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Real-Time Heart Rate Sonification Using Spectral Filtering of Preferred Music for Running Training

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ABSTRACT

The purpose of this study was to evaluate a sonification system that maps live heart rate data to real-time spectral filtering of a runner's preferred music. Assessed using a within-subjects design (n = 13), the system employs high-pass and low-pass filters to indicate deviations from target heart rate zones, providing instantaneous biofeedback without requiring visual attention. Quantitative analysis revealed no statistically significant differences in target zone accuracy or response time between auditory, visual, and combined conditions. However, qualitative thematic analysis identified a clear division in user preference. Participants favoring the auditory condition demonstrated faster mean response times to audio biofeedback. Findings suggest that while sonification promotes environmental focus and "gamifies" training, its efficacy is highly dependent on individual processing styles and music familiarity.

1 Introduction

Sonification is the transformation of data into an auditory domain, a process with extensive scientific use cases across healthcare, entertainment, and education [1]. By leveraging precise human auditory processing capabilities such as pattern recognition and "parallel listening," sonification allows for the effective processing of information as an alternative to visual displays [2]. This approach is particularly advantageous in sporting environments where athletes benefit from the instantaneous and non-invasive delivery of performance data without diverting focus from their surroundings.

Despite these advantages, sonification has not yet achieved the widespread adoption of visual displays, partly due to a lack of standardised mapping guidelines or systematic evaluation methods. Physical dimensions may be mapped onto auditory dimensions in numerous combinations, and while certain "intuitive" mapping pairings (e.g., spatial audio for kinematic parameters) are more frequently employed, evidence highlights that these designs may not be universally agreed upon, particularly when they rely on visual associations [3].

Research [4] demonstrates that music can promote ergogenic (performance-enhancing) and psychological benefits during aerobic and anaerobic exercise. Self-selected or "preferred" music is particularly effective, acting as a dissociative tool that narrows attentional focus and diverts the mind from sensations of fatigue [5]. This effect can result in a significant reduction in perceived exertion during moderate-intensity treadmill running. Music serves as a distraction, mitigating the perception of negative sensations like fatigue and exertion [6]. Consequently, allowing athletes to use their own

music can promote better performance metrics and motivation. [7]

One athletic metric ideally suited for both sonification and performance evaluation is heart rate (HR) [8]. HR provides an objective, personalised measurement of training intensity that accounts for environmental factors as well as personal factors, such as fatigue and stress. As an involuntary function of the autonomic nervous system, HR cannot be directly manipulated; instead, athletes must adjust their pace and intensity to maintain a desired range. HR Zone Training is a technique used to monitor and control effort expenditure and is a standard indicator for athletic performance evaluation. Zones are calculated as a percentage of a runner's Maximum Heart Rate (MHR), MHR = 220 – age [9]. Each zone represents a specific level of intensity, allowing athletes to optimise effort across a workout [10]. For experimental purposes, this structure ensures participants exert a similar relative level of effort.

While HR data is temporal and therefore well-suited for sonification, it is typically presented visually on sports watches or smartphones. Existing audio feedback applications often rely on vocal prompts, which require significant cognitive processing and can only deliver data discretely (e.g., at set distance markers) rather than continuously. This lack of continuity prevents athletes from receiving an indication of the degree of effort required to reach the next target in real-time [11]. Continuous sonification resolves these issues, enabling athletes to monitor physiological metrics without diverting attention from their immediate surroundings. Research into Auditory Progress Bars (APB) provides a framework for addressing this method of communication; an effective auditory "thermometer" should indicate the scope (overall size and timescale), progression rate, and clear initiation/termination of a task [12]. APBs enable users to process information without detriment to a separate primary task. Existing APB research also presents useful guidance for establishing appropriate approaches to sonification mapping scaling and polarity. For example, [13] comparative study demonstrated successful estimation of waiting times using variation in segmented tone pitch and duration as stimuli.

A notable limitation identified in previous studies is the tolerance of the listener for the selected sonification stimuli. Consistently low subjective ratings indicate that sounds used were deemed annoying or unpleasant to listen to and are therefore unsuitable for a system designed for extended use. For such applications, stimuli must not only communicate sufficient temporal information but must also prove appropriate for extended listening. The findings of the present study provide a sonification system which evaluates the appropriateness of mapping between real-time HR data and listener feedback, and the efficacy of such a system in a real-world training context for running performance.

2 Method

The HR sonification system was designed and programmed in Max/MSP to apply filtering to real-time music playback. The system received live HR data from an H10 Heart Rate Monitor via Bluetooth (Polar Electro, Kempele, Finland). Using scaled low and high-pass filters, the system altered the frequency content of users' music in accordance with deviations from specified target HR zones.

2.1 DSP design choices

A preliminary testing phase was conducted to inform and calibrate the sonification system design, determining which configurations provided the most effective and intuitive solutions. This exploratory phase involved four volunteer participants and informed necessary adaptations to the workout structure and filtering scales.

A filter-based processing system where spectral filtering was applied to the participants' choice of music was employed to provide real-time auditory biofeedback. To achieve effective and intuitive communication, the filtering model incorporated assets of both pitch- and loudness-based mapping techniques as the two most frequently occurring auditory dimensions across existing sonification mapping strategies [3]. Studies corresponding pitch with kinematic and kinetic dimensions such as velocity, distance, and force informed the initial design considerations of the sonification model, with particular regard to scale polarity where a higher frequency has typically represented an increased value in the above parameters. In accordance with Landry et al. (2016), a prescriptive (rather than descriptive) model was employed, indicating the athlete's required HR in accordance with predetermined target zones.

- **Below Target Zone:** A high-pass filter was applied, signalling a requirement to increase HR.
- **Above Target Zone:** A low-pass filter was applied, signalling a requirement for HR decline.
- **Within Target Zone:** The music continued to play unaffected, allowing the athlete to hear the full frequency content.

To ensure perceptually linear control over the filter movement, HR values were mapped to cut-off frequency using a linear scaling curve with an exponent value of 1.06, resulting in a reduction in frequency content corresponding to magnitude of error. Based on preliminary testing, the low-pass filter (LPF) scale was set from 80 Hz to 800 Hz, while the high-pass filter ranged from 750 Hz to 6000 Hz. For both filters, a Q of 0.7 was used. This broader bandwidth creates a gradual curve, preventing the unnatural "whistling" effect or resonance peaks that were observed with higher Q values in early iterations. These conditions featured a 3-octave cut-off frequency range which created a subtle but audible "jump" in frequency content when heart rate transitioned outside of the target zone.

The filter sweeping model affected participants' preferred music while satisfying criteria including being continuous, intuitive, and tolerable (Section 1). With music quality diminishing as a result of significant filtering, audible effects were introduced only when HR deviated from a target zone, thus preventing listening fatigue from prolonged exposure to the stimuli and encouraging participants to maintain the correct HR in order to experience music in its unaffected state.

In addition to reserving unpleasant stimuli as an indicator of error, the model also utilised the loudness bias effect observed in subjective evaluation of audio quality wherein louder stimuli are subconsciously associated with greater quality [14]. The greater the deviation from the target zone, the greater the number of frequencies attenuated by the filter, resulting in an overall reduction in amplitude corresponding to the magnitude of error. Music was therefore loudest when participants were responding correctly to the feedback, providing further motivation to adhere to the target zone and receive music at a greater perceived quality as a result.

Due to the non-linear sensitivity of the human ear across the frequency spectrum, a standard low-pass filter often results in a perceptually quieter sound than a high-pass filter with equivalent attenuation. To account for this perceptual difference, the model incorporated equal-loudness compensation based on the ISO 226:2023 standard. An additional scale of up to +6 dB of gain was automatically applied to the overall output level during LPF modulation. This adjustment balanced the perceived loudness between the two filter states, ensuring that the guidance signal remained clear and consistent regardless of the direction of the HR deviation. This gain compensation allowed users to focus on the frequency content changes (the instruction) rather than unintended fluctuations in volume.

2.2 Participant information

A total of 13 volunteers took part in the primary experiment. Participants were moderately to highly active runners aged between 19 and 61 (M=32, SD=12) and were 77% male. Based on self-reported training history, participants were classified between Tier 1 (Recreationally Active) and Tier 2 (Trained/Developmental) according to the Participant Classification Framework by McKay et al, [15]. This range reflects a cohort that varies from health-motivated joggers to those engaged in structured, sport-specific running training. All participants were pre-screened using a Physical Activity Readiness Questionnaire (PAR-Q) to ensure suitability for participation.

2.3 Environment

Testing took place in a controlled Exercise Physiology Laboratory using a Woodway 4Front Pro XL motorised treadmill (Waukesha, WI, USA). All participants completed a 9-minute interval-style workout three times, with each trial corresponding to a different feedback condition (audio, visual, combined). In the audio condition, participants used Beyerdynamic DT 770 Pro closed-back headphones to receive real-time playback (or filtered playback) of their preferred music. These headphones have the advantage of partially masking the treadmill motor noise. For the visual condition, a computer monitor positioned at a 45-degree angle displayed red and green screens with plus (+), minus (-), or equals (=) symbols to indicate HR instructions. Participants continued to listen to unaffected music during visual trials to maintain a constant auditory environment. The angle of the monitor was chosen to replicate the cognitive and physical effort of checking a sports watch or smartphone during exercise. It required participants to actively turn their heads to receive HR

instructions, mirroring the "glance" behaviour common in mobile fitness tracking. Additionally, all standard treadmill performance metrics (speed, distance, time) were hidden from the participants, who were also instructed not to use their own fitness trackers. This arrangement forced total reliance on the auditory or visual guidance systems under test. In the combined condition, participants received both the visual display and audio feedback simultaneously. To mitigate the effects of order, learning, and physical fatigue, the sequence of the three conditions was randomised for each participant.

2.4 Max implementation

The real-time data processing pipeline was managed entirely within Max/MSP. HR data was transmitted wirelessly from the Polar H10 via Bluetooth, with HR values isolated from the incoming data stream and routed into the mapping engine. Biometric data were synchronised and recorded at precise one-second intervals with incoming beats per minute (bpm) values stored against a time-axis to generate a real-time table of performance data. A secondary counter recorded total "Time in Zone" by comparing the live bpm stream against the participant's pre-calculated target boundaries. At the conclusion of each 9-minute trial, the accumulated data was exported directly as a CSV file for analysis. The system's automation ensured that zone detection, music filtering, and data recording occurred without researcher intervention, standardising the procedure across all participants. A block diagram of the signal flow is shown in Figure 1.

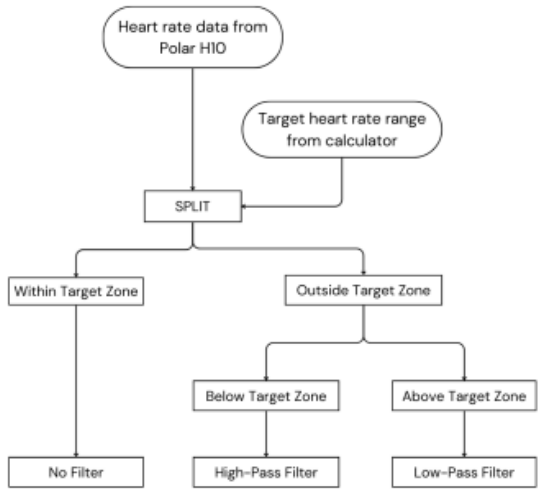


Figure 1. Signal flow block diagram showing HR data branching into HPF, LPF, and No Filter states

2.5 Workout structure

The 9-minute workout was designed to enable evaluation of the system across various levels of zone intensity and transitions. The workout began with 2 minutes in Zone 2 (60–70% MHR), followed by 1 minute in Zone 3 (70–80% MHR) and 1 minute in Zone 4 (80–90% MHR). The intensity then decreased for 2 minutes back in Zone 2 (60–70% MHR), before rising again for 1 minute in Zone 4 (80–90% MHR), 1 minute in Zone 3 (70–80% MHR), and a final minute in Zone 2 (60–70% MHR)..

Target zones were calculated as percentages of each participant's estimated max HR, using the formula of 220 minus the participant's age [16]. Quantitative data, including response time and total time spent within the target zone were recorded at one-second intervals via Max/MSP. Following each trial, qualitative data were gathered through semi-structured interviews to gain insight into the participant's experience with each system.

3 Results

A thematic analysis of the 52 semi-structured interviews identified several trends regarding the participants' experience with the sonification system. The most frequently cited advantage was the ability to focus on the experience of running. Participants felt the audio system removed the need to check visual displays, allowing them to pay more attention to their form, breathing, and surroundings. Many compared the experience to a game, noting that the restoration of music quality provided an "enjoyable" incentive to adhere to the workout guidance. Furthermore, the sonification system was described as intuitive; the scale of the audio filtering helped users gauge their distance from the target heart rate zone. A recurring theme was the system's ability to reduce visual cognitive burden.

Participants reported that the auditory feedback permitted a more "natural" focus on their physiological state: "I felt like I could focus a lot more on my running. So, I could think more about my form, pay more attention to my breathing". One participant stated that they found the audio system far superior to existing text-to-speech prompts: "I'd take that ten times over because there's nothing more annoying to me than being right at the end of a speed run and being

told 30 more seconds... let me just listen to my music".

Confusion stemming from the system design was a common drawback. The reduction in volume at extreme ends of the filtering scale occasionally led to uncertainty, with participants recognising a change in HR was required but struggling to identify the indicated direction. The efficacy of spectral filtering was found to be highly dependent on the "spectral profile" of the selected music. Additionally, certain musical genres, particularly "trebly" tracks or those already featuring heavy filtering in the music itself (as is common in dance music), mimicked the sonification response and led to further confusion: "When Blondie first started playing, I wasn't sure if the high pass was on it or not, because it's quite a trebly track". For some, the heavy filtering was perceived as an annoying interruption that diminished the enjoyment of the track over time: "I want to listen to my music... clearly. So, when it goes muffly for a long period of time, it's slightly less enjoyable".

Some feedback indicated an improvement with practice as participants developed an understanding of the system's logic. In the combined condition, the visual display was primarily used for confirmation or "re-calibration" if the participant became lost. However, some users found the combination of cues distracting, feeling as though the two conditions counteracted one another.

One-way repeated measures ANOVAs were conducted to evaluate performance across the three conditions, visual, audio, and combined, shown in Table 1. Although the one-way repeated measures ANOVA did not reach statistical significance, post-hoc pairwise comparisons with Bonferroni corrections were conducted to evaluate the magnitude of differences between conditions. Effect sizes were calculated using Hedge's *g* to account for the small sample size. These comparisons revealed trivial-to-moderate differences across trials, with effect sizes ranging from $g = 0.14$ to 0.59. Notably, the faster response time in the audio condition (M = 34.37 s, SD = 12.68 s) compared to the visual condition (M = 36.37 s, SD = 15.32 s) presented a moderate effect size.

Measurement	Condition	Mean ± SD	*p*	Hedge's *g (vs. Visual)*
Time in Zone (Proportion)	Visual	0.50 ± 0.09	$p = 0.827$	
	Audio	0.44 ± 0.11		
	Combined	0.48 ± 0.10		
Response Time (S)	Visual	36.37 ± 15.32	$p = 0.195$	
	Audio	34.37 ± 12.68		0.59 (Moderate)
	Combined	34.84 ± 17.52		
	Condition	Mean Value	Statistical Significance (p)	

Table 1. Descriptive and ANOVA results between conditions.

Time in Zone represents the total decimal proportion - which can be interpreted as a percentage (e.g., 0.50 = 50%) - of the 540-second workout that participants spent within target boundaries. Response Time indicates the mean number of seconds participants took to return their heart rate to the target zone after exceeding a limit; thus, a lower value represents a more efficient response.

No statistically significant differences were observed in time spent within the target zone across the three systems, $F(2, 24) = 0.19$, $p = 0.827$, $\eta^2_p = 0.02$. However, the visual condition presented the highest mean, while the audio condition presented the lowest.

Some participants demonstrated a paradox between their subjective self-report and their objective performance data. Participant P6, shown in Figure 2, explicitly stated a dislike for the audio system, claiming they "struggled to hear anything" and found the visual condition significantly easier to follow. Despite this perceived difficulty, the participant's Time in Zone was higher in the Audio condition (65.37%) than in the Visual condition (60.19%).

Participant P7 was identified as a significant outlier within the audio condition, recording a mean response time of 89 seconds—nearly double the cohort average. During demographic screening, P7 was the only participant to report a hearing impairment (tinnitus). The high response time suggests a difficulty in perceiving the spectral changes, corroborated by their performance in the

visual condition which was within the normal range. To preserve the statistical power of the small sample size and maintain the within-subjects comparison across all conditions, Participant P7's Response Time in the audio condition was Winsorized. Their value was modified from 89.00s to 51.76s (calculated as the next highest value plus an epsilon of 0.01s). This technique is a recognised method for attenuating the influence of outliers while preserving the participant's relative rank within the dataset. This approach was deemed more appropriate than exclusion because P7 demonstrated typical performance in the Visual and Combined conditions, suggesting that their participation provided valid baseline data for the study's primary comparisons.

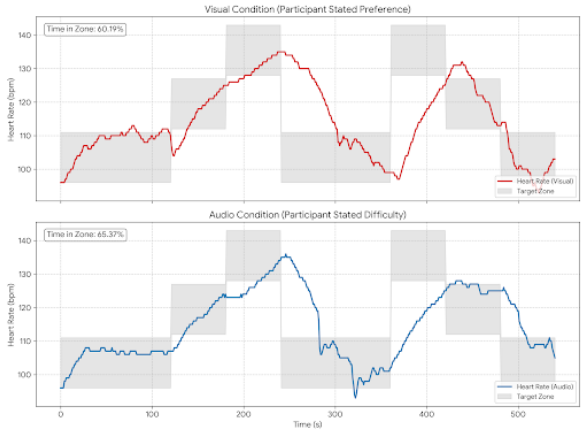


Figure 2: Participant paradox. Top row: Visual condition where the participant felt most comfortable. Bottom row: Audio condition which the participant reported as frustrating, yet where they achieved higher accuracy in maintaining the target heart rate.

No statistically significant differences were observed in time spent within the target zone across the three systems, $F(2, 24) = 0.19$, $p = 0.827$, $\eta^2_p = 0.02$. However, the audio condition presented the fastest mean response time, followed by the combined and visual conditions. While the primary ANOVA revealed no statistically significant, the raw performance metrics indicate a slight speed advantage for the auditory domain.

The faster response time in the audio condition (34.37 s) compared to the visual control (36.37 s) supports the hypothesis that auditory cues can trigger faster physiological adjustments, even if total Time in Zone is lower due to the "binary" clarity of a red/green screen.

Finally, to evaluate the impact of enjoyment on performance, participants were split into two groups based on their stated preference. While independent samples t-test results were not statistically significant ($p = 0.738$ for audio, 0.429 for visual), participants who preferred the audio system demonstrated a faster response time (2.23 ± 6.48 s) for the audio condition than those who did not, and were slower (7.1 ± 8.64 s) to respond to visual cues than the "Preferred Other" group.

4 Discussion

The most evident finding emerging from both the quantitative and qualitative analysis was that response to the sonification was notably divided. While the quantitative data did not provide statistically significant evidence to identify meaningful differences in response time or total time spent in zone between the audio, visual, and combined systems, the results observed a faster mean response time for the audio condition compared to the visual condition. This finding is consistent with previous literature positing that auditory reaction time is faster than visual reaction time [11].

Analysis of response time by preference revealed that participants who described audio as their preferred condition achieved a faster mean response time in the audio condition than in either the visual or combined conditions. It may therefore be the case that a sonification system of this nature would likely be most effective for individuals who display a propensity for auditory communication.

One element observed was the impact of practice and training on the efficacy of the sonification system. Participants demonstrated progression in their response as exposure to the system increased. This is likely due to the lack of standardised guidelines for sonification mapping; for each instance, participants must learn new associations specific to that system. Furthermore, familiarity with the music proved extremely advantageous. Comparing data from both the preliminary and primary experiments showed that heart rate adhered far more closely to target ranges for participants whose preferred music was selected. Familiarity allowed users to more easily recognise subtle variations in frequency content against the original track.

The audio filtering model was scaled to become more pronounced as deviation from target HR (magnitude of error) increased. Qualitative feedback pertaining to

the system design revealed that this scaling was fundamental to the intuitiveness, enjoyability, and overall usability of the sonification system, demonstrating effective communication of task scope and status in accordance with existing APB approaches.

The most frequently reported justification for enjoyment of the audio system was its ability to allow participants to focus on their running. By passively receiving aural data, participants could pay more attention to factors such as form, breathing, and surroundings without distraction. Maintaining focus on running mechanics and postural alignment is critical for injury risk reduction [4] as it allows runners to monitor for fatigue-induced technical breakdown that often leads to overuse injuries.

4.1 Limitations

Participants selected their preferred music volume prior to the workout, which did not account for the additional broadband noise generated by the treadmill motor. While this effect was mitigated by using closed-back headphones, auditory masking at certain frequencies remains a potential confounding variable. Furthermore, the psychoacoustic effect of equal-loudness contours is more pronounced at lower decibel levels. Participants who selected a lower initial volume reported greater difficulty differentiating between the extreme variances of the filtering scale, suggesting that future iterations should incorporate automated loudness normalisation. Additionally, while studio headphones supported detection of subtle auditory cues, their use may compromise external validity of the results as runners are unlikely to use such headphones in their regular training. In fact, many runners use open-ear headphones which typically present a noticeable reduction in low-frequency response in exchange for increased situational awareness. Similarly, the controlled conditions of the exercise laboratory permitted accurate and consistent evaluation but are not representative of outdoor conditions where background noise is not only more prevalent but often a necessary safety precaution.By allowing participants to select their own music, the study lost control over tempo and dynamic range variables. Variation in tempo likely influenced participant cadence through subconscious entrainment, potentially interfering with the required HR adjustments. Additionally, the frequency content of certain genres (e.g., dance music with existing heavy filtering) mimicked the sonification response, leading to participant uncertainty. Notably, some participants found the filtering annoying, stating that while the system was fun initially, the heavy modulation might become frustrating over extended periods. Discrepancies were also noted where a participant's assessment of a system did not always correspond with their quantitative performance.

5 Conclusions

The findings from this study successfully establish a sonification mapping technique that allows users to interpret real-time HR data as consistently as with a standard visual display. By scaling HR values to the cut-off frequencies of low-pass and high-pass filters, the system provided an intuitive mechanism for runners to adjust their intensity. The results corroborate existing literature suggesting that auditory parameters, such as pitch and loudness, can be effectively mapped onto biometric measurements and abstract concepts like magnitude of error. Qualitative responses highlighted a clear division in preference, with participants demonstrating distinct leanings toward either visual or auditory feedback. These preferences were verified by corresponding variances in performance data, where those who preferred the audio condition exhibited faster mean response times. However, as the quantitative results were not statistically significant, these conclusions must be interpreted with caution.

Although HR was measured as a primary response variable, as part of the automatic nervous system (ANS) it is an involuntary physiological function which is innately delayed from direct efforts of control or manipulation. Accordingly, participants were observed responding to feedback (e.g., altering treadmill speed controls) before a noticeable change in HR occurred as a result. Further study could implement more direct measures of response time or perceptual thresholds to mitigate effects of variation in HR delay between participants and provide greater insight into cognitive responses to the auditory feedback.

Future work should also investigate the impact of different headphone types and consider methods of audio personalisation to account for variation in listener preference and anatomy (e.g., using HRTFs). Additionally, future research should address the "spectral profile" of different music types to develop

filtering approaches that remain robust regardless of the track's genre or frequency content.

Sonification offers promising solutions for the development of training tools for blind and visually impaired individuals. Further research is required to ensure that mapping approaches are intuitive for users for whom visual input has not influenced their cognitive frame of reference.

Ultimately, while visual displays remain a reliable standard, the findings from this study demonstrate that continuous sonification of preferred music is a functional and enjoyable alternative that enhances environmental focus for athletes.

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