Biophysiologically synchronous computer generated music improves performance and reduces perceived effort in trail runners

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ABSTRACT
Music has previously been shown to be beneficial in improving runners performance in treadmill based experiments. This paper evaluates a generative music system, HEARTBEATS, designed to create biosignal synchronous music in real-time according to an individual athlete's heart-rate or cadence (steps per minute). The tempo, melody, and timbral features of the generated music are modulated according to biosensor input from each runner using a wearable Bluetooth sensor. We compare the relative performance of athletes listening to heart-rate and cadence synchronous music, across a randomized trial (*N*=57) on a trail course with 76ft of elevation. Participants were instructed to continue until perceived effort went beyond an 18 using the Borg rating of perceived exertion scale. We found that cadence-synchronous music improved performance and decreased perceived effort in male runners, and improved performance but not perceived effort in female runners, in comparison to heart-rate synchronous music. This work has implications for the future design and implementation of novel portable music systems and in music-assisted coaching.

Author Keywords
Algorithmic composition, biosynchronous music generation, running, physical activity, music mediated perceived effort, music perception

CCS Concepts
• **Human-centered computing → Human computer interaction (HCI) • HCI design and evaluation methods →** *Field studies*;

1. INTRODUCTION
Trail running is a growing sport which has become the focus of academic investigation in recent years [1-3]. The use of music for improving athletic performance has also been the subject of significant research, including findings that suggest:

- Music can mediate physical responses to pain [4]
- Musical cues (sonification of biomedical data) can encourage good form in strength and conditioning activities [5]
- Music may improve athletic performance, and reduce the perceived effort involved [6], [7]
- Appropriate music selection is not trivial [8], [9]

Existing work has shown that there is a neurological and physiological connection between emotional state, human performance, and music listening [10]. When listening to our favourite music, our bodies respond physically, inducing reactions such as pupil dilation, increased heart-rate, blood pressure, and skin conductivity [11]. Previous work has evaluated the role that music selection might play in mediating heart-rate and perceived exertion in running for 20 minute periods [7], in a treadmill condition [12], and in more recent studies investigating affectively-driven music selection on the basis of biosensing [13], whereby music selection is made according to a target heart-rate. A number of suggestions for optimal running cadence have been made (where cadence, or gait, is the number of full cycles per minute, i.e., by both feet) but these values are highly variable, dependent on individual stride length, technique, and other bio-mechanical factors [14]. Nevertheless, cadence selection has been shown to reduce running-related injuries and reduction of time taken to fatigue [15], [16]. Music selection has also been shown to enhance running performance, by encouraging optimal running cadence by means of music [17].

Music has also been suggested as a mediator of psychological and physiological discomfort whilst engaging in sport [18], [19]. Music can be used to increase motivation, or as a tool to help an athlete achieve a desirable mental state before partaking in sport, due to the ability of music to influence emotional states. For a full treatment of the use of music in enhancing athletic performance the interested reader is referred to a relatively recent survey in [20].

1.1 Music features and affective correlates
Previously, three specific aspects of music have widely reported as having a significant influence on athletic performance:

1. The tendency to synchronise movements with music (auditory-motor entrainment)
2. The tendency of music to distract an athlete from discomfort whilst participating in sport (dissociation)
3. The ability of music to increase emotional arousal

Certain musical features have been suggested as highly correlated to emotional and perceptual responses, including rhythmic responses whilst exercising [21]. Musical rhythm has been found to be influential in many cases, either by encouraging motor responses which are synchronous with the temporal characteristics of music (as occurs when people dance to music), or asynchronous effects [22]. Tempo, for example, can be used synchronously by matching the speed of a piece of music to the athlete's heart-rate [23], [24], or asynchronously by switching between slow and fast tempo in order to try and heighten the athlete's motivation and increase work output, with marked effects shown across a range of sports [25-27].

Music has been shown to be able to narrow focus and athlete's attention whilst exercising, diverting their attention from sensations such as fatigue [21], [28], as well as from other distractions such as environmental cues (for example bad weather, which is of particular

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concern in trail running, unlike treadmill evaluations). There is a psychological parallel to total immersion or flow [29], wherein the subject is so involved in the activity that other distractions are pushed out of their cognitive processes. These distractions might include - in the case of trail running - thoughts about competitors, or the runner's own technique, which would optimally become autonomic.

Music might also influence athletic performance by deliberately replicating bodily motion in the rhythmic features, or using positive or 'technique relevant' lyrics to reinforce skill development in the athlete [18]. However, there are also cases where skill development might be hindered by music, for example when music becomes distracting (particularly in early stages of skill development for an athlete).

Arousal as an affective correlate is a means of quantifying the activation strength of a particular emotional state. Sporting activities, particularly competitive activities, are very likely to cause an increase in arousal of both athletes and spectators. Music can be used to stimulate or attenuate arousal (e.g., to calm an athlete down before undertaking competitive activity), or to increase arousal when being performed synchronously with the activity [30]. Musical features which have a strong correlation with induced or perceived arousal include tempo (higher tempi are often correlated with higher arousal), mode (where minor keys are often associated with lower valence, and major keys with higher valence, or positive states), and rhythmic density (with less dense patterns being associated with decreased arousal) [31].

Both perceived amplitude and tempo of music have been previously evaluated in the context of improvement in running performance [6]; louder, faster music was found to influence a quicker running pace. Previous research investigating synchronous music to movement has found significant ergogenic influence on running shorter distances [32], with a marked increase in work output (faster sprint times) and in endurance capacity [21]. Asynchronous music has been shown to reduce the heart rate and perceived exertion (amongst other physiological measures) of the athlete during running [33], wherein participants exposed to asynchronous classical music exhibited decreased heart rate and blood pressure. Some more recent work suggests that asynchronous music was less motivating than synchronous music for treadmill running [34]. Beyond running specific evaluations, asynchronous music was suggested to have a greater degree of influence on valence [22], [35]. Some research suggests that synchronous music has a greater influence on mood [36], promotes greater endurance [37], and may further reduce limbed discomfort and increase arousal level [21]. There is also increasing evidence of correlation between athletic endurance and levels of valence [38].

2. AIMS

Across the growing body of work outlined above, little work exists considering the influence of real-world environment (i.e., outdoor running), the use of biophysiologically synchronous generated music, or the relative performance between heart-rate and cadence synchronous music. Music generation by algorithmic means is not novel: A huge variety of music generation systems exist, with perhaps the earliest example being Mozart's Musikalisches Würfelspiel, the 'dice game', which uses the roll of a dice as a control signal to inform the selection of pre-composed musical segments. Algorithmic composition systems also include transformative systems, wherein source musical passages are adjusted according to various functions (transposition, retrograde inversions, etc), and purely generative systems, whereby rulesets and constraints are used to modulate otherwise randomly generated source material. The latter approach is particularly well suited to data-driven approaches using machine learning. Using any of these approaches for algorithmic composition has the advantage over 'traditional' music selection in facilitating continuous music playback (hence no pauses between song selections), and the ability to be precisely synchronous with the given heart-rate or running cadence. Matching optimal cadence (between 150-180 steps per minute) is also challenging for traditional music selection – there are not vast quantities of existing music at 180bpm - but producing music at these tempos is possible with careful selection of generative parameters.

Does cadence or heart-rate synchronous algorithmically generated music improve athletic performance, or reduce perceived exertion in trail runners?

HEARTBEATS is a system developed to track runner's cadence and/or heartbeat to stimulate optimal running. It makes use of generative music production techniques, as described in [39], to create new music according to a second order Markov model specifying rhythmic and melodic musical feature generation in real-time with varying degrees of repetition. Repetition can create a range of emotional responses in listeners [40]. Music is generated at a synchronous pace for the athlete based on either their heart-rate or cadence whilst running. Latency is minimal but transformations occur at bar breaks, which gives the impression of being instantaneous at all but very slow tempo values. This system, as shown in Figure 1, was then subjected to an evaluation in a real-world trail running context.

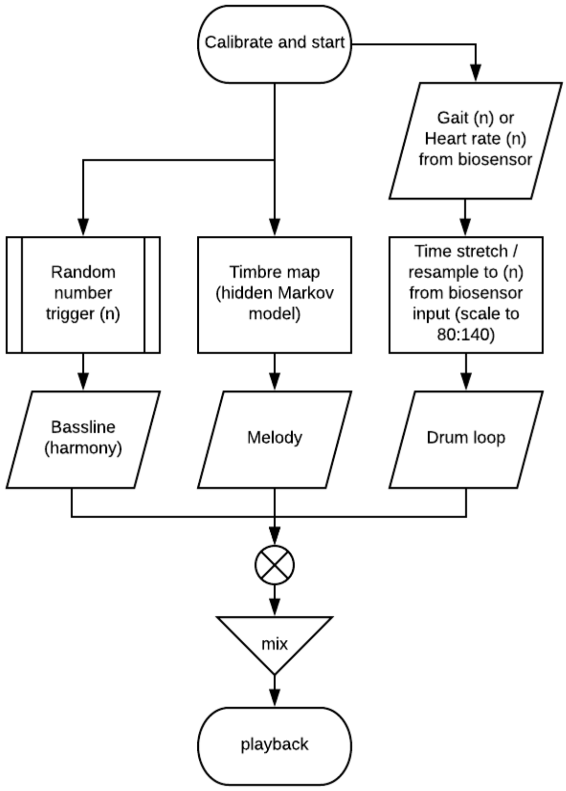

Figure 1. The tempo, melody, and timbral features of the generated music are modulated according to biosensor input from each runner using a wearable Bluetooth sensor. Timbre map is created by training a second order hidden Markov model on a source musical excerpt. See also a video of the system in use at https://youtu.be/ZwC3zcJ5tkY

3. METHOD

HEARTBEATS is a generative music system which can create synchronous music in real-time from an individual according to heart-rate and accelerometer information via a wearable Bluetooth sensor. The rhythmic, melodic, and timbral features of the generated music are modulated according to a combination of biosensor input for tempo and metrical data, and random number selection of a series of prescribed musical feature mappings based on the features described above. Source sound files from a preselected pool are combined, and may also be resampled, time-stretched, or pitch shifted, according to the desired cadence or heart-rate.

HEARTBEATS was tested by a group of volunteers from a trail running club. Volunteers were recruited via the club social secretary as part of a series of social runs - volunteers were not screened according to ability or experience. The runners were self-timed on a course segment with 76ft of elevation including a steep section with a 26% grade, as shown in Figure 2. The course segment was chosen to be representative of a variety of trail race conditions, including fell and mountain racing, and trials were conducted over a weeklong period in December 2017, with runners submitting their results via the Strava social networking tool. Participants were instructed to continue until perceived effort went beyond an 18 on the Borg scale from 6-20, with 6 being no exertion at all, and 20 corresponding to maximal exertion. Participants did not need prior experience of the scale as full instructions on the use of the scale were provided in a short training session. Of the 57 trials returned, 29 were carried out with cadence synchronous music, and 28 with heart-rate synchronous music. The music condition was assigned randomly.

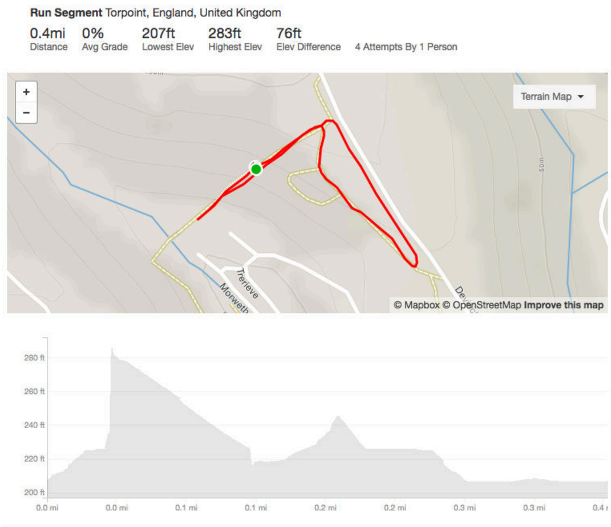

Figure 2. Course and elevation profile. Note section with steep grade.

RESULTS AND DISCUSSION

Metrics for distance, duration, and pace were considered in the heart-rate and cadence synchronous conditions, including within gender variation. Box-plots for the pace-per-mile across both conditions and genders are shown in Figure 3.

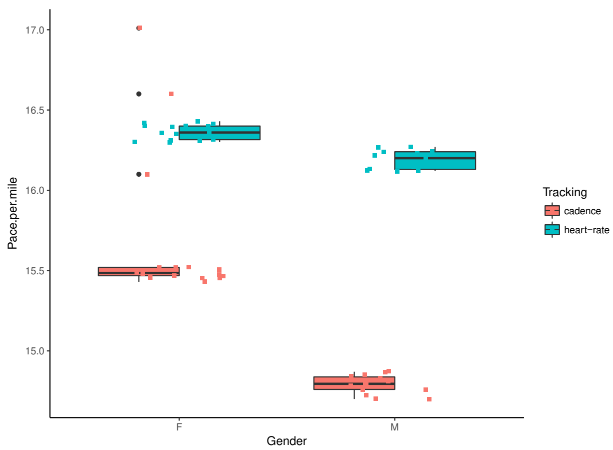

Figure 3. Box plots showing distribution of pace results in both music conditions. Although the data was not checked for normal distribution, homogenous variances can be seen.

A summary of participant results including, pace, and distance is shown in Table 1. In the cadence synchronous condition, average run duration decreased from 37.11 minutes to 35.29 minutes, while the average pace increased from 16.27 to 15.20 (an improvement of 1.07 or ~6.5%), and the distance increased from 2.26 to 2.33 (an improvement of 0.07m or ~3%).

Table 1. Summary of cadence and heart-rate synchronous conditions across all participants, and for male and female participants in heart-rate synchronous (HR Male, HR Female) and cadence synchronous (C Male, C Female) conditions. Values rounded up to 2 decimal places.

	Number of participants	**Run duration Mean / SD**	**Pace per mile Mean / SD**	**Distance (miles) Mean / SD**
HR synchronous (Male and Female)	28	40.59 / 10.59	16.28 / 0.10	2.22 / 0.98
HR Male	14	30.44 / 1.72	16.22 / 0.06	1.55 / 1.11
HR Female	14	49.56 / 5.28	16.36 / 0.05	2.81 / 0.11
C synchronous (Male and Female)	29	35.53 / 6.88	15.27 / 0.57	2.39 / 0.92
C Male	14	40.58 / 1.64	14.79 / 0.06	2.89 / 0.98
C Female	15	31.13 / 6.39	15.68 / 0.47	1.95 / 0.62

This suggested that runners in the cadence synchronous music condition ran further, faster, in less time that runners in the heart-rate synchronous condition. However, a two-way ANOVA showed that the effect of gender and music condition was highly significant on pace, but not on the total distance achieved by participants, as shown in Tables 2, 3, and 4. A box-plot showing the distribution of effect across gender and both music conditions on duration of run is shown in Figure 4.

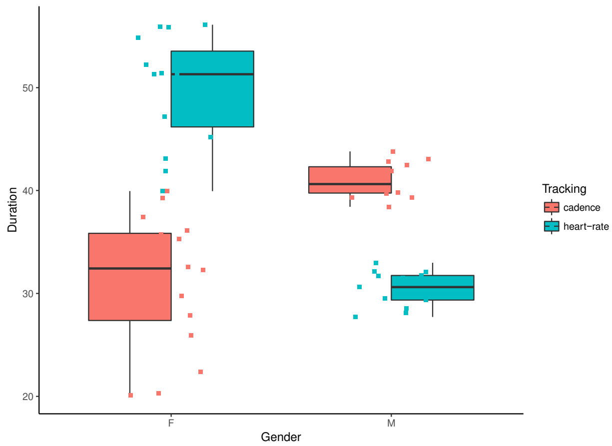

Figure 3. Box plots showing distribution of duration results in both music conditions.

Table 2. Two-way ANOVA showing effect on distance, non-significant

Distance Df	Sum	Sq	Mean Sq	F value	Pr(>F)
Gender	1	0.23	0.2334	0.254	0.616
Tracking	1	0.39	0.3943	0.429	0.515
Residuals	55	50.50	0.9182		

Table 3. Two-way ANOVA showing effect on duration, significant

Duration Df	Sum	Sq	Mean Sq	F value	Pr(>F)
Gender	1	260	259.8	3.452	0.0685
Tracking	1	369	369.3	4.907	0.0309
Residuals	55	4139	75.3		

Table 4. Two-way ANOVA showing effect on pace, highly significant

Pace Df	Sum	Sq	Mean Sq	F value	Pr(>F)
Gender	1	4.323	4.323	44.76	1.21e-08
Tracking	1	14.930	14.930	154.60	<2e-16
Residuals	55	5.311	0.097		

4.1 Gender specific variation

Some inter-gender variation can be seen in Table 1, which suggests that male runners in the cadence synchronous condition ran not only faster (14.79 down from 16.22) and further (2.89 miles up from 1.55 miles) but for a longer duration until they reached the perceived effort threshold (40.58 minutes instead of 30.44 minutes). This effect is not shown in female runners in the cadence synchronous music condition, which still showed an increased pace (from 16.36 to 15.68) but a reduced duration and, hence a reduced overall distance (from 2.81 miles down to 1.95).

The standard deviation across duration in females in both the conditions was large, especially in the cadence synchronous condition. Individual participant data was examined. Three of the twenty-nine female participants, all using cadence synchronous music, provided data which might be considered outliers – running for, on average, only 20.11 minutes at a pace of 16.52 for a distance of 1.2 miles, all below the mean average values. Data collected from individual runners was anonymised so examining other factors (e.g., runners previous history, etc) was not possible, but the three runs in question took place on 20th December 2017 – not all the runs took part on the same date. The historic weather report for the region on this date showed a higher than average West-South-Westerly wind (>10mph) and thunderstorms in the area. This might have contributed to the duration and subsequent distance in this group of data, especially as parts of the course segment are at a significant elevation compared to the surrounding area, and therefore are relatively exposed to wind. Equally, these participants may not have enjoyed the generated music - the current system makes no attempt to accommodate individual musical preferences. Data on individual musical preferences was not collected from participants in this study, however in future work the use of the Short Test of Musical Preferences questionnaire [41] prior to participation would allow for further analysis according to musical preference when evaluating this type of system.

4.2 Cross domain applications (music and performance)

A large body of work documenting improved athletic performance in response to music exists. Previous work specifically documenting running has included synchronous and asynchronous music. The growing field of affectively driven algorithmic composition has been adapted to the task of musical stimulus generation to create biophysiologically synchronous music, specifically heart-rate and cadence, in order to evaluate the effect of such a system on perceived effort and work output.

The results suggest that cadence synchronous music was most beneficial for athletic performance. Both male and female athletes ran faster in the cadence synchronous music condition. Male athletes took longer to reach the perceived effort threshold in the cadence synchronous music condition, than the heart-rate synchronous music condition, though this was not the case for female athletes. This study only investigated one iteration of the music generator, but a number of other musical features could be incorporated in a more advanced system, for example individual musical preferences. There remains a significant amount of work in the specific tailoring of the generator to listeners' own musical preferences, and particular state requirements (motivating in the pre-exercise state, or recovering post-exercise). Moreover, due to the wide range of tempi required by the generator in this trial (typically varying from 86-150 bpm), it is likely that this system would not be appropriate for certain activities, for example, highly anaerobic activity with heart rates that would be beyond tempo ranges that might typically be considered musical. This is similar to the problem of an optimal cadence at 150-180 rpm, and might be solved by considering different metric levels in the generation of musical material (for example the use of 12/8 time, so that strong beats do not have to fall solely on the first beat of the bar, allowing for divisions of the target cadence).

Generative music technology has the potential to produce infinite soundtracks in sympathy with an athlete's biosignals: this need not be restricted to the extracted biosignal value of the athlete and, in future, trials with target tempi could be conducted, i.e., encouraging the runner to move at a specific goal speed, rather than following the runner's speed. For example, to generate music with optimal tempo as a function of current heart-rate or cadence, and optimal heart-rate or cadence, depending on the stage of training (warm-up, main training, cool-down, or particular heart-rate target zones depending on the athlete's goal). This suggests the very real possibility of 'smart music coaching' systems, according to heart-rate (for example, in maximal fat burning) or cadence (in injury treatment or seeking maximal athletic performance).

5. CONCLUSIONS

An algorithmic music generator able to produce continuous music at a variable tempo according to an input derived from portable biosensor was evaluated in a real-world context using a group of trail runners. Cadence synchronous music improved running performance in male subjects (who ran further and faster). Cadence synchronous music partially improved running performance in female subjects (who ran faster but not further). Time taken to reach maximal perceived effort was sustained in male subjects in the cadence synchronous music condition but not in female subjects.

6. ETHICAL STANDARDS

Participants gave informed consent according to ethical approval from the Physical Sciences committee of the host institution. Participant data was stored anonymously.

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