RESEARCH QUARTERLY FOR EXERCISE AND SPORT
https://doi.org/10.1080/02701367.2020.1726859

Routledge
Taylor & Francis Group

Sonification of Golf Putting Gesture Reduces Swing Movement Variability in Novices

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

Aix Marseille University, CNRS, ISM

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

ARTICLE HISTORY
Received 12 October 2019
Accepted 3 February 2020

KEYWORDS
Auditory guidance; error-based sonification; motor control; golf

Complex motor skill performance improvement can pertain to a myriad of things, from goal attainment to movement efficiency and consistency. Humans of course are multi-sensory, but vision is regarded as the primary sensory modality for provision of feedback in the performance of complex motor tasks and goal attainment (Zhao & Warren, 2014). However, findings from recent studies suggest other senses play important roles in the guiding of motor actions (Arnott & Alain, 2011; Kohler et al., 2002; Sigrist, Rauter, Riener, & Wolf, 2013). In this study we examined whether novices can use *sonification*, the mapping of data onto sound, to enhance golf putting performance and swing movement.

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

Online sonification can also be modeled to give information based on errors of performance. In this way, sonification functions like an index that points to an error or deviation from an ideal motor action. van Vugt and Tillmann (2015) found that participants engaged with error-based sonification improved motor regularity when performing tapping tasks. Dailly et al. (2012) similarly reported that participants who were presented error-based sonification significantly reduced their spatial error completing a simple figure-tracing task. Wolf, Sigrist, Rauter, and Riener (2011) showed that novice participants were able to immediately use auditory feedback to enhance their rowing performance by reducing spatial

CONTACT Benjamin O'Brien benjamin.o-brien@univ-amu.fr Faculty of Sport Science, UMR 7287 CNRS & Aix-Marseille Université, CP 910, 163, av. de Luminy F-13288, Marseille cedex 09, France
Supplementary data for this article can be accessed publisher's website.

and temporal errors during training. However, none of the aforementioned studies focused on the effects of error-based sonification on complex motor tasks.

An example of a complex motor skill is golf putting (Frank, Land, & Schack, 2013; Wulf & Shea, 2002), a gesture with well defined sub-movements and, due to the design of the putter club, requires a clear translation from the person's movement velocity to energy, so the ball can travel the distance required. It also requires visual concentration on the ball before making contact. Because of this, there is an opportunity to stress other sensory cues for motor-skill guidance. Keogh and Hume (2012) demonstrated that a primary focus in golf training is kinematics and posited that errorless learning might be afforded by using different visual feedback strategies. A similar approach that replaces visual with auditory feedback may prove to be particularly useful, as it would free attentional resources required to visually monitor club and ball positions.

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

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

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

Our first objective then was to develop a method of sonification that was participant-dependent, so as to accurately reflect swing idiosyncrasies and, moreover, personalize the sounds presented to participants. We decided to present participants auditory guidance based on their individual average swing performance, which was calculated following a series of successful putts at different distances. A major advantage of this method is that it adjusts to the kinematic capacities of the individual, which may prove useful in both healthy and rehabilitation research.

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

Methods

Participants

Forty right-handed participants (28 male; mean age: 22.4; standard deviation: 7.2) affiliated with Aix-

Marseille University participated in the experiment. All participants self-reported good or corrected vision and normal hearing. All participants consented to voluntary participation in the study and were informed of their right to withdraw at any time. This study was performed in accordance with the ethical standards of the Declaration of Helsinki (Salako, 2006). The Ethics Committee of Aix-Marseille University approved the protocol.

Experimental setup

Participants used an Odyssey White Ice putter (length: 0.97 m; weight: 0.59 kg) to hit Titleist PRO V1X balls. A synthetic grass terrain was used (length: 5 m; width: 1.8 m). White circles with 0.11 m diameters were painted at the starting position and the 2 m and 4 m target distances. Participants wore Sennheiser headphones when presented sound.

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

Procedure

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

Protocol

A custom program developed in Python streamed and recorded all values monitored by CodaMotion. To present personalized MVPs to participants, their successful Baseline trials were selected and synchronized at impact point, where after their club head velocities were shifted and averaged offline. During the Experimental trials we estimated the time to impact with the ball by using club head marker values to calculate its velocity and distance from the ball. Once the backswing velocity reached a minimum threshold of 0.1 m.s, we began the process of comparing the current position of the club head with the starting position of the club (near the ball) and the current club head velocity with the MVP. Error was then calculated by comparing the current estimated time to impact with the MVP time of impact. This estimated time to impact was then compared in real-time to the participant's MVP, which, in turn, gave us a real-time difference, or *error*, between her observed and MVP swings. Figure 1 illustrates the real-time error between a participant's observed and MVP swings for a 2 m putt.

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

Sound design

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

The remaining two groups were presented online sonification based on the calculated errors between observed and MVP swings. Similar to the MVP group, both groups were presented auditory signals generated by mapping and scaling velocity values to the frequency of a sinusoidal oscillator, however they were modulated differently depending on the group. In both cases, the magnitude of the error was directly mapped to the magnitude

[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.

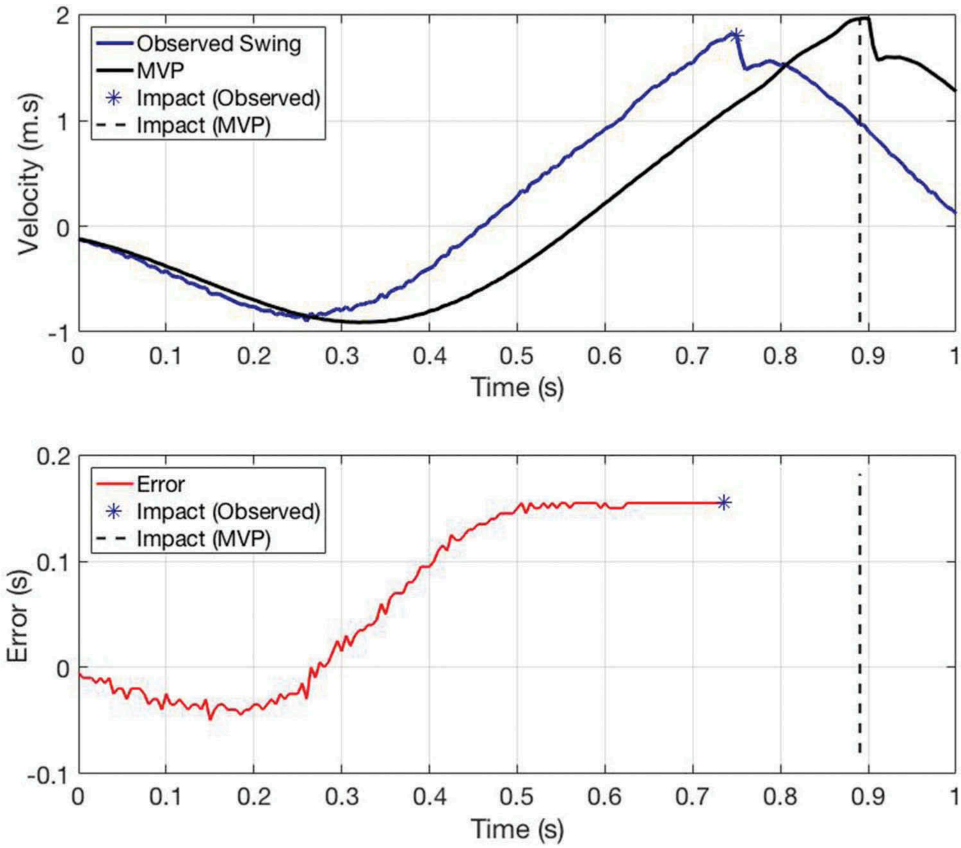

Figure 1. Top: comparison between observed (blue) and MVP (black) swings. Bottom: error (red).

of the modulation. The "Directivity" group was presented online sonification based on stereo display, where the auditory signal was panned right if the error was negative (and vice-versa). This design was based on a study by Libkum, Otani, and Steger (2002), which found participants who trained by synchronizing their hands and feet with a stereophonic metronome improved performance. The "Roughness" group was presented online sonification based on error sign to modulate the *roughness*[2] of the auditory signal: if negative, it was processed by a Coulomb friction sound synthesizer to become more "grating" if positive, it was modulated by a von Kármán model (Diedrich & Drischler, 1957) to evoke wind speeds. The **Supplementary Materials** demonstrate the differences between all auditory conditions.

Data processing and statistics

To investigate whether sonification affected putting performance, we examined the distance between the final location of the ball and the target—the target distance error. Both target distance error mean (TDE_μ) and standard deviation (TDE_σ) were used in our analysis of all Baseline and Experimental trials. In addition, we calculated the *percentage of improvement* for both TDE_μ and $TDE_\sigma$by dividing the difference between Baseline and Experimental trials by Baselines trials and multiplying it by 100.

To investigate the effects of sonification on movement and timing variability, we examined participant deviation from average swing speed and temporal ratio, respectively. To measure the former, we synchronized trials at impact, shifted their velocities to the time of impact, and then calculated the Normalized Root Mean Standard Deviation from their MVP (1), where $\hat{x}$ represents participant MVP, x is the collection of velocity values from the start of the backswing up to impact for trial n, and N is the number of successful trials. These deviations were then averaged ($NRMSD_\mu$). To measure temporal ratio variability (TR_σ), we calculated the standard deviation of the temporal ratio, which is the ratio of the backswing duration to downswing duration. 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 modeling (Conan et al., 2014).

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

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

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

Preliminary analysis

All participants were included in our analysis. At first glance it appeared participants found the 2 m target (mean target distance error: 0.44 m; SD target distance error: 0.14 m) to be less difficult than the 4 m target (mean target distance error: 0.62 m; SD target distance error: 0.16 m). Repeated measures ANOVA tests revealed main effects on mean target distance error $F_{1,3} = 47.51$, $p < .001$, $\eta_p^2 = 0.94$ and SD target distance error $F_{1,3} = 15.53$, $p < .001$, $\eta_p^2 = 0.67$. Our preliminary observations were substantiated by post-hoc tests that revealed mean target distance error at 2 m was significantly less than 4 m (0.18 ± 0.03), $p < .001$. Similarly participants showed significantly lower SD target distance error at 2 m when compared to 4 m (0.12 ± 0.03), $p < .001$.

Results

Target distance error

We first examined the percentage of improvement for mean target distance error (TDE_μ) at 2 m and 4 m and found a main effect on distance $F_{1,3} = 5.11$, $p < .05$, $\eta_p^2 = 0.38$, but no group effects, $p > .05$. Post-hoc tests revealed participants significantly improved their percentage of improvement for TDE_μ at 2 m when compared to 4 m (9.38 ± 4.15), $p < .05$.

Next, to examine the effects of sonification on putting performance, we compared TDE_μ during Baseline and Experimental trials at 2 m and 4 m and found main effects on distance $F_{1,3} = 108.47$, $p < .001$, $\eta_p^2 = 0.94$ and trial type $F_{1,3} = 37.61$, $p < .001$, $\eta_p^2 = 0.93$, but no significance on group, $p > .05$. Post-hoc tests showed participants were closer to the target at 2 m (18.77 ± 1.8) and during the Experimental trials (10.18 ± 1.66), $p < .001$.

Similarly, we first examined the percentage of improvement for standard deviation of target distance error (TDE_σ) at 2 m and 4 m and found no significance for neither group nor distance, $p > .05$.

Next we compared TDE_σ during Baseline and Experimental trials at 2 m and 4 m and similarly found main effects on distance $F_{1,3} = 43.9$, $p < .001$, $\eta_p^2 = 0.82$ and trial type $F_{1,3} = 31.56$, $p < .001$, $\eta_p^2 = 0.85$ and a distance * group interaction $F_{3,36} = 3.13$, $p < .05$, $\eta_p^2 = 0.21$. Post-hoc tests showed participants performed with lower variability at 2 m (12.22 ± 1.8) and during the Experimental trials (8.74 ± 1.56), $p < .001$. Additionally, the following groups had significantly lower variability at 2 m rather than at 4 m, $p < .001$: Control (13.37 ± 3.69), Directivity (11.27 ± 3.69), and Roughness (20.04 ± 3.69).

Average swing velocity deviation from MVP

We examined the percentage of improvement for average swing velocity deviation from MVP ($NRMSD_\mu$) trials at 2 m and 4 m and found main effects on group $F_{3,36} = 3.17$, $p < .05$, $\eta_p^2 = 0.21$ and distance $F_{1,3} = 6.62$, $p < .01$, $\eta_p^2 = 0.67$. Post-hoc tests revealed the MVP group significantly improved in comparison to the Control group (25.2 ± 8.56), $p < .05$ (Figure 2). There were no other significant differences between groups, $p > .05$. When compared to the 4 m target, participants improved performance at 2 m (18.27 ± 6.52), $p < .05$.

Next we examined participant $NRMSD_\mu$ from during Baseline and Experimental trials at 2 m and 4 m, where we observed main effects on distance $F_{1,3} = 14.63$, $p < .001$, $\eta_p^2 = 0.8$, trial type $F_{1,3} = 14.93$, $p < .001$, $\eta_p^2 = 0.57$, and interactions on trial type * group $F_{3,36} = 3.76$, $p < .05$, $\eta_p^2 = 0.24$. Post-hoc tests revealed participants significantly lowered their $NRMSD_\mu$ at 4 m (0.64 ± 0.17) and during Experimental trials (0.61 ± 0.16), $p < .001$. Additionally, participants in the MVP group significantly lowered their $NRMSD_\mu$ during Experimental trials (1.5 ± 0.31), $p < .001$ (Figure 3).

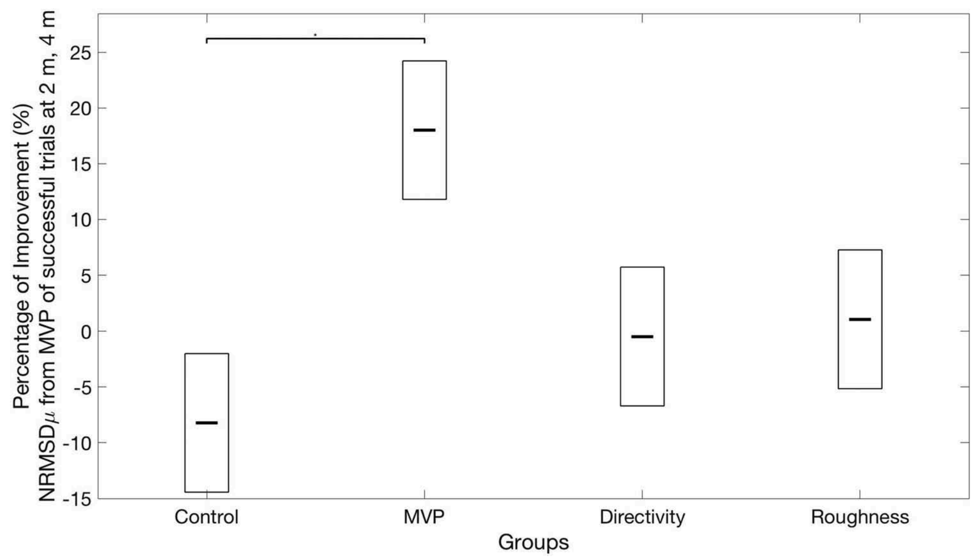

Figure 2. Percentage of improvement for average swing velocity deviation from MVP of successful trials at 2 m, 4 m by group.

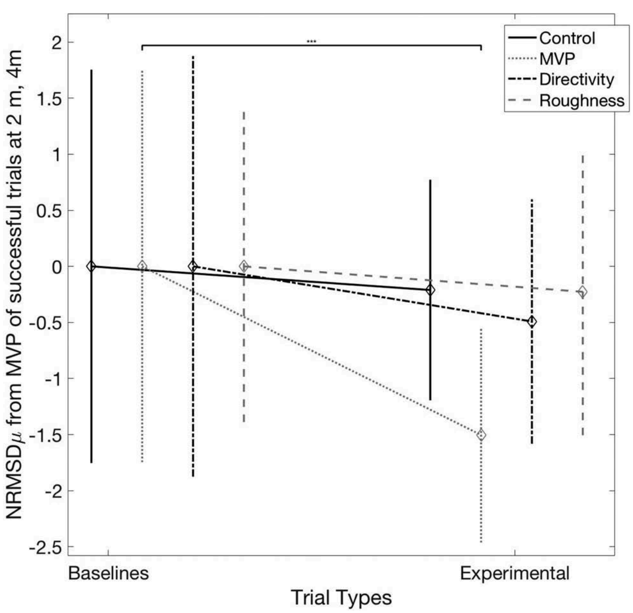

Figure 3. Average swing velocity deviation from MVP of successful baseline and experimental trials at 2 m, 4 m.

Temporal ratio

We first examined the percentage of improvement for standard deviation of temporal ratio (TR_σ) trials at 2 m and 4 m and found no significance for neither group nor distance, $p > .05$.

Next we examined participant TR_σ during Baseline and Experimental trials at 2 m and 4 m, and we observed main effects on trial type $F_{1,3} = 7.68$, $p < .01$, $\eta_p^2 = 0.46$ and interactions on trial type * group $F_{3,36} = 3.02$, $p < .05$, $\eta_p^2 = 0.2$, distance * group $F_{3,36} = 3.28$, $p < .05$, $\eta_p^2 = 0.21$, and distance * trial type * group $F_{3,36} = 3.22$, $p < .05$, $\eta_p^2 = 0.21$. Post-hoc tests revealed participants significantly lowered their TR_σ during Experimental trials (0.05 ± 0.02), $p < .01$. The Directivity group significantly lowered their TR_σ during Experimental trials (0.13 ± 0.04), $p < .01$, when compared to Baseline trials (Figure 4); during 2 m trials (0.07 ± 0.03), $p < .05$, when compared to 4 m trials; and during Experimental trials at 4 m (0.2 ± 0.06), $p < .01$, when compared to Experimental trials at 2 m. The Control group significantly lowered their TR_σ during 4 m (0.07 ± 0.03), $p < .05$, when compared to 2 m trials, and Experimental trials at 2 m (0.14 ± 0.04), $p < .05$, when compared to Experimental trials at 4 m.

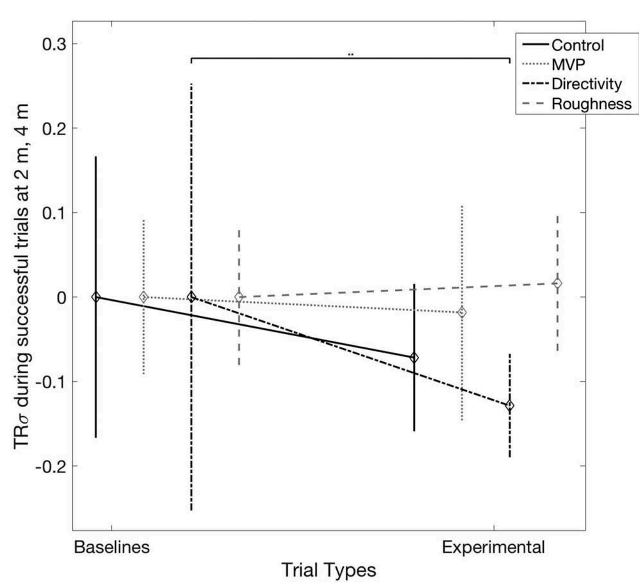

Figure 4. Temporal ratio standard deviation of successful baseline and experimental trials at 2 m, 4 m by group.

Correlations between putting performance and swing movement variability

Noting our significant findings for average swing velocity deviation from MVP for the MVP group and temporal ratio standard deviation for the Directivity group, we wanted to test if any of the groups had significant correlations between putting performance (target distance error mean and standard deviation) and swing movement variability (deviation from average swing velocity, temporal ratio standard deviation). Using linear regression models, Table 1 illustrates the Group R^2 coefficients and *p*-values for relationships between putting performance and swing movement variability, where: TDE_μ and TDE_σ are the target distance error mean and standard deviation, respectively; $NRMSD_\mu$ is the average swing velocity deviation from MVP; and TR_σ is the temporal ratio standard deviation.

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

Discussion

Putting performance

The goal of our study was to investigate whether novices were able to use sonification to improve golf putting performance and reduce swing movement variability. While participants significantly improved their target distance error average by 0.10 ± 0.02 m and standard deviation by 0.09 ± 0.02 m during the Experimental trials, we reported no group effects. In addition, though the percentage of improvement was positive for mean target distance error, there were no group differences in the magnitude of the percentage improvement. Because participants exposed to static pink noise similarly improved to those who were presented auditory guidance or error-based sonification, at first glance these results suggest performance enhancement was not influenced by the presence of artificial sound, but rather based on movement familiarization. There are, of course, countless factors that contribute to golf putting performance, which have been the subject of study, such as the putting green (Pataky & Lamb, 2018). This point is underlined by a report by Kammerer, Menshik, Erlemann, and Lafortune (2014), which found putting robots made only 80% putts at 5 m. These observations taken together suggest that when studying its effect on novices, sonification may play a more important role enhancing putting movements, rather than directly influencing ball distance from the target.

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

	$TDE\mu$				$TDE\sigma$			
	$NRMSD\mu$		$TR\sigma$		$NRMSD\mu$		$TR\sigma$	
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	

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

Swing movement variability

Our analysis showed swing movement variability was enhanced differently among groups. The MVP group showed a 25.2 ± 8.56% greater percentage of improvement for deviation from average swing velocity when compared to the Control group. This important finding demonstrates the benefits of personalized sonification, which, in this case, was based on the average speed of successfully executed golf putts. Similar benefits were reported in a study by Bieńkiewicz et al. (2019), which found novices improved putting performance when presented sonification based on the club head velocity of an expert golfer performing putts at multiple distances. However, unlike their study, where participants trained with sonification over an eight-week period, the MVP group enhanced its performance when presented personalized sonification, as it improved its average swing movement variability. This point is underscored by our results that found MVP participants significantly reduced their deviation from average swing velocity ($NRMSD_\mu$) during Experimental trials by 1.5 ± 0.31 residuals. An important distinction then between the two studies is that, while their study focused on examining the effects of sonification on learning the golf putting gesture, we examined and found participants were able to use auditory guidance based on their unique physiological constraints to enhance their movement by reducing variability.

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

Although both Directivity and Roughness groups were presented online sonification based on errors of performance by modifying the same type of auditory guidance signal presented to the MVP group, our analysis of the timing of swing movements showed that only Directivity participants were able to use sound to significantly reduce their temporal ratio standard deviation (TR_σ) by 0.13 $\pm$ 0.04. As the timbre between the sounds presented to both MVP and Directivity groups was the same, the major difference was the latter presented online sonification based on performance. By modifying the stereo display of the auditory guidance signal, Directivity participants were given additional information for which to perceive, interpret, and then use to reduce the variability in the timing of their swing movements. Our findings support those reported by Libkum et al. (2002), who found training with auditory stimuli improved putting performance, and add evidence to the role of sound spatialization on human movement (Gandemer, Parseihian, Kronland-Martinet, & Bourdin, 2017).

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

What does this article add?

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

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

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

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).

Data availability statement

The data described in this article are openly available in the Open Science Framework at DOI:10.17605/OSF.IO/TPA6U.

ORCID

Benjamin O'Brien http://orcid.org/0000-0002-1255-8410
Marta Bieńkiewicz http://orcid.org/0000-0003-2863-4219
Lionel Bringoux http://orcid.org/0000-0003-3939-8151
Christophe Bourdin http://orcid.org/0000-0003-4149-1347

References

Agostini, T., Righi, G., Galmonte, A., & Bruno, P. (2004). The relevance of auditory information in optimizing hammer throwers performance. *Biomechanics and sports: Proceedings of the XI Winter Universiads 2003, 473,* 67–74. doi:10.1007/978-3-7091-2760-5_9.

Arnott, S., & Alain, C. (2011). The auditory dorsal pathway: Orienting vision. *Neuroscience & Biobehavioural Reviews*, *35*(10), 2162–2173. doi:10.1016/j.neubiorev.2011.04.005

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

Bonassi, G., Biggio, M., Bisio, A., Ruggeri, P., Bove, M., & Avanzino, L. (2017). Provision of somatosensory inputs during motor imagery enhances learning-induced plasticity in human motor cortex. *Scientific Reports*, *7*, 9300. doi:10.1038/s41598-017-09597-0

Burchfield, R., & Venkatesan, S. (2010). *A framework for golf training using low-cost inertial sensors*. Proceedings of the 2010 International Conference on Body Sensor Networks. doi:10.1109/BSN.2010.46

Conan, S., Thoret, E., Aramaki, M., Derrien, O., Gondre, C., Ystad, S., & Kronland-Martinet, R. (2014). An intuitive synthesizer of continuous-interaction sounds: Rubbing, scratching, and rolling. *Computer Music Journal*, *38*, 24–37. doi:10.1162/COMJa00266

Craig, C., Delay, D., Grealy, M., & Lee, D. (2000). Guiding the swing in golf putting. *Nature*, 295–296. doi:10.1038/35012690

Dailly, A., Sigrist, R., Kim, Y., Wolf, P., Erckens, H., Cerny, J., … Sulzer, J. (2012). *Can simple error sonification in combination with music help improve accuracy in upper limb movements?* Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (pp. 1423–1427). doi:10.1109/BioRob.2012.6290908.

Diedrich, F., & Drischler, J. (1957). *Effect of spanwise variations in gust intensity on the lift due to atmospheric turbulenc: NACA TN 3920*. Hampton, VA: National Advisory Committee for Aeronautics.

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

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

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

Effenberg, A., Ursula, F., Schmitz, G., Krueger, B., & Mechling, H. (2016). Movement sonification: Effects on motor learning beyond rhythmic adjustments. *Frontiers in Neuroscience*. doi:10.3389/fnins.2016.00219

Frank, C., Land, W. M., & Schack, T. (2013). Mental representation and learning: The influence of practice on the development of mental representation structure in complex action. *Psychology of Sport and Exercise*, *14*, 353–361. doi:10.1016/j.psychsport.2012.12.001

Gandemer, L., Parseihian, G., Kronland-Martinet, R., & Bourdin, C. (2017). Spatial cues provided by sound improve postural stabilization: Evidence of a spatial auditory map? *Frontiers in Neuroscience*, *11*. doi:10.3389/fnins.2017.00357

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

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

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

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

Kohler, E., Keysers, C., Umilta, A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing sounds, understanding actions: Action representation in mirror neurons. *Science*, *297*(5582), 846–848. doi:10.1126/science.1070311

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

Murgia, M., Prpic, V. O. J., McCullagh, P., Santoro, I., Galmonte, A., & Agostini, T. (2017). Modality and perceptual-motor experience influence the detection of temporal deviations in tap dance sequences. *Frontiers in Psychology*, *8*, 1340. doi:10.3389/fpsyg.2017.01340

O'Brien, B., Juhas, B., Bienkiewicz, M., Pruvost, L., Buloup, F., Bringnoux, L., & Bourdin, C. (2018). *Considerations for developing sound in golf putting experiments*. Post-proceedings of CMMR 2017 - Music Technology with Swing, Lecture Notes in Computer Science. Heidelberg: Springer-Verlag. doi:10.1007/978-3-030-01692-0

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

Richardson, A., Mitchell, A., & Hughes, G. (2018). The effect of movement variability on putting proficiency during the golf putting stroke. *International Journal of Sports Science & Coaching*, *13*, 590–597. doi:10.1177/1747954118768234

Salako, S. E. (2006). The declaration of Helsinki 2000: Ethical principles and the dignity of difference. *Medicine and Law*, *2*, 341–354. doi:10.1515/9783110208856.233

Schaffert, N., Janzen, T., Mattes, K., & Thaut, M. (2019). A review on the relationship between sound and movement in sports and rehabilitation. *Frontiers in Psychology*, *10*, 244. doi:10.3389/fpsyg.2019.00244

Sigrist, R., Fox, S., Riener, R., & Wolf, P. (2016). Benefits of crank moment sonification in cycling. *Procedia Engineering*, *147*, 513–518. doi:10.1016/j.proeng.2016.06.230

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. doi:10.3758/s13423-012-0333-8

Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J.-L., & Ystad, S. (2014). From sound to shape: Auditory perception of drawing movements. *Journal of Experimental Psychology: Human Perception and Performance*, American Psychological Association, *40*(3), 983–994. doi:10.1037/a0035441

van Vugt, F., & Tillmann, B. (2015). Auditory feedback in error-based learning of motor regularity. *Brain Research*, *1606*, 54–67. doi:10.1016/j.brainres.2015.02.026

Wolf, P., Sigrist, R., Rauter, G., & Riener, R. (2011). Error sonification of a complex motor task. *BIO Web of Conferences*, *1*, 00098. EDP Sciences. doi:10.1051/bioconf/20110100098

Wu, H., Miyamoto, Y., Castro, L., Olveczky, B., & Smith, M. (2014). Temporal structure of motor variability is dynamically regulated and predicts motor learning ability. *Nature Neuroscience*, *17*(2), 185–211. doi:10.1038/nn.3616

Wulf, G., & Shea, C. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin and Review*, *9*(2), 185–211. doi:10.3758/BF03196276

Young, W., Rodger, M., & Craig, C. (2014). Auditory observation of stepping actions can cue both spatial and temporal components of gait in Parkinson's disease patients. *Neuropsychologia*, *57*, 140–153. doi:10.1016/j.neuropsychologia.2014.03.009

Zhao, H., & Warren, W. (2014). On-line and model-based approaches to the visual control of action. *Vision Research*, *110*, 190–202. doi:10.1016/j.visres.2014.10.008

Zwicker, E., & Fastl, H. (1999). Psychoacoustics. *Facts and Models*. doi:10.1007/978-3-540-68888-4