Page Proof Instructions and Queries

Journal Title: Musicae Scientiae

Article Number: 847496

Thank you for choosing to publish with us. This is your final opportunity to ensure your article will be accurate at publication. Please review your proof carefully and respond to the queries using the circled tools in the image below, which are available **by clicking "Comment"** from the right-side menu in Adobe Reader DC.*

Please use *only* the tools circled in the image, as edits via other tools/methods can be lost during file conversion. For comments, questions, or formatting requests, please use [T]. Please do *not* use comment bubbles/sticky notes.

*If you do not see these tools, please ensure you have opened this file with **Adobe Reader DC**, available for free at get.adobe.com/reader or by going to Help > Check for Updates within other versions of Reader. For more detailed instructions, please see us.sagepub.com/ReaderXProofs.

No.	Query
	Please note, only ORCID iDs validated prior to acceptance will be authorized for publication; we are unable to add or amend ORCID iDs at this stage.
	Please confirm that all author information, including names, affiliations, sequence, and contact details, is correct.
	Please review the entire document for typographical errors, mathematical errors, and any other necessary corrections; check headings, tables, and figures.
	Please ensure that you have obtained and enclosed all necessary permissions for the reproduction of art works (e.g. Illustrations, photographs, charts, maps, other visual material, etc.) Not owned by yourself. Please refer to your publishing agreement for further information.
	Please note that this proof represents your final opportunity to review your article prior to publication, so please do send all of your changes now.
	Please confirm that the funding statements are accurate.
1	in references to author Szabo/Szabó, please confirm correct use of accented o/ó in each case
2	the ciation https://cycling74.com has no corresponding reference. Please either include full reference details or delete citation. Please also include correct citation details (author/organisation name and date) if possible.

MUSICÆ SCIENTIÆ

The effect of (a)synchronous music on runners' lower leg impact loading

Musicae Scientiae
1–16

DOI: 10.1177/1029864919847496
journals.sagepub.com/home/msx
SAGE

Valerio Lorenzoni
Institute for Psychoacoustics and Electronic Music (IPEM), Ghent University, Belgium

Tijl de Bie
Internet Technology and Data Science Lab (IDLAB), Ghent University, Belgium

Thierry Marchant
Data Analysis Department, Ghent University, Belgium

Edith Van Dyck
Institute for Psychoacoustics and Electronic Music (IPEM), Ghent University, Belgium

Marc Leman
Institute for Psychoacoustics and Electronic Music (IPEM), Ghent University, Belgium

Abstract

Running with musical accompaniment is becoming increasingly popular and several pieces of software have been developed that match the music tempo to the exerciser's running cadence, that is, foot strikes per minute. Synchronizing music with running cadence has been shown to affect several aspects of the performance output and perception. The purpose of this study was to investigate the effect of synchronous music on runners' foot impact loading. This represents the ground reaction force on the runner's lower leg when the foot impacts the ground and is an important parameter for the prevention of tibial fracture injuries. Twenty-eight participants ran five times for three minutes and 30 seconds with a short break between each run. During the first 30 seconds of each running sequence, participants ran at a self-paced tempo without musical accompaniment, and running speed and cadence were measured. Subsequently, they were requested to keep their reference speed constant for the following three minutes, with the help of three monitoring screens placed along the track. During this part of the experiment, the music was either absent (*No Music*), matched to the runner's cadence (*Tempo-entrained Sync*), phase-locked with foot strikes (*Phase-locked Sync*), or played at a tempo 30% slower (*Minus 30%)* or faster (*Plus 30%)* than the initially measured running cadence. No significant differences between synchronous and asynchronous

Corresponding author:
Valerio Lorenzoni, Faculty of Arts and Philosophy, Department of Arts, Music and Theatre Sciences, IPEM, Ghent University, De Krook, Miriam Makebaplein 1, Ghent, 9000, Belgium.
Email: valerio.lorenzoni@ugent.be

music were retrieved for impact loading. However, a non-negligible average increase of impact level could be observed for running sessions with music compared to running in silence. These findings might be especially relevant for treatment purposes, such as exercise prescription and gait retraining, and should be taken into account when designing musical (re-)training programmes.

Keywords
Music, movement, running, synchronization, empowerment, impact loading

In recreational running settings, the use of music is remarkably popular and a wide range of music player software and devices is available, often tailored to the specific requirements of recreational and/or professional runners. This does not come as a surprise, as several authors have reported the positive effects of music in sports and physical activities. In particular, music has been shown to distract from fatigue and discomfort (Bood, Nijssen, Van Der Kamp, & Roerdink, 2013; Fritz et al., 2013; Yamashita, Iwai, Akimoto, Sugawara, & Kono, 2006), enhance work output (Edworthy & Waring, 2006; Rendi, Szabo, & Szabó, 2008), increase arousal (Szabo, Balogh, Gáspár, Váczi, & Bösze, 2009; Karageorghis & Priest, 2012; Karageorghis & Terry, 2011), and boost mood states (Edworthy & Waring, 2006; Shaulov & Lufi, 2009). [AQ: 1]

These motivational, psychophysical and ergogenic effects can be associated with the empowering mechanisms deriving from musical interactions. Humans possess an innate expressive system that is responsible for encoding expressions into sonic cues (while playing), as well as decoding (while listening), and converting them into movements (Leman, Buhmann, & Van Dyck, 2017). Simply listening to music generates motor coordination-inducing schemes that respond to external sensory sources in such a way that they allow auditory-motor alignment and even the prediction of musical events (Maes, Leman, Palmer, & Wanderley, 2014). This prediction-fulfilment process represents a type of expressive alignment that generates reward (Salimpoor, Zald, Zatorre, Dagher, & McIntosh, 2015) and empowerment (Leman et al., 2017).

In this article we focus on a specific expressive aspect of musical interaction, namely synchronization or, in this case, the adjustment of the musical tempo (and phase) to the running foot strikes. Previous research found that the above-described effects of music are further emphasized when synchronous music is used to accompany motor tasks (Karageorghis et al., 2009; Simpson & Karageorghis, 2006; Terry, Karageorghis, Mecozzi Saha, & D'Auria, 2012). Synchronization with the musical pulses or beats (conceived as basic musical elements, from which more complex structures emerge; see e.g. Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2013) is a fundamental component of musical interaction, as it is a straightforward and spontaneous way to deal with the perceived stimulus. Leman (2016) refers to the use of movements for active control, imitation and prediction of beat-related features in the music as *inductive resonance*. According to Morillon, Hackett, Kajikawa, and Schroeder (2015), the human motor system acts cooperatively with attention that is sharpened by the perception of periodic signals. Music is an example of a periodic stimulus (via pulse and beat), so it is not surprising that it is composed specifically for movement and dance (Wang, 2015).

Several studies have exploited synchronization and entrainment mechanisms as sources of reward, based on principles of prediction and agency (Buhmann, Moens, Lorenzoni, & Leman, 2017; Moens et al., 2014). Van Dyck et al. (2015) found that runners adapt their exercising cadence when spontaneously synchronizing to a musical stimulus. Leman et al. (2017) showed that being locked to the beat of the music produces a feeling of agency in the listener, as though they had taken control of generating the music, thus evoking a state of physical and mental stimulation experienced as *empowerment*.

Some have examined the use of synchronous versus asynchronous music in sports and exercise activities. Bacon, Myers, and Karageorghis (2012), for instance, studied the effects of synchronous and asynchronous music on oxygen uptake, heart rate (HR), perceived exertion and motivation while cycling at sub-maximal intensities. Oxygen uptake levels were lower in the synchronous music condition than in the asynchronous music condition, but there were no other significant results. Similar tests by Lim, Karageorghis, Romer, and Bishop (2014) focused on the effect of synchronization on oxygen uptake, HR, ratings of dyspnea and limb discomfort, affective valence and arousal during cycling at fixed exercise intensities. Cyclists' performances were compared in the following conditions: with synchronous and asynchronous music, without music, and with a metronome. Synchronization had no effect on oxygen uptake, but positive affective valence was higher in the two conditions with music than the conditions without music or with a metronome. Arousal was higher in the synchronous music condition than in the asynchronous music condition.

The effect of musical synchronicity was further investigated for treadmill walking and circuit-type exercises. In a treadmill experiment, results indicated that motivational synchronous music elicits ergogenic effects and enhances in-task affect during an exhaustive endurance task (Karageorghis et al., 2009). For circuit-type exercises, synchronous music was not shown to elicit significant ergogenic or psychological effects. However, there were differences between the sexes such that men showed more positive affective responses to the metronomic regulation of their movements than women (Karageorghis et al., 2010).

In an experiment on running performance by Bood et al. (2013), participants ran to exhaustion on a treadmill in a control condition without acoustic stimuli, a synchronized metronome condition, and a condition with synchronous motivational music matched to the assessed running cadence. Music with a prominent beat synchronized to the exerciser's pace was found to elicit the best performance as it helped to increase physiological effort and optimize running economy. Similarly, in experiments on 400-metre sprinting performances, Simpson and Karageorghis (2006) demonstrated that the qualities of the music promoting synchronization, but not its motivational qualities, are beneficial to recreational runners' anaerobic endurance performance. In a similar vein, Terry et al. (2012) showed that the motivational qualities of music were less important than the prominence of the musical beat and the degree to which triathletes are able to synchronize their movements to the tempo of the stimulus. They therefore suggest using synchronized, self-selected music during triathlon training programmes. The improvements to performance reported in previous research are thus due mainly to the rhythmical structure of music rather than its motivational aspects. Those who engage in sports such as cycling, walking and running benefit from synchronization, since coupling their movements to a constant musical beat enables them to work more efficiently.

The results of the studies outlined above indicate that music, especially synchronized music, has a significant ergogenic and psychophysical effect on sports and exercise performance, in particular on running and cycling. However, not much is known about the effect of music synchronization on biomechanical parameters. In the present study, the aim is to investigate the effect of synchronized music on runners' impact loading, that is, lower leg loading when the foot strikes the ground. This represents an important biomechanical factor, which has not yet been studied with respect to music-to-movement synchronization, for two reasons: the severity of the impact loading is a known cause of runners' lower limb injuries, and it is directly linked to leg movement kinematics (van Gent et al., 2007). As such, influencing impact loading might have a direct effect on the health of the runner. Recent studies have focused on the reduction of impact loading through the use of real-time feedback. Using audio and visual feedback, Clansey, Hanlon, Wallace, Nevill, and Lake (2014) were able to reduce the impact of treadmill running performance. In this case, audio feedback was shown to be more beneficial than visual feedback. Moreover, Wood and Kipp (2014) stressed the efficacy of auditory feedback for reducing runners' peak tibial acceleration (PTA), an effect that was sustained in further retention tests.

Since a great number of runners listen to music while exercising, we believe that an adequate understanding of the possible effects of synchronized music on impact loading is crucial in order to further optimize running technique and avoid injuries. In the present study, the effect of synchronized music on recreational runners' impact loading is scrutinized. As it has been shown that unintentional coordination is often manifested as relative or intermittent coordination (i.e. movements are attracted to a 0° or 180° but are not phase-locked; see e.g. Kelso, 1995; Lopresti-Goodman, Richardson, Silva, & Schmidt, 2008; von Holst, 1973), we tested the effect of both (a) synchronization based on entrainment of musical tempo and running cadence, without further coupling of foot strikes and musical beats, and (b) synchronization incorporating phase-locking, thus matching foot strikes and beats. These conditions were further compared with a silent condition and two asynchronous conditions where music was either played 30% slower or faster than the exerciser's running cadence. We hypothesized that synchronization with the tempo of the music would generate a sense of empowerment in the exercisers (Leman, 2016) due to a stronger feeling of agency in music-to-movement alignment (Fritz et al., 2013), leading to an increase in foot strike vigour and consequently a higher impact loading.

Methods and materials

Ethics statement

The study was approved by the Ethics Committee of the Faculty of Arts and Philosophy of Ghent University, and all procedures followed were in accordance with the statements of the Declaration of Helsinki. In addition, all participants signed a form to declare that they participated voluntarily, that they had received sufficient information concerning the tasks, the procedures and the technologies used, that they had the opportunity to ask questions, and that they were aware of the fact that running movements were measured, for scientific and educational purposes only.

Participants

To establish sample size, a power analysis for a repeated-measures design was conducted using G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007). With an α level of .05 and a power of $1\text{-}\beta = .95$, based on an estimated low to moderate effect size, it was indicated that around 26 participants would be required.

Participants consisted of 28 non-professional runners (13 female and 15 male) aged between 18 and 42 years (mean = 24.43, *SD* = 5.27). Seventeen of the participants were formally trained in music: 13 were educated in a music academy, two were self-educated musicians, and two received private lessons. The majority of participants (27) went jogging at least once a month: six about once a month, eight about once a week, and 14 several times a week.

Apparatus

The runners were equipped with two 3-axes digital accelerometers, attached in front of the tibial bone to the lower legs, to detect impact strength and cadence. The accelerometers were connected to a Teensy 3.2 micro-controller, in turn connected via USB to a 7-inch tablet (Panasonic Roughpad FZM1) mounted on a backpack carried by the runner. Step detection was performed in real time using an in-house developed JAVA program, which ran on the tablet. The music player and music adaptation tools were implemented in MAX/MSP from Cycling '74 (https://cycling74.com) and ran on the same tablet. The music was played through Sennheiser HD60 headphones. [AQ: 2] Speed measurements were performed in real time using a sonar system (MaxBotix, LV-MaxSonar-EZ: MB1010) connected to the tablet. The sonar detected marker rods of 1.90 m height, placed at regular intervals of 10.10 m next to the running track. Absolute speed was determined by computing the time intervals between the rods. The speed values, sent from the tablet, were displayed on three screens placed along the track at intervals of 107 m, to provide visual feedback to the runners regarding their speed. Specifically, the current speed value was displayed and the background screen colour turned blue when the speed dropped more than 10% under the initial reference velocity (first 30 seconds). It turned red when the speed was more than 10% above the reference and green if within +/− 10% of the reference, for each session independently.

Musical stimulus

The same musical stimulus was played throughout the entire experiment. The stimulus was composed specifically for this experiment by Myrthe van de Weetering[1] and fulfilled the following requirements (by analogy with Karageorghis, 2009; Van Dyck et al., 2013):

- *Unknown*: Motivated by the intention of ensuring optimal control over all musical parameters and to exclude effects of familiarity.
- *Instrumental*: To avoid extra associations or effects and cultural impact caused by lyrics.
- *Clear beats*: In order to optimize synchronization with the musical pulse.

Experimental procedure

The experiment was conducted on the outer track of the Flanders Sports Arena of Ghent, Belgium. At the start of the experiment, participants filled out a questionnaire on their personal background, music education and sports training. Next, they were equipped with the accelerometers, backpack and headphones. Each participant was asked to run five sessions on a 320 m running track, each session lasting for three minutes and 30 seconds. No information was provided concerning the real purpose of the experiment and all participants ran on their own. After each session, a break of approximately five minutes was introduced to enable the participants to recover sufficiently. During the break they were asked to fill out a Rating of Perceived Exertion (RPE) questionnaire and indicate how heavy the effort had been during the exercise, ranging from 6 ('no exertion at all') to 20 ('maximal exertion') (Borg, 1998). In addition, for the conditions with music, they rated the level of physical enjoyment of the run they had just completed on an 8-item version of the Physical Activity Enjoyment Scale (PACES) (Kendzierski & DeCarlo, 1991), using a 7-point Likert scale. In order to test the motivational properties of the musical alignment strategy they had used, participants also performed the Brunel Music Rating Inventory 2 (BMRI-2) test (Karageorghis, Priest, Terry, Chatzisarantis, & Lane, 2006).

A different condition was tested in each of the five running sessions. The conditions were presented in randomized order across participants. Running speed, cadence and impact loading were measured in all sessions. The first 30 seconds of each session ('assessment phase')

Table 1. Overview of the experimental conditions.

No Music	Reference condition: No music
Minus 30%	Asynchronous condition: Music tempo adaptively 30% lower than running cadence
Plus 30%	Asynchronous condition: Music tempo adaptively 30% higher than running cadence
Tempo-entrained Sync	Synchronous condition: Music tempo matched to initial running cadence
Phase-locked Sync	Synchronous condition: Musical beats locked to foot strikes

featured no music and were used to calculate the initial impact level and cadence, as well as the runner's own comfort speed. Runners were asked to maintain the same speed in the following three minutes of each session ('testing phase'), with the help of the three monitoring screens placed along the track. Speed could vary across conditions, as the experiment was designed to be as ecologically valid as possible and minimize fatigue effects.

During the three minutes of the testing phase the following experimental conditions were imposed:

No Music was a control condition in which no music was played for the entire duration of the session.

Minus 30% and *Plus 30%* were both asynchronous conditions in which the music was played in a tempo differing by 30% from the assessed cadence. In *Minus 30%*, the tempo of the music (BPM) was adjusted continuously to a level 30% lower than the actual running cadence (SPM), while in *Plus 30%*, the same adaptation occurred but in a 30% faster tempo than the actual cadence. No auditory-motor synchronization could be achieved by the runner in either case.

In the *Tempo-entrained Sync* and *Phase-locked Sync* conditions, the musical stimulus was synchronized with the runner's behaviour. In the *Tempo-entrained Sync* condition, the tempo of the music was matched to their initial cadence, as measured in the assessment phase. In the *Phase-locked Sync* condition, a customized version of D-Jogger (Moens, van Noorden, & Leman, 2010) was used. Based on Kuramoto's numerical synchronization model (Acebrón, Bonilla, Vicente, Ritort, & Spigler, 2005), this enables the phase-locking of each beat of the music to each of the runner's foot strikes.

A time-stretching algorithm (MAX/MSP elastic~ object) was used in the four music conditions to modify the tempo of the music without affecting its pitch. Table 1 provides an overview of the experimental conditions.

Data acquisition

For each condition, the peaks of the resultant tibial acceleration measured by the accelerometers were calculated using an in-house JAVA program. These are representative of the runner's lower leg impact loading. Hereafter, impact loading values are referred to as *impact level* and expressed in *g*. Cadence was also calculated (through a moving average over five steps) by the same program. The impact level and cadence were transmitted continuously as OSC messages to an in-house MAX/MSP program running on the same tablet. The program implemented the synchronization strategies and provided the audio stimulus through the headphones. In addition, impact level and cadence were collected for every step detected and stored as .txt files on the tablet, together with the speed measurements from the sonar.

Table 2. Mean speed [*km/h*] comparisons between the assessment and testing phase across conditions.

Condition	Assessment phase	Testing phase	Test statistic	*p*	*r*
No Music	11.06	10.81	$z = 1.88$	.063	.25
Minus 30%	11.05 (0.37)	11.01(0.37)	$t = 0.34$	.731	.07
Plus 30%	10.81	10.91	$z = -1.43$	.104	−.18
Tempo-entrained Sync	10.85 (0.32)	10.89 (0.33)	$t = -0.52$	.606	−.10
Phase-locked Sync	11.21 (0.34)	11.13 (0.36)	$t = 0.57$	.576	.12

Note. For *t*-tests, standard errors (*M* (*SE*)) and test statistics (*t*) are reported. For Wilcoxon tests, median (*Mdn*) and test statistics (z) are reported. For both tests, significance values (*p*) (* significant main effect) and effect sizes (*r*) are reported.

Data analysis

To avoid possible start-up effects, median values of the impact level, cadence and speed were calculated, respectively, after 10 seconds from the start of the assessment phase and after 30 seconds from the start of the testing phase. The final 30 seconds of the testing phase were also excluded from the analysis, as it is possible that participants altered their running behaviour (e.g, slowing down or speeding up) in anticipation of the ending of the sequence.

To evaluate the effect of the different conditions on the impact level, *g-difference* (i.e. difference between median impact level of the testing and assessment phase) was computed for each participant and each condition. Due to minor technical issues during the acquisition (mainly due to loosening of the accelerometers caused by sweat), the data collected in one of the experimental conditions for four of the participants were disregarded. In total, 136 observations were included in the analysis. A mixed linear model was applied with one independent variable (*g-difference*), two fixed effects (*speed* and *condition*) and one random effect (*participant id*). Speed in this case refers to the average speed throughout the whole condition, which was shown to be constant between assessment and testing phase, for all participants and conditions (see Table 2). Four versions of this model were considered, varying the set of predictors (but always including *participant id*): the null model (model 0, without *speed* and *condition*), the full model (model F, with *speed* and *condition*), and two intermediate models (model S with *speed* and model C with *condition*). The models were fitted by means of the R function 'lmer' (package lme4) and compared with each other using the R function 'ANOVA'.

Results

Preliminary analysis of speed

As previous research indicated that doubling running speed corresponds to an approximate 80% increase of impact loading (Breine, Malcolm, Frederick, & De Clercq, 2014; Mercer, Vance, Hreljac, & Hamill, 2002), participants were requested to keep a constant speed throughout each running sequence. This was facilitated by visual speed feedback on the three screens placed along the track.

To check if this constraint was met, post hoc statistical tests were performed on the difference between median speed in the *assessment* and testing phase for all participants and conditions. The differences for the *Minus 30%, Tempo-entrained Sync* and *Phase-locked Sync* conditions were normally distributed over the participants (Shapiro-Wilk test, $p = .758$, .922, and .633), while differences for the *No Music* and *Plus 30%* conditions were non-normally distributed (p = .006 and $p < 0.001$)

Paired *t*-tests were performed on the normally distributed pairs and Wilcoxon tests on the non-normally distributed ones. Comparisons showed no significant differences between the distributions in assessment phase and testing phase for any of the conditions. Results are shown in Table 2. Therefore, speed was assumed to be constant throughout the different phases in all conditions.

Differences between conditions

The effect of the different conditions on impact loading level was investigated using the four mixed linear models described above. Visual analysis of the normal Q-Q plots of the residuals for all the models revealed some deviations from normality. Therefore, 16 observations corresponding to extreme residuals in all four models were considered as outliers and deleted. The four models were then again fitted using the clean data set. Four Shapiro-Wilk tests for the residuals of the four models with the clean data revealed no deviation from normality (p = .082, .271, .157, .129 for model 0, C, S and F, respectively). The lowest Akaike Information Criterion (AIC) was obtained for model S (AIC_S = 354.00, AIC_0 = 357.50, AIC_F = 357.80, AIC_C = 360.50). Besides, analysis of variance (ANOVA) showed that the amount of variance explained by model S was significantly higher than that explained by the null (0) model (p = .023, df = 3), while the same analysis for model S and the full model (model F) yielded p = .153 (df = 4). Comparison of model C (condition only) with the null model (0) yielded p = .296. It can therefore be concluded that speed is a predictor of g-difference while condition is not. The estimated regression coefficient for speed was .20.

Pairwise differences

Comparisons were made between the distributions of impact levels in the assessment and testing phase, for each condition separately. Median values are presented in Figure 1.

Shapiro-Wilk tests revealed that impact level differences in the *Minus 30%* condition were normally distributed (p = .194) as were those in the *Plus 30%* condition (p = .132). Impact level differences in the *Tempo-entrained Sync* ($p < .001$), *Phase-locked Sync* ($p < .001$) and *No Music* (p = .002) conditions were not normally distributed. Paired *t*-tests were used to compare the normally distributed pairs, Wilcoxon tests the non-normally distributed ones. A summary of the results is shown in Table 3.

Significant differences between median impact levels in the two phases were found in all conditions, except the *No Music* condition. Overall, in the music conditions, impact level was about 17% higher in the assessment phase than in the testing phase, on average.

A comparison of the g-difference (impact level in testing phase minus impact level in assessment phase*)* between people with and without music education was carried out using Mann-Whitney U tests. The two groups were not observed to differ significantly across conditions, as shown in Table 4.

Mean cadence was analysed using the same mixed linear models as described before. Comparison of the null model (0) with model 1 (condition only) revealed a barely significant difference (p = .051, df = 6). There was no significant difference between the null model and model S (speed only) (p = .216). These results suggest that, in the present experiment, neither synchronization nor running speed significantly influenced running cadence. However, synchronization to music has the potential to affect running cadence (p = .051). Pairwise

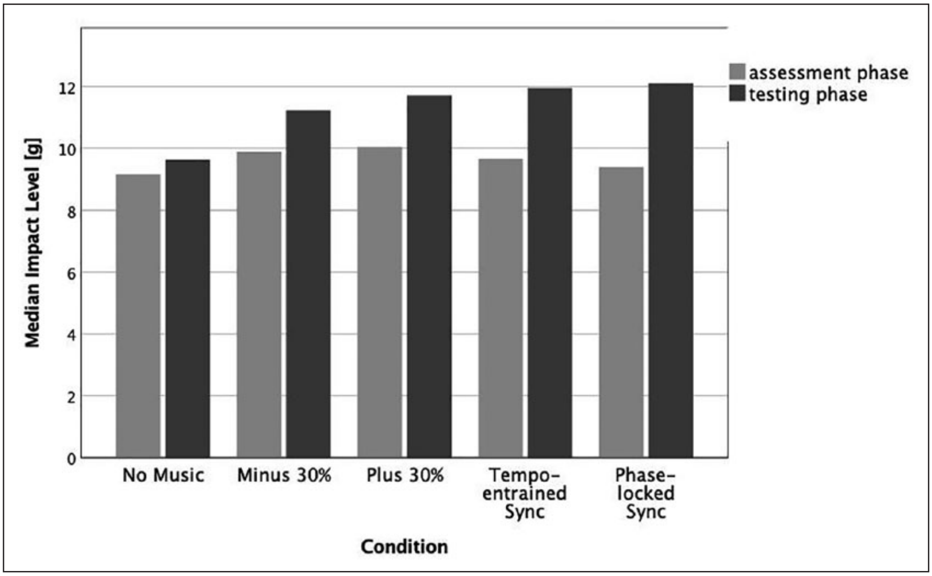

Figure 1. Median impact levels across all participants for the five conditions, for the assessment and testing phase respectively.

Table 3. Impact level [*g*] comparisons between the assessment and testing phase across conditions.

Condition	Assessment phase	Testing phase	Test statistic	*p*	*r*
No Music	9.16	9.63	$z = -1.48$	.137	−.20
Minus 30%	10.48 (0.87)	12.03 (0.93)	$t = -4.17$	< .001*	−.63
Plus 30%	10.05 (0.88)	11.71 (0.99)	$t = -3.78$	.001*	−.59
Tempo-entrained Sync	9.66	11.95	$z = -3.73$	< .001*	−.49
Phase-locked Sync	9.39	12.10	$z = -4.08$	< .001*	−.54

Note. For *t*-tests, standard errors (*M* (*SE*)) and test statistics (*t*) are reported. For Wilcoxon tests, median (*Mdn*) and test statistics (z) are reported. For both tests, significance values (*p*) (* significant main effect) and effect sizes (*r*) are reported.

comparisons of median cadence distributions in each condition in the assessment and testing phase did not yield any significant differences, as shown in Table 5.

Questionnaire data

Participants were asked to rate perceived exertion levels (RPE), level of enjoyment (PACES) and the motivational properties (BMRI-2) of the different synchronization strategies. Friedman tests yielded no overall significant difference across conditions (RPE: $X^2(4) = 1.95$; $p = .744$; PACES: $X^2(3) = 7.36$; $p = .113$; BMRI-2: $X^2(3) = 9.02$; $p = .081$).

Mann-Whitney U tests were used to compare the perceived exertion levels (RPE) of habitual runners (running multiple times per week) ($n = 13$) and non-habitual runners (running once a week or less) ($n = 15$). No significant differences between the two groups were found (see Table 6).

Table 4. g-difference (testing phase – assessment phase) [g] comparisons between musically trained (n = 17) and non-musically trained (n = 11) participants.

Condition	Musical training	No musical training	z	p	r
No Music	–0.07	0.52	−1.22	.237	−.23
Minus 30%	1.07	0.78	0.65	.537	.12
Plus 30%	0.95	0.81	0.16	.890	.03
Tempo-entrained Sync	1.62	0.68	2.14	.033	.40
Phase-locked Sync	0.84	0.73	0.11	.935	.02

Note. Median g-differences (*Mdn*) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 5. Cadence [*SPM*] comparisons between the assessment and testing phase across conditions.

Condition	Assessment phase	Testing phase	Test statistic	p	r
No Music	163.83 (2.27)	163.50 (2.31)	t = 0.55	.727	.07
Minus 30%	163.67 (2.14)	163.33 (2.01)	t = 0.64	.527	.13
Plus 30%	164.02 (2.18)	163.13 (2.04)	t = 1.05	.302	.20
Tempo-entrained Sync	163.29 (2.15)	162.48 (2.77)	t = 0.56	.580	.11
Phase-locked Sync	164.51 (2.18)	164.98 (2.06)	t = –0.69	.494	–.13

Note. Mean cadence (*SPM*) and standard errors (*M* (*SE*)) are reported, as well as test statistics (t), significance values (p), and effect sizes (r) for each experimental condition.

Table 6. Comparison of level of perceived exertion (RPE) (on a 6-20 Borg Scale) for habitual (n = 13) and non-habitual (n = 15) runners.

Condition	Habitual runners	Non-habitual runners	z	p	r
No Music	13	15	−0.65	.525	−.12
Minus 30%	13	15	−0.93	.363	−.17
Plus 30%	12	16	−0.63	.555	−.12
Tempo-entrained Sync	13	15	−0.72	.496	−.14
Phase-locked Sync	11	17	−1.83	.072	−.35

Note. Median levels of perceived exertion (*Mdn*) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Significant differences between the ratings of enjoyment and motivational characteristics of musically (n = 17) and non-musically trained participants (n = 11) were observed for some of the experimental conditions (see Tables 7 and 8). The *Plus 30%* and *Phase-locked Sync* conditions were enjoyed more by musically- than non-musically trained participants, and the *Phase-locked Sync* condition was perceived as more motivational by musically- than non-musically trained participants.

Discussion

The aim of this study was to investigate the effect of auditory-motor synchronization on runners' impact loading. We hypothesized that this type of expressive interaction with music would generate an increased sense of empowerment and, consequently, increase the foot impact

Table 7. Comparison of level of enjoyment ratings (PACES) (on a 7-point Likert scale) between musically trained (n = 17) and non-musically trained (n = 11) participants, across conditions.

Condition	Musical training	No musical training	z	p	r
Minus 30%	5	4	−1.62	.122	−.31
Plus 30%	5	4	−2.24	.029*	−.42
Tempo-entrained Sync	5	5	−1.62	.134	−.31
Phase-locked Sync	5	4	−2.60	.013*	−.49

Note. Median levels of enjoyment ratings (*Mdn*) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 8. Comparison of music motivational characteristics ratings (BMRI-2) (on a 7-point Likert scale) between musically trained (n = 17) and non-musically trained (n = 11) participants across conditions.

Condition	Musical training	No musical training	z	p	r
Minus 30%	5	4	−1.21	.251	−.22
Plus 30%	5	4	−0.41	.711	−.08
Tempo-entrained Sync	5	5	−1.51	.147	−.28
Phase-locked Sync	5	3	−2.08	.043*	−.39

Note. Median levels of music motivational characteristics ratings (*Mdn*) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

strength, resulting in an increased lower leg loading. This hypothesis was rejected by the present study, as no significant effect on impact loading could be ascribed to either tempo-entrained or phase-locked synchronization with the musical stimulus, nor to a non-synchronously played musical stimulus. Although previous research suggested that synchronized music might influence some characteristics of the performance output (e.g. Bood et al., 2013; Simpson & Karageorghis, 2006; Terry et al., 2012), our results suggest that impact loading is not one of the movement parameters that can be influenced by music aligned with running behaviour.

Our results showed no significant differences between the motivational properties of, or enjoyment ratings for synchronous and asynchronous musical accompaniment. This is in line with the findings of research on sub-maximal intensity cycling performance, which yielded no differences in reported motivational qualities or affective valence ratings for similar stimuli (Bacon et al., 2012; Lim et al., 2014).

Most of the previous research dealing with auditory-motor coupling in sports and exercise performance has focused on tempo entrainment, or the alignment of the musical tempo with the exerciser's running cadence, without considering the relationship between foot strikes and musical beats. However, Leman (2016) indicated that this relationship should be taken into account when analysing the psychophysical, motivational and ergogenic effects on motor activities of synchronization, specifically, as this is directly related to embodiment and agency ~~(Leman, 2016).~~ In the present study, therefore, a condition in which musical beats and foot strikes were phase-locked, thus perfectly matched, was included as well as the tempo-entrained condition. As the findings of previous research have shown that not all people are inclined to synchronize to music spontaneously or even to do so when instructed (Buhmann, Desmet, Moens, Van Dyck, & Leman, 2016), synchronization was imposed externally by matching musical tempo/beats with running cadence/foot strikes.

Analysis of questionnaire data yielded no significant differences between the perceived exertion levels reported in the different conditions, or by habitual and non-habitual runners. Although musical training did not have a direct influence on impact loading levels, musically- and non-musically trained participants differed in terms of their enjoyment of and perception of the motivational qualities of the music: in particular, musically trained participants found the *Phase-locked Sync* and the *Plus 30%* conditions more enjoyable than non-musically trained participants, and considered the music in the *Phase-locked Sync* condition more motivational. In this condition, the musical beats were constantly aligned with the runners' foot strikes, thus creating an even stronger connection between the movement behaviour and the musical stimulus. This time-locking of internal and external pulses is believed to evoke a strong empowering effect, generating a feeling of agency in the listener as though they had taken control of generating the music (Leman et al., 2013; Moens et al., 2014). Similar agency is experienced when playing a musical instrument, potentially explaining why musically trained participants enjoyed this experimental condition more than those who were not musically trained.

Interestingly, a non-negligible average difference in impact loading levels, but not speed or cadence, was found in running sequences without (assessment phase) and with music (testing phase). In all conditions with music, once it had started, an overall average increase of 17% was observed. This is one of the most striking findings of the present study, as it suggests that, irrespective of synchronization strategy, music has an empowering effect on the runner, resulting in an increased impact loading.

This effect on impact loading is possibly due to the attention shift mechanism as reported by Tenenbaum et al. (2004) and Karageorghis and Terry (2011). It might also be related to the often-reported arousal effect of music (Karageorghis & Priest, 2012; Karageorghis & Terry, 2011; Szabo, Balogh, Gáspár, Váczi, & Bösze, 2009) and the general finding that music distracts from fatigue and discomfort in exercise performance at sub-maximal intensities (Bood et al., 2013; Fritz et al., 2013; Yamashita, Iwai, Akimoto, Sugawara, & Kono, 2006), thus producing in augmented impact loading levels.

To our knowledge, the above-reported effect of music on this specific biomechanical parameter has not been revealed before and would benefit from more specific and dedicated experimentation. Future research could possibly include other biomechanical parameters (e.g. vertical displacement and/or foot contact time) and could be more directly connected to injury prevention. Analysis of the kinematics of the process by use of cameras or multiple tracking sensors could shed more light on this phenomenon.

It would also be interesting to modify the relative durations of the phases with and without music, as fatigue effects might alter foot strike dynamics in a later phase of the session, leading to different lower leg loading levels, irrespective of musical onset (for a discussion of muscular fatigue effects on impact level, see Sheerin, Reid, & Besier, 2018).

No level of enjoyment (PACES) questionnaire was filled out for the *No Music* condition, since the physical activity to be rated in the PACES questionnaire was relative to running to music. This could be investigated in further experiments, although previous research clearly highlighted the higher level of enjoyment derived from music while exercising (Bood, Nijssen, Van Der Kamp, & Roerdink, 2013; Fritz et al., 2013).

It should be noted that, in the present case, the same musical stimulus (with clear and regular beats) was used in all conditions, which could have led to a general accentuation of movement properties due to the activating character of the music (Leman et al., 2013). Music with less pronounced beats might have affected the movement characteristics under study in a different manner. However, this stimulus was selected and maintained throughout the experiment to facilitate synchronization maximally and minimize possible confounding effects of, for instance, familiarity, preference, lyrics, or possible other (personal or musical) parameters. Further experiments could be dedicated to investigating the effect of the same synchronization strategies employing different musical stimuli. This subject was beyond the scope of the present article; however, we are aware of the coupling of specific musical features and particular synchronization parameters.

In order to control for possible effects of fatigue, participants were entitled to select their own comfort speed at the start of each running session. In order to exclude it as a confounding variable, participants were asked to maintain the same speed throughout each experimental condition, and indeed no significant differences between speed measurements in the assessment and testing phases were found. Speed feedback was provided to the runner via the three screens placed along the track. These provided visual feedback by changing colour if the speed in the testing phase changed more than 10% with respect to the assessment phase. This 10% range for feedback was selected to allow for some flexibility and to distract participants minimally. However, it could be argued that this range of variability might have been too extensive in terms of foot impact loading. The (almost significant) reduction in speed in the *No Music* condition (see Table 2) could partly explain the missing increase in impact level between assessment phase and testing phase for the *No Music* condition compared to the other experimental conditions (see Table 3). Smaller ranges for speed feedback in later experiments could reduce the influence of speed as a covariate when analysing the effect of music-to-movement synchronization on impact loading.

Biomechanical studies by Mercer, Vance, Hreljac, and Hamill (2002) have revealed that an increase in running speed is directly coupled to an increase in impact loading. The analysis of the g-differences in the present experiment further revealed that average running speed is also a predictor of differences between impact loading before and after the start of the music with a positive regression coefficient ($r = .20$), implying that increasing speed causes an increase in impact level at the onset of the music. We ascribe this effect to the possibility that small variations in biomechanical parameters (foot-landing mechanism, knee angles, etc.) evoked by the onset of the music could lead to greater dynamical effects at higher running speeds than at lower speeds.

In order to make the experiment as ecologically valid as possible, we allowed speed to vary between conditions and participants. Although this enabled participants to exercise at their preferred pace, it increased the complexity of the analyses, as speed was shown to be a covariate for differences in impact loading. This could be overcome in future experiments by imposing a standard comfort speed per participant.

Some technical problems occurred during the experiment, mainly because of the way the accelerometers were attached to the participants. Irregular oscillations of the sensors could result if the accelerometer became loose due to sweat. This occurred in a small number of cases, but these data were excluded from the analysis.

To summarize, the findings of this study suggest that running to music significantly increases recreational runners' impact loading, irrespective of the specific alignment of the musical beats and foot strikes. This is especially relevant for treatment purposes, such as exercise prescription and gait retraining, and should be borne in mind when planning further research on impact reduction through acoustic feedback and when designing musical (re-) training programmes. As far as we know, this aspect has not been investigated before and could be of particular relevance for high-impact runners. Further tests with fixed running speed and different music tracks would be required for strong conclusions to be drawn as to the effect of music on impact loading and other biomechanical factors. Nevertheless, the use of music in running training has been shown in a range of studies to increase arousal and improve performance, both of which are valid reasons to keep using music while exercising.

Acknowledgements

The authors acknowledge the Methusalem project, awarded by the Flemish Government, for funding this study.
The authors acknowledge the students of the Systematic Musicology course of Ghent University for the help during the acquisition phase of the experiments.

Funding

This research was conducted in the framework of the EmcoMetecca II project, granted by Ghent University (Methusalem-BOF council) to Prof. Dr. Marc Leman. Founding was received from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement no. 615517, and from the FWO (project no. G091017N, G0F9816N).

Note

1. www.myrthevandeweetering.com

ORCID iD

Valerio Lorenzoni https://orcid.org/0000-0001-6666-0659

References

Acebrón, J. A., Bonilla, L. L., Vicente, C. J. P., Ritort, F., & Spigler, R. (2005). The Kuramoto model: A simple paradigm for synchronization phenomena. *Reviews of Modern Physics*, *77*(1), 137–185.

Bacon, C., Myers, T., & Karageorghis, C. I. (2012). Effect of music-movement synchrony on exercise oxygen consumption. *Journal of Sports Medicine and Physical Fitness*, *52*(4), 359–365.

Bood, R. J., Nijssen, M., Van Der Kamp, J., & Roerdink, M. (2013). The power of auditory-motor synchronization in sports: Enhancing running performance by coupling cadence with the right beats. *Plos One*, *8*(8), e70758.

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Breine, B., Malcolm, P., Frederick, E. C., & De Clercq, D. (2014). Relationship between running speed and initial foot contact patterns. *Medicine and Science in Sports and Exercise*, *46*(8), 1595–1603.

Buhmann, J., Desmet, F., Moens, B., Van Dyck, E., & Leman, M. (2016). Spontaneous velocity effect of musical expression on self-paced walking. *Plos One*, *11*(5), e0154414.

Buhmann, J., Moens, B., Lorenzoni, V., & Leman, M. (2017). Shifting the musical beat to influence running cadence. In E. Van Dyck (Ed.), *Proceedings of the 25th Anniversary Conference of the European Society for the Cognitive Sciences of Music* (pp. 27–31). Ghent, Belgium: Ghent University.

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S., & Toiviainen, P. (2013). Influences of rhythm and timbre-related musical features on characteristics of music-induced movement. *Frontiers in Psychology*, *4*, 183.

Clansey, A. C., Hanlon, M., Wallace, E. S., Nevill, A., & Lake, M. J. (2014). Influence of tibial shock feedback training on impact loading and running economy. *Medicine and Science in Sports and Exercise*, *46*(5), 973–981.

Edworthy, J., & Waring, H. (2006). The effects of music tempo and loudness level on treadmill exercise. *Ergonomics*, *49*(15), 1597–1610.

Elliott, D., Carr, S., & Savage, D. (2004). Effects of motivational music on work output and affective responses during sub-maximal cycling of a standardized perceived intensity. *Journal of Sport Behavior*, *27*(2), 134–147.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191

Fritz, T. H., Hardikar, S., Demoucron, M., Niessen, M., Demey, M., Giot, O., Li, Y., Haynes, J. D., Villringer, A., & Leman, M. (2013). Musical agency reduces perceived exertion during strenuous physical performance. *Proceedings of the National Academy of Sciences*, *110*(44), 17784–17789.

Karageorghis, C. I., Mouzourides, D. A., Priest, D. L., Sasso, T. A., Morrish, D. J., & Walley, C. L. (2009). Psychophysical and ergogenic effects of synchronous music during treadmill walking. *Journal of Sport and Exercise Psychology 31*(1), 18–36.

Karageorghis, C. I., & Priest, D. L. (2012). Music in the exercise domain: A review and synthesis (Part II). *International Review of Sport and Exercise Psychology*, *5*(1), 67–84.

Karageorghis, C. I, Priest, D. L., Terry, P. C., Chatzisarantis, N. L., & Lane, A. M. (2006). Redesign and initial validation of an instrument to assess the motivational qualities of music in exercise: The Brunel music rating inventory – 2. *Journal of Sports Sciences*, *24*(8), 899–909.

Karageorghis, C. I., Priest, D. L., Williams, L., Hirani, R., Lannon, K., & Bates, B. (2010). Ergogenic and psychological effects of synchronous music during circuit-type exercise. *Psychology of Sport and Exercise*, *11*(6), 551–559.

Karageorghis, C. I., & Terry, P. C. (1997). The psychophysical effects of music in sport and exercise: A review. *Journal of Sport Behavior*, *20*(1), 54–68.

Karageorghis, C. I., & Terry, P. (2011). *Inside sport psychology*. Champaign, IL: Human Kinetics.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: The MIT Press.

Kendzierski, D., & DeCarlo, K. J. (1991). Physical activity enjoyment scale: Two validation studies. *Journal of Sport and Exercise Psychology*, *13*(1), 50–64.

Leman, M. (2016). *The expressive moment: How interaction (with music) shapes empowerment*. Cambridge: MA: The MIT Press.

Leman, M., Buhmann, J., & Van Dyck, E. (2017). The empowering effects of being locked into the beat of the music. In C. Wöllner (Ed.), *Body, sound and space in music and beyond: Multimodal explorations* (pp. 13–28). London, UK: Routledge.

Leman, M., Moelants, D., Varewyck, M., Styns, F., van Noorden, L., & Martens, J. P. (2013). Activating and relaxing music entrains the speed of beat synchronized walking. *Plos One*, *8*(7), e67932.

Lim, H. B., Karageorghis, C. I., Romer, L. M., & Bishop, D. T. (2014). Psychophysiological effects of synchronous versus asynchronous music during cycling. *Medicine and Science in Sports and Exercise*, *46*(2), 407–413.

Lopresti-Goodman, S. M., Richardson, M. J., Silva, P. L., & Schmidt, R. C. (2008). Period basin of entrainment for unintentional visual coordination. *Journal of Motor Behavior*, *40*, 3–10.

Maes, P. J., Leman, M., Palmer, C., & Wanderley, M. (2014). Action-based effects on music perception. *Frontiers in Psychology*, *4*, 1008.

Mercer, J. A., Vance, J., Hreljac, A., & Hamill, J. (2002). Relationship between shock attenuation and stride length during running at different velocities. *European Journal of Applied Physiology*, *87*(4–5), 403–408.

Moens, B., & Leman, M. (2015). Alignment strategies for the entrainment of music and movement rhythms. *Annals of the New York Academy of Sciences*, *1337*(1), 86–93.

Moens, B., Muller, C., van Noorden, L., Franěk, M., Celie, B., Boone, J., Bourgois, J., & Leman, M. (2014). Encouraging spontaneous synchronisation with D-Jogger, an adaptive music player that aligns movement and music. *Plos One*, *9*(12), e114234.

Moens, B., van Noorden, L., & Leman, M. (2010). D-jogger: Syncing music with walking. In *Proceedings of the 7th Sound and Music Computing Conference, SMC 2010* (pp. 451–456). Barcelona, Spain: Universidad Pompeu Fabra.

Morillon, B., Hackett, T. A., Kajikawa, Y., & Schroeder, C. E. (2015). Predictive motor control of sensory dynamics in auditory active sensing. *Current Opinion in Neurobiology*, *31*, 230–238.

Rendi, M., Szabo, A., & Szabó, T. (2008). Performance enhancement with music in rowing sprint. *The Sport Psychologist*, *22*(2), 175–182.
Salimpoor, V., Zald, D. H., Zatorre, R. J., Dagher, A., & McIntosh, A. R. (2015). Predictions and the brain: How musical sounds become rewarding. *Trends in Cognitive Sciences*, *19*(2), 86–91.
Shaulov, N., & Lufi, D. (2009). Music and light during indoor cycling. *Perceptual and Motor Skills*, *108*, 597–607.
Sheerin, K. R., Reid, D., & Besier, T. F. (2018). The measurement of tibial acceleration in runners. A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. *Gait & Posture*, *67*, 12–24.
Simpson, S. D., & Karageorghis, C. I. (2006). The effects of synchronous music on 400-m sprint performance. *Journal of Sports Sciences*, *24*(10), 1095–1102.
Stupacher, J., Hove, M. J., Novembre, G., Schütz-Bosbach, S., & Keller, P. E. (2013). Musical groove modulates motor cortex excitability: A TMS investigation. *Brain and Cognition*, *82*(2), 127–136.
Szabo, A., Balogh, L., Gáspár, Z., Váczi, M., & Bösze, J. (2009). The effects of fast- and slow-tempo music on recreational basketball training. *International Quarterly of Sport Science*, *2*, 1–13.
Tenenbaum, G., Lidor, R., Lavyan, N., Morrow, K., Tonnel, S., Gershgoren, A., ... Johnson, M. (2004). The effect of music type on running perseverance and coping with effort sensations. *Psychology of Sport and Exercise*, *5*(2), 89–109.
Terry, P. C., Karageorghis, C. I., Saha, A. M., & D'Auria, S. (2012). Effects of synchronous music on treadmill running among elite triathletes. *Journal of Science and Medicine in Sport*, *15*(1), 52–57.
Van Dyck, E., Moelants, D., Demey, M., Deweppe, A., Coussement, P., & Leman, M. (2013). The impact of the bass drum on human dance movement. *Music Perception: An Interdisciplinary Journal*, *30*(4): 349–359.
Van Dyck, E., Moens, B., Buhmann, J., Demey, M., Coorevits, E., Dalla Bella, S., & Leman, M. (2015). Spontaneous entrainment of running cadence to music tempo. *Sports Medicine – Open*, *1*(1), 15.
van Gent, B. R., Siem, D. D., van Middelkoop, M., van Os, T. A., Bierma-Zeinstra, S. S., & Koes, B. B. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine*, *41*(8), 469–480.
von Holst, E. (1973). Relative coordination as a phenomenon and as a method of analysis of central nervous system function. In R. Martin (Ed.), *The collected papers of Erich von Holst, Vol. 1: The behavioral physiology of animal and man* (pp. 33–135). Coral Gables, FL: University of Miami Press.
Wang, T. (2015). A hypothesis on the biological origins and social evolution of music and dance. *Frontiers in Neuroscience*, *9*, 30.
Wood, C. M., & Kipp, K. (2014). Use of audio biofeedback to reduce tibial impact accelerations during running. *Journal of Biomechanics*, *47*(7), 1739–1741.
Yamashita, S., Iwai, K., Akimoto, T., Sugawara, J., & Kono, I. (2006). Effects of music during exercise on RPE, heart rate and the autonomic nervous system. *Journal of Sports Medicine and Physical Fitness* *46*(3), 425–430.