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Research article

Music Timing Differentiates Fatigue Perception and Performance during Isometric Strength Exercises: A Crossover Randomised Trial

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Abstract
Music is well-known to elicit ergogenic effects on exercise performance; however, the moderating role of application timing remains unclear. This study examined the effects of the timing of music on fatigue perception and performance during isometric strength exercises. Using a within-subject, randomised crossover design, twelve recreationally active young adults performed two isometric strength tasks (plank-hold and wall-sit) in three separate conditions (MEE: music played during the entire exercise task; MDF: music played during fatigue alone; CON: no music). The total time to volitional exhaustion (TTE), time to the onset of fatigue perception (TFP), heart rate, and blood lactate responses were assessed during each trial. MEE resulted in a significantly longer TTE than CON in both the plank-hold ($p < 0.05$, $d = 0.76$) and wall-sit exercises ($p < 0.05$, $d = 0.72$), whereas MDF led to a significantly longer TTE than CON in wall-sit exercises alone ($p < 0.05$, $d = 0.60$). TFP was significantly longer in MEE than in CON in both the plank-hold ($p < 0.05$, $d = 0.54$) and wall-sit exercises ($p < 0.05$, $d = 0.64$). The music condition did not influence the heart rate or blood lactate changes in any of the trials. Our results suggest that listening to music during the entire exercise can delay the onset of fatigue perception in isometric strength tasks, whereas listening to music during fatigue has only a modest effect. Athletes and exercisers should consider extending music exposure throughout the entire exercise task to maximise performance benefits.

Key words: Music, exercise, fatigue, performance, strength exercise, isometric.

Introduction

Music can significantly impact exercise and sports performance (Greco et al., 2022; Karageorghis and Priest, 2012; Terry et al., 2020). It promotes psychological (e.g., more positive affect valence), physiological (e.g., reduced oxygen consumption), psychophysical (e.g., reduced perceived effort), and physical performance benefits (Greco et al., 2022; Terry et al., 2020) by modifying the interplay between the central motor drive, central cardiovascular command, and perceived exertion (Karageorghis and Priest, 2012). Specifically, music can divert exercisers' attention from discomfort and fatigue typically associated with physical exertion (Karageorghis and Priest, 2012). Several musical characteristics, including tempi, rhythm, synchronicity with activity, motivational qualities, lyrics, and loudness, have been associated with ergogenic effects on performance (Karageorghis and Priest, 2012; Terry et al., 2020). For instance, listening to loud music at a fast tempo enhances cardiorespiratory responses, leading to improved treadmill running performance (Edworthy and Waring, 2006). Incorporating preferred music during high-intensity continuous cycling also increases exercise distance and lowers perceived discomfort compared to playing non-preferred music (Nakamura et al., 2010).

Although the aforementioned musical characteristics have been relatively well investigated, the timing of the music application is another noteworthy feature that can potentially moderate the effect of music on performance. However, existing research examining the association between music timing and exercise performance remained inconclusive. Previous works have explored the application of music at different time points: before a task (pre-task music); during a task (in-task music) that is further subdivided into two types of synchronous and asynchronous; during the rest periods of interval sessions (respite music); and after an activity (recuperative music) (Karageorghis and Priest, 2012; Terry et al., 2020). For instance, listening to music during a 6-minute all-out running test resulted in greater mean running speed and total distance covered compared to listening to music during the warm-up-only or no-music conditions (Jebabli et al., 2022). In contrast, delivering music at different times during the exercise session (during warm-up or exercise) did not affect the physical condition, heart rate, rating of perceived exertion (RPE), or mood state during a 5-km cycling time trial (Bigliassi et al., 2012). The discrepancy in the findings among these studies could be due to the choice of music, study population, or exercise protocols (Jebabli et al., 2022). Further studies are required to compare the effects of incorporating music at different times into various exercise tasks.

Furthermore, existing research on music timing and performance exhibits a restricted scope and has primarily concentrated on dynamic and aerobic exercises such as running and cycling tasks (Bigliassi et al., 2012; Jebabli et al., 2022). While there have been studies exploring the impacts of different musical attributes (such music preference, loudness, tempi etc.) on strength exercises (Grgic, 2022), the examination of music timing effects remains limited to only one study (Crust, 2004). Crust, (2004) suggested that music played during a portion of or the entire isometric strength task resulted in longer contractions than music played prior to the exercise. However, although the grip task employed in the above study can be easily measured, it is not commonly performed by athletes during rou-

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tine training, thus limiting the generalisability of the findings. In addition, the isometric grip strength task involved only small forearm muscle groups, which elicited a relatively low level of overall exertion. Therefore, using functional isometric strength tasks that are more frequently practised by athletes, such as plank-holding and wall-sitting, would help address issues regarding external validity (Feiss et al., 2021). To the best of our knowledge, no study has examined the effects of music timing on fatigue perception and performance during functional isometric strength exercises. Acquiring such knowledge could be crucial for sports and fitness professionals in applying more effective music-timing strategies to enhance muscular training performance and facilitate adaptations.

Therefore, the primary aim of the current study was to examine the effects of applying music at different time points during two functional isometric strength exercises (plank-hold and wall-sit) compared to a no-music control condition. Based on previous findings that the incorporation of music can play a significant role in physical performance (Greco et al., 2022; Karageorghis and Priest, 2012; Terry et al., 2020), we hypothesised that listening to music during the entire exercise task or during fatigue could improve isometric strength performance (i.e., time to volitional exhaustion) compared with the no-music condition. We also hypothesised that delivering music during the entire exercise task would be more ergogenic than applying music during fatigue alone.

Methods

Participants

Twelve healthy university students (5 males and 7 females; mean age = 22.1 ± 2.3 years; mean height = 164.9 ± 8.2 cm; mean body mass = 58.3 ± 9.9 kg) from various sports teams were recruited for the study. Participants self-reported as being recreationally active, indicating that they engaged in structured aerobic training or resistance training, or both, on most days throughout the week. Participants were excluded if they performed less than 30 min of exercise twice per week and reported neuromuscular disorders or specific musculoskeletal injuries during the past year. All eligible participants were screened by a certified exercise physiologist to confirm the absence of high cardiovascular risk using the Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) (Bredin et al., 2013). Based on previous research investigating the impact of self-selected music and its timing on muscular endurance task (Crust, 2004), an effect size of f = 0.4 for the primary outcome (i.e., total time to volitional exhaustion [TTE]) was anticipated across trials, with $\alpha = 0.05$ and $\beta = 0.20$ (G*Power version 3.0.10).). Consequently, a sample size of 12 participants was determined for this study, which also aligns with relevant research in the field (Ballmann et al., 2021; Jones et al., 2017; Lima-Silva et al., 2012).

Detailed explanations of the aims, procedures, benefits, and potential risks of the study were provided to the participants, and all provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Human Research Ethics Committee of the authors' university.

Experimental procedure

This study followed a randomised within-subject crossover design (Figure 1). Participants were asked to visit the laboratory (Human Performance Laboratory at the authors' university) and perform two isometric strength exercises (plank-hold and wall-sit exercises). Upon the first laboratory visit, participants' height and body mass were measured using a stadiometer (Seca, Leicester, UK) and a body composition analyser (MC-780MA, Tanita Corp., Tokyo, Japan), respectively. Before the tests started, the participants performed a standard 3-minute warm-up consisting of dynamic stretching. The participants were positioned such that visual and other audio distractions were minimised (i.e., they faced a blank wall in a quiet area). The researcher verbally explained and demonstrated each exercise. Participants were allowed to practice each exercise (i.e., to ensure the correct technique) and ask questions prior to the start of the experiment. The participants then individually completed one of the following three experimental conditions in a randomised crossover order using a random-number generator:

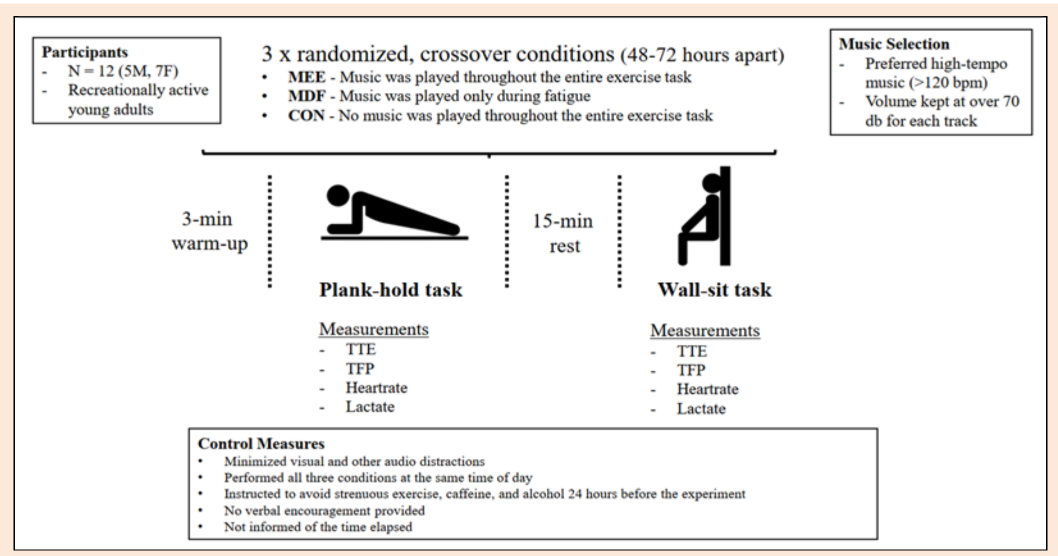

Figure 1. Study design.

(i) MEE: Music was played throughout the entire exercise task
(ii) MDF: Music was played only during fatigue (i.e., since the onset of fatigue perception). This time point for onset of fatigue is indicated by a level of 13 in Borg's RPE 6-20 scale, which is equivalent to "somewhat hard" [subjective exercise intensity] or "a little tired" [subjective exercise fatigue] on the scale (Borg, 1982))
(iii) CON: No music was played throughout the entire exercise task

Participants were instructed to perform the plank-hold and wall-sit tasks for as long as possible, separated by a 15-minute break. TTE, time to onset of fatigue perception (TFP), heart rate, and blood lactate responses were assessed during each exercise task under all conditions. Immediately upon the completion of the session, each participant completed a commitment check. To eliminate potential carryover effects, a 48 to 72-hour washout period was used between each condition (Lima-Silva et al., 2012). The participants performed all three conditions at the same time of the day and were instructed to avoid strenuous exercise, caffeine, and alcohol 24 hours before the experiment. Additionally, they were asked to report their food intake during the preceding 24 hours during the first trial and replicate the same diet on the day prior to each subsequent trial. No verbal encouragement was provided during any test. The participants were also not informed of the time elapsed to avoid external influences on their performance.

Music selection
Before the start of the experiment, participants were asked to choose their preferred high-tempo music (>120 bpm), with the loudness maintained at over 70 dB for each track. These selected features were based on the current recommendations for optimizing the ergogenic effects of music on resistance exercise performance (Grgic, 2022). Allowing participants to choose their preferred music could also help mimic a real-world exercise setting, thereby enhancing the ecological validity of the study. The music tempo was measured using an audio app (Moises; Moises Systems, Inc.), whereas the volume was tested using sound meter software (YOULEAN Loudness Meter v2.4.3, Youlean. co, USA). Music was played on a tablet computer (iPad Pro; Apple Inc.) using wireless earbuds (PowerBeats Pro; Beats; Apple Inc.).

Exercises
Plank-hold
Each participant was instructed to hold a plank facing down with their forearms and toes on the floor. The exercise was held until volitional exhaustion or until the participant could no longer hold the correct position (e.g., arching the back, dropping the hips towards the floor, or raising the hips upward).

Wall-sit
Each participant was asked to slide back down the wall slowly until their thighs were parallel to the ground (i.e., the knees reached a 90° angle). The feet were placed slightly wider than the shoulder. The exercise was held until the point of volitional exhaustion or when the participant could no longer hold the correct position (i.e., the thigh could no longer remain parallel to the ground).

Time to onset of fatigue perception
Borg's RPE 6-20 scale was used to gauge the subjective exertion of both isometric exercises (Borg, 1982). The participants were instructed to incorporate both central cardiorespiratory and muscular feelings into their overall perception of effort. The scale was presented to participants throughout each trial (Karageorghis et al., 2006). The time from the start of the exercise task to when the RPE level reached 13 (i.e., TFP) was recorded in all trials. In the MDF condition, music was played once the participants reported an RPE of 13.

Total time to volitional exhaustion
Once the participants could no longer maintain the correct form, the researcher instructed them to stop. The time from the start of the exercise task to the time when the exercise was terminated (i.e., TTE) was recorded.

Heart rate and lactate measurement
The heart rate and lactate levels were assessed before and immediately after each exercise task. Heart rate was measured using a heart rate monitor (M430, Polar Electro Oy, Finland), whereas blood lactate was measured via capillary blood samples (approximately 25 µL) from the fingertips with a portable analyser (Lactate Plus, Nova Biomedical, Waltham, Massachusetts). The inter-assay coefficient of variation of the current lactate analyser was reported to be 8.5% (Tanner et al., 2010).

Commitment check
Participants rated how much effort they invested in the exercise task from 1 (none) to 10 (very much) to indicate their commitment to the exercise tasks.

Statistical analyses
Data are expressed as the means ± standard deviations (SD). SPSS for Windows (version 26; IBM, NY, USA) was used for the statistical analysis. The normality of the data was assessed and confirmed using the Kolmogorov–Smirnov test. A series of one-way analyses of variance (ANOVAs) with repeated measures were conducted to examine the differences in TTE, TFP, heart rate, lactate, and commitment levels for each exercise task across the three conditions. When significant differences were observed, Bonferroni post hoc tests were performed for pairwise comparisons. To estimate the practical relevance of the ANOVA between-group effects, effect sizes (partial eta squared, η^2_p) were calculated. Scores of 0.01, 0.06, and > 0.14 were considered small, moderate, and large effect sizes, respectively (Cohen, 1992). Cohen's d was used to indicate the magnitude of the difference between the two groups upon pairwise comparisons where appropriate (Cohen, 1992). Scores of 0.2, 0.5, and > 0.8 were considered small, moderate, and large effect sizes, respectively. The significance level (p-value) was set to 0.05.

Table 1. **Effects of music timing on fatigue perception, performance, and physiological changes**

	Plank-hold (n =12)					Wall-sit (n =12)				
	MEE	MDF	CON	*p*-value	η^2_p	MEE	MDF	CON	*p*-value	η^2_p
TTE (sec)	171.0 ± 40.9*	163.1 ± 58.3	144.8 ± 43.5	0.05	0.22	294.8 ± 117.2*	278.7 ± 106.9^	222.0 ± 88.1	<0.01	0.46
TFP (sec)	105.2 ± 27.1*#	81.2 ± 27.8	89.8 ± 29.4	0.02	0.30	137.8 ± 38.9*	122.6 ± 45.6	111.8 ± 42.2	0.01	0.36
Δ Heart rate (bpm)	41.0 ± 14.0	38.2 ± 14.9	37.6 ± 9.9	0.44	0.07	40.5 ± 9.5	37 ± 11.1	35.8 ± 9.3	0.20	0.14
Δ Lactate (mmol/L)	1.5 ± 1.1	1.6 ± 0.8	1.4 ± 1.0	0.67	0.04	0.7 ± 0.5	0.9 ± 0.6	0.8 ± 0.6	0.78	0.02

Values are presented as the mean ± SD. Δ Heart rate = post-exercise heart rate – baseline heart rate; Δ Lactate = post-exercise lactate level – baseline lactate level. *p < 0.05 between MEE and CON; #p < 0.05 between MEE and MDF; and ^p < 0.05 between MDF and CON. MEE: music played during the entire exercise task; MDF: music played during fatigue only; CON: no music; TFP: Time to onset of fatigue perception; TTE: Total time to volitional exhaustion

Results

All the participants successfully completed the three trials, and no adverse events were reported. The mean tempo of the music chosen by participants was 151.3 ± 20.5 bpm.

Total time to volitional exhaustion

A significant main effect of condition was found for plank-hold ($p < 0.05$, $\eta^2_p = 0.22$) and wall-sit ($p < 0.05$, $\eta^2_p = 0.46$) tasks. MEE resulted in a significantly longer TTE than CON in both plank-hold ($p < 0$ .05, $d = 0.76$) and wall-sit exercises ($p < 0.05$, $d = 0.72$), whereas MDF showed a significantly longer TTE than CON in wall-sit exercises alone ($p < 0.05$, $d = 0.60$) (Table 1 and Figure 2).

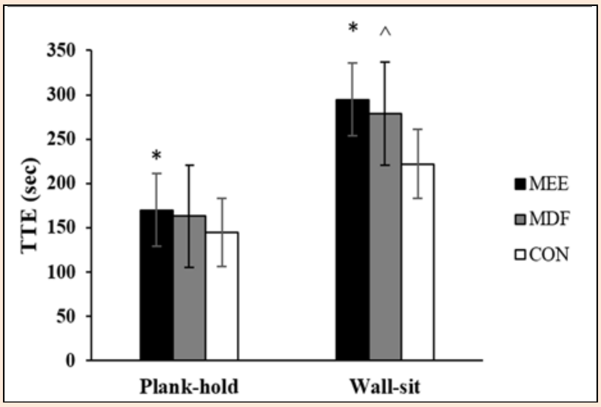

Figure 2. TTE performance in the plank-hold and wall-sit exercise tasks. *p < 0.05 between MEE and CON; ^p < 0.05 between MDF and CON

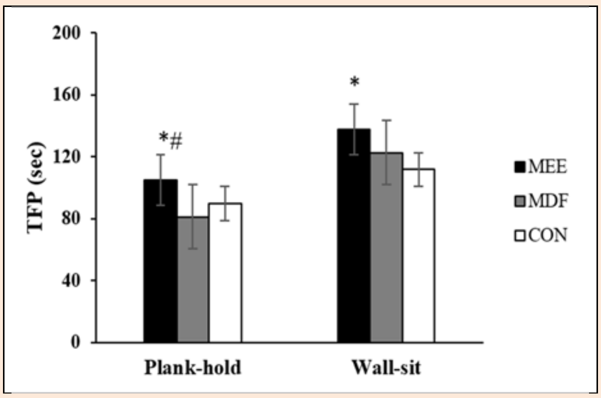

Figure 3. TFP performance in the plank-hold and wall-sit exercise tasks. *p < 0.05 between MEE and CON; #p < 0.05 between MEE and MDF

Time to fatigue perception

A significant main effect of condition was found for both plank-hold ($p < 0.05$, $\eta^2_p = 0.30$) and wall-sit tasks ($p < 0.05$, $\eta^2_p = 0.46$). TFP was significantly longer in MEE than in CON in both the plank-hold ($p < 0.05$, $d = 0.54$) and wall-sit exercises ($p < 0.05$, $d = 0.64$), whereas MEE showed significantly longer TFP than MDF in the plank-hold exercises ($p < 0.05$, $d = 0.87$). No significant differences were observed between the MDF and CON groups in either exercise task ($p > 0.05$) (Table 1 and Figure 3).

Heart rate and lactate level

No music condition influenced heart rate or blood lactate level changes in all trials ($p > 0.05$, $\eta^2_p = 0.02$-0.14) (Table 1).

Commitment check

Participants showed a tendency to invest higher effort in both MEE and MDF (both 8.8 ± 1.1) compared to CON (7.9 ± 0.9, p= 0.052).

Discussion

This study examined music timing as an important mediator of fatigue perception and performance during exercise. Our results revealed that listening to music during the entire session of the two isometric strength tasks (i.e., plank-hold and wall-sit) could delay the onset of fatigue perception and improve subsequent performance, as indicated by the extension of TFP and TTE. Adding to the existing body of research, this study found that the positive effects of music may subside if it is applied only during fatigue. These findings suggest that the timing of the music application should not be overlooked when optimising exercise performance.

Our findings are consistent with those of several laboratory studies that showed the ergogenic effects of music incorporated during exercise on functional task performance (Arazi et al., 2015; Ballmann et al., 2019; Ballmann et al., 2021). It has been speculated that music may play a significant role in changing the attentional focus of athletes or exercisers by distracting them from the unpleasant sensations associated with physical effort and fatigue (Terry et al., 2020). Based on the socio-cognitive model (Baden et al., 2004), individuals direct their attentional focus during exercise via two pathways: association, where individuals focus on internal body signals, and disassociation, where attention is directed to external cues in the surrounding environment (Lima-Silva et al., 2012). Given our limited attentional focus capacity, more attentional space would be occupied by dissociative thoughts if distractive sources were present. Music, as a powerful external dissociative stimulus, may help diversify the intentional focus from physical sensations, leaving less room for the perception of fatigue to be processed. In our study, participants in the MEE condition showed extended TFP (i.e., delayed onset of fatigue) and TTE over the CON condition in the plank-hold and wall-sit exercises. These observed benefits may be attributable to the external cues provided by music throughout the entire exercise task, which compete with cues arising from physiological alterations to occupy a considerable part of the attentional focus. Findings from a recent *f*MRI study (Bigliassi et al., 2018) investigating the cerebral effects of music during isometric exercise further supported the role of music in externally reallocating attention by modulating the activity of the left inferior frontal gyrus (lIFG). The activation of the lIFG appears to moderate the processing of interoceptive signals, providing a neurophysiological mechanism responsible for reducing exercise consciousness and ameliorating fatigue-related symptoms (Bigliassi et al., 2018).

In addition to the general influence, our study revealed a lower ergogenic effect when music was applied only during fatigue. In the MDF condition, no significant differences in TFP were observed compared to the CON condition in either exercise task. An absence of improvement in TTE was also observed when MDF was compared with CON in the plank-hold exercise task. It has been proposed that the attentional focus effect is more prominent only when exercise intensity is low to moderate (Lima-Silva et al., 2012; Tenenbaum et al., 2004). When exercise intensity exceeds a certain attention threshold, thoughts naturally become more associative because of increased somatic awareness and pain (e.g., increased breathing rate, burning muscles, and overall fatigue) (Razon et al., 2009). This notion is supported by the findings of Baden et al. (Baden et al., 2004), who showed a tendency toward increased associative thoughts at the end of 8- and 10-mile races, probably owing to an increase in fatigue sensations when approaching the end of the exercise. Similarly, while the introduction of music during the beginning (i.e., first 1.5 km) of a 5-km running trial reduced thoughts related to the physical sensations associated with exercise and allowed for increased running velocity and improved performance, the same beneficial effect was not observed when music was applied at the end of the trial (i.e., last 1.5 km) (Lima-Silva et al., 2012). According to the parallel processing model of pain (Rejeski, 1985), sensations derived from various sources compete for attentional focus; however, the extent to which these sensations are dominant depends on the strength and magnitude of the stimulus. When music was played at a relatively high level of perceived exertion (e.g., in the MDF condition of our study), the participants had already experienced significant metabolic and physiological perturbations, leading to an attentional shift towards the associative domain with bodily sensations. Furthermore, participants may tend to rely on internal task-related focus to maintain the appropriate form of isometric tasks to prevent disruption of biomechanics towards the end of the exercises when the body has accumulated a certain degree of fatigue (D'Agata et al., 2023). In contrast, participants may be better able to retain a reasonable focus on more pleasant external cues when listening to music at the early stage of isometric strength exercises (i.e., at the beginning of the MEE condition). This may help delay the perception of fatigue when somatic sensations are not a dominant factor in attentional focus (Tenenbaum et al., 2004).

Another noteworthy observation of the current study is that neither the music condition influenced the heart rate nor blood lactate level changes in all trials. Our finding is in contrast with a recent study by Jebabli et al. (2022) (Jebabli et al., 2022), which showed a significant decrease in blood lactate concentrations when participants listened to their preferred music during a 6-minute all-out running test. Such discrepancies in the physiological changes between the two studies could be attributed to the nature of the exercise tasks. Compared with the dynamic, high-intensity running task in the Jebabli et al. study, the isometric strength tasks in our study were characterised by prolonged static muscle contraction without any significant joint movement, which generally resulted in a slower increase in heart rate and lactate production (Lum and Barbosa, 2019). Our findings are in accordance with those of another recent study that showed no effect of music on physiological responses when music with either a fast or slow tempo was applied during isometric strength exercises (Feiss et al., 2021). It is also known that the plasma volume variation may influence the lactate measurements in response to supramaximal exercise (e.g., sprinting) (Zouhal et al., 2007), but its effect on isometric exercise appeared to be modest. Altogether, our results suggest that the moderating effect of music on isometric strength exercises does not correlate with major changes in physiological responses, which distinguishes it from the effects observed in dynamic exercise. Future studies should expand our understanding of the effects of music timing on physiological responses by using a broader range of exercise tasks.

This study has several strengths, including the use of a crossover randomised controlled trial that can eliminate problems arising from between-subject differences. While most previous studies focused on the general effect of listening to music on performance during exercise, the current study advances the current literature by investigating the moderating effect of application timing on fatigue perception during isometric exercises. Moreover, most previous studies adopted less-functional exercise tasks (e.g., grip strength tasks), which might have potentially limited the generalisability of the findings. The isometric strength tasks (plank-hold and wall-sit) applied in the current study should be deemed more valid and have similar external validity to dynamic strength tasks (i.e., they are comparable to tasks commonly performed by athletes). Therefore, our study should help unmask the effects of music timing on muscular endurance performance from a wider range of perspectives and conditions.

Despite these strengths, the major limitations of the present study include the lack of a counterbalanced experimental design, as all participants completed the plank-hold task followed by the wall-sit task. It is possible that fatigue from the plank-hold exercise was carried over to the subsequent wall-sit exercise. However, sufficient rest (i.e., a 15-minute break) was provided between exercises to minimise this effect. Moreover, the neurophysiological mechanisms underlying fatigue were not explicitly investigated. Some of the explanations of our results remained speculative and should be interpreted with cautions. Future studies should consider directly assessing attentional focus and applying the EEG technique to explore how music timing might impact the central brain regions involved in fatigue perception. In addition, it is known that biological sex may influence several responses to exercise such as heart rate, lactate, and fatigue perception (Lewis et al., 1986), but our relatively small sample size precluded us from performing sub-group analyses. Future research on how music timing may affect exercise preference in males and females differently is warranted. Finally, our commitment check results suggested a tendency for participants to invest more effort in both music-exposed conditions than in the CON condition. This implies that motivation level may be a confounding factor that partially moderates performance results. For instance, listening to self-preferred music is associated with increased motivation and the subsequent enhancement of resistance exercise performance (Ballmann et al., 2021). Thus, the interaction between exercise performance and the motivational quality of music warrants further investigation.

From a practical perspective, our findings should assist practitioners in applying more effective music timing strategies to enhance muscular endurance performance and training adaptations. The ergogenic effect of music is mainly attributed to its ability to delay fatigue perception (i.e., longer time to “get tired”) rather than an increased capacity to resist accumulated fatigue. To obtain optimal ergogenic effects on isometric strength exercises, athletes and exercises may consider extending music exposure, such as delivering music before and during the entire exercise task as well as throughout rest periods. The use of wireless earbuds to deliver individualised, self-preferred music, as in this study, could be an effective and convenient option in practical training settings.

Conclusion

Our results suggest that listening to music during the entire exercise can delay the onset of fatigue perception in isometric strength tasks, whereas listening to music during fatigue has only a modest effect. The moderating effect of music timing on isometric strength exercises did not seem to correlate with any changes in major physiological outcomes such as heart rate and lactate levels. Our findings may assist practitioners in applying more effective music timing strategies to enhance muscular endurance performance and training adaptation.

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Key points

- Listening to music during the entire exercise can delay the onset of fatigue perception and subsequently improve performance in isometric strength exercises, but the ergogenic effects may subside if the music is applied during fatigue only.
- The ergogenic effect of music may be attributed to its ability to delay fatigue perception (i.e., longer time to "get tired") rather than an increased capacity to resist accumulated fatigue.
- To obtain the optimal ergogenic effects on isometric strength exercises, athletes and exercises may therefore consider extending music exposure, such as delivering music prior to and during the entire exercise task as well as throughout rest periods.

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