), $p < 0.05$.

244 Next, to examine the effects of sonification on putting performance, we
245 compared TDE_{μ} during Baseline and Experimental trials at 2 m and 4 m and found
246 main effects on distance $F_{1,3} = 108.47, p < 0.001, \eta_p^2 = 0.94$ and trial type $F_{1,3} = 37.61, p$
247 $< 0.001, \eta_p^2 = 0.93$, but no significance on group, $p > 0.05$. Post-hoc tests showed
248 participants were closer to the target at 2 m (18.77 ± 1.8) and during the Experimental
249 trials (10.18 ± 1.66), $p < 0.001$.

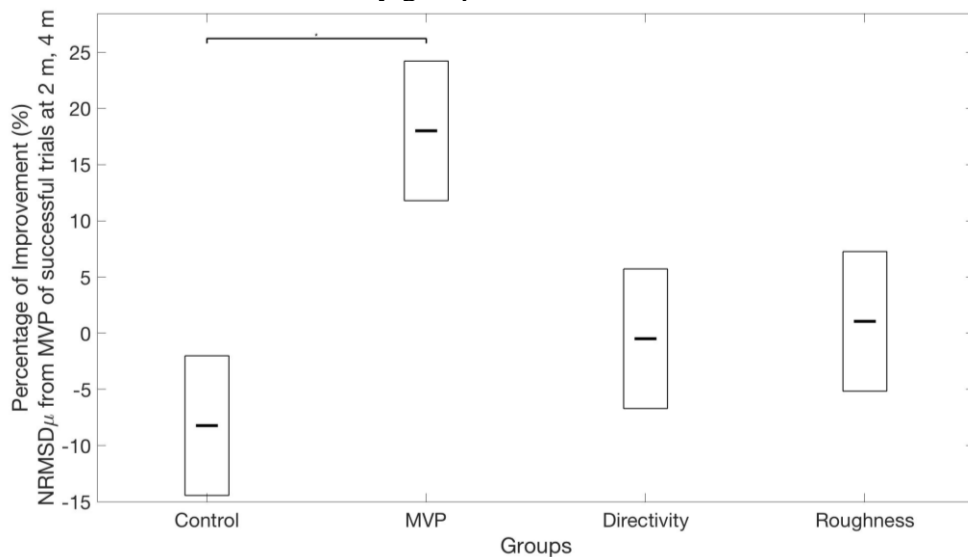
250 Similarly, we first examined the percentage of improvement for standard
251 deviation of target distance error (TDE_{σ}) at 2 m and 4 m and found no significance for
252 neither group nor distance, $p > 0.05$.

253 Next we compared TDE_{σ} during Baseline and Experimental trials at 2 m and 4
254 m and similarly found main effects on distance $F_{1,3} = 43.9, p < 0.001, \eta_p^2 = 0.82$ and
255 trial type $F_{1,3} = 31.56, p < 0.001, \eta_p^2 = 0.85$ and a distance * group interaction $F_{3,36} =$
256 $3.13, p < 0.05, \eta_p^2 = 0.21$. Post-hoc tests showed participants performed with lower
257 variability at 2 m (12.22 ± 1.8) and during the Experimental trials (8.74 ± 1.56), $p <$
258 0.001 . Additionally, the following groups had significantly lower variability at 2 m
259 rather than at 4 m, $p < 0.001$: Control (13.37 ± 3.69), Directivity (11.27 ± 3.69), and
260 Roughness (20.04 ± 3.69).

261 **Average swing velocity deviation from MVP**

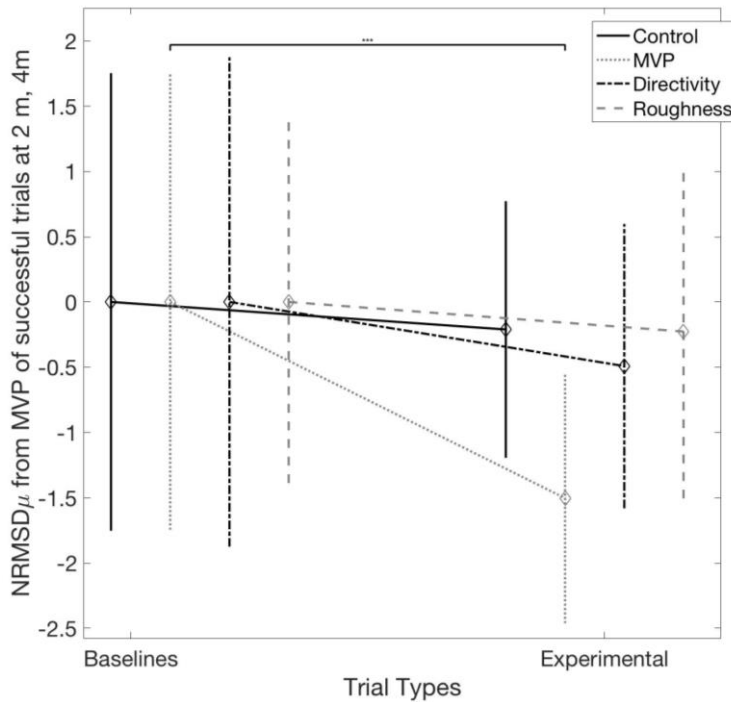
262 We examined the percentage of improvement for average swing velocity deviation from
263 MVP ($NRMSD_{\mu}$) trials at 2 m and 4 m and found main effects on group $F_{3,36} = 3.17, p <$
264 $0.05, \eta_p^2 = 0.21$ and distance $F_{1,3} = 6.62, p < 0.01, \eta_p^2 = 0.67$. Post-hoc tests revealed the
265 MVP group significantly improved in comparison to the Control group (25.2 ± 8.56), p
266 < 0.05 (**Figure 2**). There were no other significant differences between groups, $p >$
267 0.05 . When compared to the 4 m target, participants improved performance at 2 m
268 (18.27 ± 6.52), $p < 0.05$.

269 Figure 2 Percentage of improvement for average swing velocity deviation from MVP of
270 successful trials at 2 m, 4 m by group.



271
272 Next we examined participant $NRMSD_{\mu}$ from during Baseline and Experimental trials
273 at 2 m and 4 m, where we observed main effects on distance $F_{1,3} = 14.63, p < 0.001, \eta_p^2$
274 $= 0.8$, trial type $F_{1,3} = 14.93, p < 0.001, \eta_p^2 = 0.57$, and interactions on trial type * group
275 $F_{3,36} = 3.76, p < 0.05, \eta_p^2 = 0.24$. Post-hoc tests revealed participants significantly
276 lowered their $NRMSD_{\mu}$ at 4 m (0.64 ± 0.17) and during Experimental trials ($0.61 \pm$
277 0.16), $p < 0.001$. Additionally, participants in the MVP group significantly lowered
278 their $NRMSD_{\mu}$ during Experimental trials (1.5 ± 0.31), $p < 0.001$ (**Figure 3**).

279 Figure 3 Average swing velocity deviation from MVP of successful baseline and
 280 experimental trials at 2 m, 4 m.



281

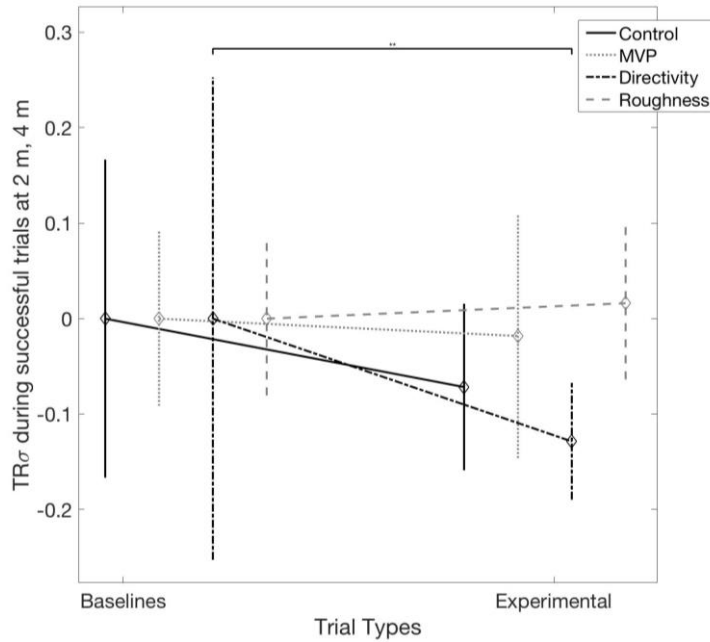
282 **Temporal ratio**

283 We first examined the percentage of improvement for standard deviation of temporal
 284 ratio (TR_{σ}) trials at 2 m and 4 m and found no significance for neither group nor
 285 distance, $p > 0.05$.

286 Next we examined participant TR_{σ} during Baseline and Experimental trials at 2
 287 m and 4 m, and we observed main effects on trial type $F_{1,3} = 7.68, p < 0.01, \eta_p^2 = 0.46$
 288 and interactions on trial type * group $F_{3,36} = 3.02, p < 0.05, \eta_p^2 = 0.2$, distance * group
 289 $F_{3,36} = 3.28, p < 0.05, \eta_p^2 = 0.21$, and distance * trial type * group $F_{3,36} = 3.22, p < 0.05,$
 290 $\eta_p^2 = 0.21$. Post-hoc tests revealed participants significantly lowered their TR_{σ} during
 291 Experimental trials (0.05 ± 0.02), $p < 0.01$. The Directivity group significantly lowered
 292 their TR_{σ} during Experimental trials (0.13 ± 0.04), $p < 0.01$, when compared to
 293 Baseline trials (**Figure 4**); during 2 m trials (0.07 ± 0.03), $p < 0.05$, when compared to
 294 4 m trials; and during Experimental trials at 4 m (0.2 ± 0.06), $p < 0.01$, when compared

295 to Experimental trials at 2 m. The Control group significantly lowered their TR_{σ} during
 296 4 m (0.07 ± 0.03), $p < 0.05$, when compared to 2 m trials, and Experimental trials at 2
 297 m (0.14 ± 0.04), $p < 0.05$, when compared to Experimental trials at 4 m.

298 Figure 4 Temporal ratio standard deviation of successful baseline and experimental
 299 trials at 2 m, 4 m by group.



300

301 *Correlations between putting performance and swing movement variability*

302 Noting our significant findings for average swing velocity deviation from MVP for the
 303 MVP group and temporal ratio standard deviation for the Directivity group, we wanted
 304 to test if any of the groups had significant correlations between putting performance
 305 (target distance error mean and standard deviation) and swing movement variability
 306 (deviation from average swing velocity, temporal ratio standard deviation). Using linear
 307 regression models, **Table 1** illustrates the Group R^2 coefficients and p -values for
 308 relationships between putting performance and swing movement variability, where:
 309 TDE_{μ} and TDE_{σ} are the target distance error mean and standard deviation, respectively;
 310 $NRMSD_{\mu}$ is the average swing velocity deviation from MVP; and TR_{σ} is the temporal
 311 ratio standard deviation.

312 Table 1 Group R^2 coefficients and p -values for correlations between putting
 313 performance and swing movement variability variables

| | TDE μ | | | | TDE σ | | | |
|--------------|-------------|-----|-------------|-----|--------------|-----|-------------|-----|
| | NRMSD μ | | TR σ | | NRMSD μ | | TR σ | |
| Group | R^2 | p | R^2 | p | R^2 | p | R^2 | p |
| Control | 0.07 | | 0.08 | | 0.09 | | 0.08 | |
| MVP | 0.27 | | 0.54 | * | 0.1 | | 0.57 | * |
| Directivity | 0.67 | * | 0.69 | ** | 0.82 | *** | 0.63 | ** |
| Roughness | 0.72 | ** | 0.21 | | 0.63 | ** | 0.16 | |

314 where {*,**,***} mark significance for $p < \{0.05, 0.01, 0.001\}$
 315

316 As expected, there were no significant correlations between putting performance and
 317 swing movement variability for the Control group, while the MVP and Roughness
 318 groups both reported strong correlations with putting performance, but only with
 319 temporal ratio standard deviation and average swing velocity deviation, respectively.
 320 Notably, only the Directivity group had significant correlations for all putting
 321 performance-swing movement variability combinations.

323

324 **Discussion**

325 *Putting performance*

326 The goal of our study was to investigate whether novices were able to use sonification
 327 to improve golf putting performance and reduce swing movement variability. While
 328 participants significantly improved their target distance error average by 0.10 ± 0.02 m
 329 and standard deviation by 0.09 ± 0.02 m during the Experimental trials, we reported no
 330 group effects. In addition, though the percentage of improvement was positive for mean

331 target distance error, there were no group differences in the magnitude of the percentage
332 improvement. Because participants exposed to static pink noise similarly improved to
333 those who were presented auditory guidance or error-based sonification, at first glance
334 these results suggest performance enhancement was not influenced by the presence of
335 artificial sound, but rather based on movement familiarisation. There are, of course,
336 countless factors that contribute to golf putting performance, which have been the
337 subject of study, such as the putting green (Pataky & Lamb, 2018). This point is
338 underlined by a report by Kammerer, Menshik, Erlemann, & Lafortune (2014), which
339 found putting robots made only 80% putts at 5 m. These observations taken together
340 suggest that when studying its effect on novices, sonification may play a more
341 important role enhancing putting movements, rather than directly influencing ball
342 distance from the target.

343 *Swing movement variability*

344 Our analysis showed swing movement variability was enhanced differently among
345 groups. The MVP group showed a $25.2 \pm 8.56\%$ greater percentage of improvement for
346 deviation from average swing velocity when compared to the Control group. This
347 important finding demonstrates the benefits of personalized sonification, which, in this
348 case, was based on the average speed of successfully executed golf putts. Similar
349 benefits were reported in a study by Bieńkiewicz et al. (2019), which found novices
350 improved putting performance when presented sonification based on the club head
351 velocity of an expert golfer performing putts at multiple distances. However, unlike
352 their study, where participants trained with sonification over an eight-week period, the
353 MVP group enhanced its performance when presented personalized sonification, as it
354 improved its average swing movement variability. This point is underscored by our
355 results that found MVP participants significantly reduced their deviation from average

356 swing velocity ($NRMSD_{\mu}$) during Experimental trials by 1.5 ± 0.31 residuals. An
357 important distinction then between the two studies is that, while their study focused on
358 examining the effects of sonification on learning the golf putting gesture, we examined
359 and found participants were able to use auditory guidance based on their unique
360 physiological constraints to enhance their movement by reducing variability.

361 Interestingly, like the static pink noise presented to the Control group, the
362 auditory guidance presented to MVP participants, although personalized, was
363 independent of their swing movements. Thus despite also being fixed and unchanged by
364 movement, participants were able to enhance their performance, reducing deviations
365 from their average swing velocity during putts. These results support similarly reported
366 findings regarding the benefits of repeated trainings with auditory information (Agostini
367 et al, 2004; Young, Rodger, & Craig, 2014). Our results suggest that, through repetition,
368 the auditory guidance presented to the MVP participants allowed them to more clearly
369 perceive the transition between the backswing and downswing, which, in turn allowed
370 them to reduce their deviation from average swing velocity. Specifically, at the start of
371 the downswing, velocity is zero, and, due to our method of mapping velocity to
372 frequency, no sound was produced. This absence of sound or silence may have
373 functioned like an index for users, which allowed them to assess their movements: if
374 they finished their backswing before or after the silence, then they were too fast or slow,
375 respectively. This idea of studying the effects of removing sound during the execution
376 of complex movements is certainly interesting and appears to have not been extensively
377 studied.

378 Although both Directivity and Roughness groups were presented online
379 sonification based on errors of performance by modifying the same type of auditory
380 guidance signal presented to the MVP group, only the Directivity group was able to use

381 sound to significantly reduce variability in the timing of their swing movements.. As the
382 timbre between the sounds presented to both MVP and Directivity groups was the same,
383 the major difference was the latter presented online sonification based on performance.
384 By modifying the stereo display of the auditory guidance signal, Directivity participants
385 were given additional information for which to perceive, interpret, and then use to
386 reduce the variability in the timing of their swing movements. Our findings support
387 those reported by Libkum, Otani, & Steger (2002), who found training with auditory
388 stimuli improved putting performance, and add evidence to the role of sound
389 spatialization on human movement (Gandemer et al., 2017).

390 These findings also stress the importance of the sonification strategy and use of
391 simpler sounds. As Roughness group participants were also presented online
392 sonification based on errors of performance, the constantly shifting timbres may have
393 been too difficult for them to use. If we compare our average swing deviation and
394 temporal ratio standard deviation results for the Directivity and Roughness groups, our
395 findings suggest error-based sonification might be easier to use if either a combination
396 of simpler sounds - less complex - or two-dimensional displays are presented.
397 Nevertheless, the observed differences between groups illustrate the importance of
398 considering the inter-individual differences in which humans perceive sound - artificial
399 or otherwise - and possibly use information encoded in it while performing new and
400 complex motor tasks. A study by Wu et al. (2014) demonstrated a relationship between
401 the variability in successive movements and motor learning in novice participants. By
402 exploring different movement parameters, humans are able to refine newly acquired
403 actions and assess their movements and limitations, and our results suggest sound can
404 be an important actor in highlighting these differences.

405 **What does this article add?**

406 In general, the results of our study provide further evidence of the benefits of
407 sonification for novices performing new complex motor skills. Our findings suggest
408 personalized templates for sonification help reduce variability in the execution and
409 timing of complex motor tasks. In addition, the significant correlations between putting
410 performance and swing movement variability reported for groups who were presented
411 online sonification based on performance errors add further support to the theory that
412 concurrent sonification can enhance feedback while performing motor-related tasks
413 (Dyer, Stapleton, & Rodger, 2017). With follow up research, may be used to estimate
414 performance. Our results emphasise the potential impact of conveying temporally
415 accurate information based on errors of performance to novices performing new motor-
416 related tasks. These observations lend themselves to new questions regarding whether
417 errors are essential for complex motor task development and when does stabilizing
418 variability become beneficial.

419 Although we reported that sonification produced effects on swing movement
420 and timing variability, it did not affect the overall accuracy of the shot. This finding
421 suggests that participants were able to extract information regarding deviations from
422 their average swing performance from the synthesized sound, but it did not aid the
423 accuracy of their shots in comparisons to other groups. It is important to note that motor
424 variability plays an important role in motor learning processes and allows one to explore
425 the links between different spatiotemporal dynamics of movement and the outcome of
426 action (Bonassi et al., 2017). By providing error-based real time feedback we might
427 have hindered the natural unfolding of these processes by directing the attention of
428 participants to keeping the movement as consistent as possible. Unfortunately, we did
429 not introduce an additional block of trials to measure performance without sensory
430 stimuli after performing the task with sonification.

431 Moving forward, when developing tools to optimise movement performance and
432 employ artificial sound based on previous performances, it is important to allow users to
433 include or exclude any number of trials, so as to refine the resolution and
434 personalization of their model. By continually using, adjusting, and decreasing the
435 threshold of error in which movements are identified as deviating from an ideal
436 performance, users might begin to optimise their movements and performance. But as
437 we observed in our study, depending on the goal of their use, certain sonification
438 strategies may affect humans differently and subsequently their movements and
439 performance.

440

441 References

- 442 Agostini, T., Righi, G., Galmonte, A., & Bruno, P. (2004). The Relevance of Auditory Information in
443 Optimizing Hammer Throwers Performance, *Biomechanics and Sports*. Vienna: Springer, 67—74.
444
- 445 Arnott, S. & Alain, C. (2011). The auditory dorsal pathway: Orienting vision, *Neuroscience &*
446 *Biobehavioural Reviews*, 35 (10), 2162—2173. doi:10.1016/j.neubiorev.2011.04.005
447
- 448 Bieńkiewicz, M., Bourdin, C., Bringoux, C., Buloup, F., Craig, C., Prouvost, L., & Rodger, M. (2019).
449 The Limitations of Being a Copycat: Learning Golf Putting Through Auditory and Visual Guidance,
450 *Frontiers in Psychology* 10, 92. doi:10.3389/fpsyg.2019.00092
451
- 452 Bonassi, G., Biggio, M., Bisio, A., Ruggeri, P., Bove, M. & Avanzino, L. (2017). Provision of
453 somatosensory inputs during motor imagery enhances learning-induced plasticity in human motor cortex,
454 *Scientific Reports* 7, 9300.
455
- 456 Burchfield, R. & S. Venkatesan (2010). A Framework for Golf Training Using Low-Cost Inertial
457 Sensors, *Proceedings of the 2010 International Conference on Body Sensor Networks*.
458 doi:10.1109/BSN.2010.46
459
- 460 Conan, S., Thoret, E., Aramaki, M., Derrien, O., Gondre, C., Ystad, S., & Kronland-Martinet, R. (2014).
461 An Intuitive Synthesizer of Continuous-Interaction Sounds: Rubbing, Scratching, and Rolling, *Computer*
462 *Music Journal* 38, 24—37. doi:10.1162/COMJa00266
463
- 464 Craig, C., Delay, D., Grealy, M., & Lee, D. (2000). Guiding the swing in golf putting, *Nature*, 295—296.
465 doi:10.1038/35012690
466
- 467 Dailly, Anabel, Sigrist, R., Kim, Y., Wolf, P., Erckens, H., Cerny, J., Luft, A., Gassert, R. & Sulzer, J.
468 (2012). Can simple error sonification in combination with music help improve accuracy in upper limb
469 movements? *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics*
470 *and Biomechatronics*, 1423—1427. doi:10.1109/BioRob.2012.6290908.
471
- 472 Diedrich, F. & J. Drischler (1957). Effect of Spanwise Variations in Gust Intensity on the Lift Due to
473 Atmospheric Turbulenc: NACA TN 3920.
474

475 Dubus, G. & R. Bresin. (2014). Exploration and evaluation of a system for interactive sonification of elite
476 rowing, *Sports Engineering*, 18. doi:10.1007/s12283-014-0164-0
477

478 Dyer, J., Rodger, M., & Stapleton, P. (2016). Transposing Musical Skill: Sonification of movement as
479 concurrent augmented feedback enhances learning in a bimanual task, *Psychological Research*, 81.
480 doi:10.1007/s00426-016-0775-0
481

482 Dyer, J., Stapleton, P., & Rodger, M. (2017). Mapping sonification for perception and action in motor
483 skill learning, *Frontiers in Neuroscience* 11, 463. doi:10.3389/fnins.2017.00463
484

485 Effenberg, A., Ursula, F., Schmitz, G., Krueger, B., & Mechling, H. (2016) Movement Sonification:
486 Effects on Motor Learning beyond Rhythmic Adjustments, *Frontiers in Neuroscience*.
487 doi:10.3389/fnins.2016.00219
488

489 Frank, C., Land, W. M., & Schack, T. (2013). Mental representation and learning: the influence of
490 practice on the development of mental representation structure in complex action. *Psychol. Sport Exerc.*
491 14, 353—361. doi:10.1016/j.psychsport.2012.12.001
492

493 Gandemer, L., Parsehian, G., Kronland-Martinet, R., & Bourdin, C. (2017). Spatial Cues Provided by
494 Sound Improve Postural Stabilization: Evidence of a Spatial Auditory Map? *Frontiers in Neuroscience*
495 11. doi:10.3389/fnins.2017.00357.
496

497 Johnson, D., Watson, C., & Jensen, J.. (1987). Individual differences in auditory capabilities. *The Journal*
498 *of the Acoustical Society of America*}, 81(2), 427—438. doi:10.1121/1.394907
499

500 Kammerer, B., Menshik, A., Erlemann, L., & Lafortune, M. (2014). Quantifying the performance metrics
501 of a putter, *International Journal of Golf Science* 4, S45-S46. (orally reported result).
502 doi:10.1123/ijgs.2015-0007
503

504 Keogh, J. & Hume, P. (2012). Practice conditions: How do they influence motor learning in golf?
505 *Proceedings of the 30th Annual Conference of Biomechanics in Sports*, 367--370.
506 doi:10.3389/fpsyg.2015.01981
507

508 Kleiman-Weiner, M. & Berger, J. (2006). The sound of one arm swinging: a model for multidimensional
509 auditory display of physical motion, *Proceedings of the 12th International Conference on Auditory*
510 *Display*, London, UK, June 20-23, 2006.
511

512 Kohler, E., Keysers, C., Umiltà, A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing Sounds,
513 Understanding actions: action representation in mirror neurons, *Science*, 297 (5582), 846—848.
514 doi:10.1126/science.1070311
515

516 Libkum, T., Otani, H., & Steger, N. (2002). Training in timing improves accuracy in golf, *Journal of*
517 *General Psychology* 129(1), 77—96. doi:10.1080/00221300209602034
518

519 Murgia, M., Prpic, V., O, J., McCullagh, P., Santoro, I., Galmonte, A., & Agostini, T. (2017). Modality
520 and Perceptual-Motor Experience Influence the Detection of Temporal Deviations in Tap Dance
521 Sequences, *Frontiers in Psychology* 8: 1340. doi:10.3389/fpsyg.2017.01340
522

523 O'Brien, B., Juhas, B., Bienkiewicz, M., Pruvost, L., Buloup, F., Bringnoux, L., & Bourdin, C. (2018).
524 Considerations for Developing Sound in Golf Putting Experiments, *Post-proceedings of CMMR 2017 -*
525 *Music Technology with Swing*, Lecture Notes in Computer Science, Springer-Verlag Heidelberg.
526 doi:10.1007/978-3-030-01692-0
527

528 Pataky, T. & Lamb, P. (2018). Effects of physical randomness training on virtual and laboratory golf
529 putting performance in novices, *Journal of Sports Sciences*, 36(12), 1355—1362. doi:
530 10.1080/02640414.2017.1378493
531

532 Richardson, A., Mitchell, A., & Hughes, G. (2018). The effect of movement variability on putting
533 proficiency during the golf putting stroke, *International Journal of Sports Science & Coaching*.
534 doi:10.1177/1747954118768234.

535
536 Salako, S. E. (2006). The Declaration of Helsinki 2000: ethical principles and the dignity of difference.
537 *Medicine and Law* 2, 341—354. doi:10.1515/9783110208856.233
538
539 Schaffert, N., Janzen, T., Mattes, K., & Thaut, M. (2019) A Review on the Relationship Between Sound
540 and Movement in Sports and Rehabilitation, *Front Psycho* 10: 244. doi:10.3389/fpsyg.2019.00244
541
542 Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal
543 feedback in motor learning: A review, *Psychonomic Bulletin & Review*, 20 (1), 21—53.
544 doi:10.3758/s13423-012-0333-8
545
546 Sigrist R, Fox S, Riener R, & Wolf. P. (2016). Benefits of Crank Moment Sonification in Cycling.
547 *Procedia Engineering*, 147, 513—518.
548
549 Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J-L., & Ystad, S. (2014). From sound to shape:
550 auditory perception of drawing movements, *Journal of experimental Psychology: Human Perception and*
551 *Performance*, American Psychological Association, 40(3), 983—994. doi:0.1037/a0035441
552
553 van Vugt, F. & Tillmann, B. (2015). Auditory feedback in error-based learning of motor regularity, *Brain*
554 *Research* 1606, 54—67. doi: 10.1016/j.brainres.2015.02.026
555
556 Wolf, P., Sigrist, R., Rauter, G., & Riener, R. (2011). Error sonification of a complex motor task. In *BIO*
557 *Web of Conferences* (1): 00098. EDP Sciences. doi: 10.1051/bioconf/20110100098
558
559 Wu, H., Miyamoto, Y., Castro, L., Olveczky, B., & Smith, M. (2014) Temporal structure of motor
560 variability is dynamically regulated and predicts motor learning ability, *Nature Neuroscience* 17 (2),
561 185—211. doi: 10.1038/nn.3616
562
563 Wulf, G. & Shea, C. (2002) Principles derived from the study of simple skills do not generalize to
564 complex skill learning, *Psychonomic Bulletin and Review*, 9(2): 185--211. doi:10.3758/BF03196276
565
566 Young, W., Rodger, M., & Craig, C. (2014). Auditory observation of stepping actions can cue both
567 spatial and temporal components of gait in Parkinson's disease patients, *Neuropsychologia* 57, 140—153.
568 doi: 10.1016/j.neuropsychologia.2014.03.009
569
570 Zhao, H. & Warren, W. (2014) On-line and model-based approaches to the visual control of action,
571 *Vision Research* 110, 190—202.
572
573 Zwicker, E. & Fastl, H. (1999). Psychoacoustics. Facts and Models. doi:10.1007/978-3-540-68888-4